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REGULATORY GUIDE 1.121 ANALYSIS FOR THE INDIAN POINT UNIT 2 REPLACEMENT STEAM GENERATORS

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Regulatory Guide 1.121 Analysis for the Indian Point Unit 2 Steam Generators

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WESTINGHOUSE ELECTRIC COMPANY LLC
NUCLEAR SERVICES DIVISION
P.O. BOX 355
PITTSBURGH, PENNSYLVANIA 15230

ABSTRACT

This report describes the analysis to determine tube structural limits for the Indian Point Unit 2 steam generator tubing. Based on the results, a minimum tube thickness requirement in percent of the nominal wall is established in accordance with the guidelines of the USNRC Regulatory Guide 1.121. A tube repair limit in percent of the nominal tube wall thickness is established by incorporating an allowance for uncertainties in eddy current measurements and continued tube wall degradation between consecutive inspection periods.

LIST OF ABBREVIATIONS

Abbreviation	Description
ASME	American Society of Mechanical Engineers
AVB	Anti-Vibration Bar
DBE	Design Basis Earthquake
EC	Eddy Current
EPRI	Electric Power Research Institute
FIV	Flow-Induced Vibration
FDB	Flow Distribution Baffle
FS	Factor of Safety
LOCA	Loss of Coolant Accident
NDE	Non-Destructive Examination
NSSS	Nuclear Steam Supply System
PWR	Pressurized Water Reactor
RG	Regulatory Guide
LSP	Loss of Secondary Pressure Accident
T/H	Thermal-Hydraulic
TSP	Tube Support Plate
US NRC	United States Nuclear Regulatory Commission
ΔP	Thinned Tube Burst Strength
ΔP_i	Primary-to-Secondary Pressure Gradient
ΔP_o	Secondary-to-Primary Pressure Gradient
ΔP^o	Unthinned Tube Burst Strength
a	Crack Length
A_{min}	Degraded Tube Area
A_{nom}	Nominal Tube Area
d	Depth of Thinning
ΔP	Pressure Drop
h	Depth of Thinning
I_{min}	Degraded Area Moment of Inertia
I_{nom}	Nominal Area Moment of Inertia
in	Inch
K	Shape Factor
ksi	Kips Per Square Inch
L	Length of Thinned Region
lbs	Pounds

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LIST OF ABBREVIATIONS (Continued)

Abbreviation	Description
λ	Normalized Crack Length
OD_{max}	Maximum Tube Outside Diameter
OD_{min}	Minimum Tube Outside Diameter
°F	Degrees Fahrenheit
P_b	Primary Bending Stress
P_c	Collapse Pressure
P_i	Primary Side Pressure
P_m	Primary Membrane Stress
P_N	Normalized Burst Pressure
P_o	Secondary Pressure
psi	Pounds Per Square Inch
psia	Pounds Per Square Inch Atmospheric
Q	Secondary Stress
R_i	Tube Inside Radius
r_m	Tube Mean Radius
R_o	Tube Outside Radius
SIG	Principal Stress
S_m	Allowable Stress Intensity
S_u	Ultimate Strength
S_y	Yield Strength
t	Tube Wall Thickness
t_{min}	Tube Minimum Wall Thickness
T_{hot}	Reactor Coolant Temperature to Steam Generator

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1.0 INTRODUCTION

1.1 Regulatory Requirements for Tube Plugging

The heat transfer area of steam generators in a PWR nuclear steam supply system (NSSS) comprises over 50 percent of the total primary system pressure boundary. The steam generator tubing, therefore, represents a primary barrier against the release of radioactivity to the environment. For this reason, conservative design criteria have been established for the maintenance of tube structural integrity under the postulated design-basis accident condition loadings in accordance with the ASME Code, Reference 1.

Over a period of time under the influence of the operating loads and environment in the steam generator, some tubes may become degraded in local areas. To determine the condition of the tubing, in-service inspection using eddy-current techniques is performed in accordance with the guidelines of US NRC Regulatory Guide 1.83, Reference 2. Partially degraded tubes are satisfactory for continued service provided that defined stress and leakage limits are satisfied, and that the prescribed structural limit is adjusted to take into account possible uncertainties in the eddy current inspection, and an operational allowance for continued tube degradation until the next scheduled inspection.

The US NRC Regulatory Guide 1.121, Reference 3, describes an acceptable method for establishing the limiting safe condition of degradation in the tubes beyond which tubes found defective by the established in-service inspection shall be removed from service. The level of acceptable degradation is referred to as the "repair limit".

Briefly, the regulatory guideline consists of verifying that

1. In the case of (uniform) tube thinning or wall loss, the remaining tube wall can still meet applicable stress limits during normal and accident loading conditions,
2. For tube cracking, that margins against tube burst are satisfied, and that primary-to-secondary leakage limits are satisfied.

The purpose of this evaluation is to define the "structural limits" for an assumed uniform thinning mode of degradation in both the axial and circumferential directions. The assumption of uniform thinning is generally regarded to result in a conservative structural limit for all flaw types occurring in the field. The allowable tube repair limit, in accordance with Regulatory Guide 1.121, is obtained by incorporating into the resulting structural limit a growth allowance for continued operation until the next scheduled inspection and also an allowance for eddy current measurement uncertainty.

1.2 Scope of the Structural Limit Analysis

This report describes the results of an analysis performed for the Indian Point Unit 2 replacement steam generator tubing in order to establish the tube structural limits. Indian Point Unit 2 is a four-loop NSSS that includes a Model 44F steam generator in each loop. A schematic of a Model 44F steam generator is shown in Figure 1. All tubing in the Indian Point

Unit 2 steam generators is thermally treated Alloy 600. The nominal tube geometry is 0.875" OD by 0.050" t.

This evaluation is applicable to the integrity of individual tubes with both general and local degradation. General degradation is treated by a nominal reduction in thickness over its entire length. Local degradation is treated as either a loss of wall thickness over a limited length, or as a single axial through-wall or partial-depth crack. Criteria are categorized into three tube regions, anti-vibration bar (AVB) intersections, support plate intersections, and straight leg regions of the tube.

The structural limit criteria developed herein are not applicable to circumferential cracks. Circumferential cracks, should they occur, must be considered through a degradation specific program.

The evaluation basically consists of tube load determination, tube stress analysis, minimum tube wall thickness determination, and confirmation of leak-before-break. The leak-before-break confirmation makes use of test data on leakage rates and burst strength as a function of through-wall crack length. The data is available from several programs for establishing characteristics of degraded Alloy 600 tubing.

Cracking of steam generator tubing is usually the result of corrosion mechanisms and the cracks propagate as a result of continued corrosion rather than by the loads induced during operation. Burst testing of tubes with through-wall cracks show that they do not fail in a brittle manner but by plastic instability, or fishmouthing, of the cracked region. It is for these reasons that burst testing has become the standard for demonstrating tube strength. Leakage through these tight cracks is determined also by testing to provide as realistic a leak-before-break margin as possible. The leak rate tests are performed in the lab at steam generator pressure and temperature with fatigue cracks induced in tube samples. The question of the potential occurrence of fatigue cracks under cyclic stresses is considered in the validation of leak-before-break.

In connection with the tube bundle integrity evaluation, it should be noted that both the safety and functional requirements are to be satisfied. The safety requirement, which is the basis of the Regulatory Guide 1.121 criteria, governs the limiting safe condition of the localized tube degradation, as established by in-service inspection, beyond which tubes should be repaired or removed from service. In contrast, the functional requirement applies to the overall degradation of the tube bundle. Although both the safety and functional requirements are to be evaluated as part of this analysis, the subject matter of this analysis deals mainly with the safety requirements associated with the repair limit criteria in Regulatory Guide 1.121.

Regarding the remainder of this document, specific criteria and the corresponding allowable limits and/or margins associated with the safety and functional requirements are discussed in Section 2. Details of tube loadings during the various plant conditions are discussed in Section 3. Section 4 contains a summary of the analysis results for overall bundle integrity, and

Section 5 summarizes the calculations to determine the applicable tube structural limits. Finally, Section 6 presents a summary of the tube structural limits, with report references listed in Section 7.

2.0 INTEGRITY REQUIREMENTS AND CRITERIA

The steam generator tubing represents an integral part of the primary barrier against the release of radioactivity into the atmosphere. In the event of a primary loss-of-coolant accident (LOCA), the tubing also provides the necessary heat sink, initially, for the core cooldown, and later for maintaining the plant in the safe shutdown condition. Thus, it is important to establish the structural integrity of the steam generator tubing by requiring that, based on analysis, testing, and in-service inspection, the tube bundle sustain, with recommended margins, the loads during normal operation and the various postulated accident conditions, without a loss of function of safety.

2.1 Functional and Safety Requirements

Tube walls may be affected by a number of different factors such as environment-induced corrosion (including intergranular attack and stress-corrosion cracking), erosion due to the fluid friction, and wear from mechanical and flow-induced vibrations. The wall loss due to general erosion or corrosion has been conservatively established and is assumed to be more or less uniform for the entire tube bundle during the plant operating period. However, a potential for additional wall degradation may exist locally in some tubes in the region of tube/tube support plate and tube/AVB intersections because of a higher potential for chemical concentrations and/or relative motion in these regions.

Based on steam generator operational history, the majority of the tubes are expected to be subjected to only a small, but probably a more or less uniform, tube wall loss over the design life of the unit. On the other hand, some tubes of the bundle may degrade locally to the extent that either the removal of these tubes from service or local repair to restore integrity is necessary for continued safe operation of the unit. Because of these two distinct modes of tube degradation, it is possible to separate the functional and safety requirements into those affecting the integrity of (1) the overall tube bundle, and (2) a locally-thinned or degraded tube. In evaluating the overall bundle for general erosion and corrosion, an end-of-life general erosion on the inside of the tube is assumed to be [ ]^{a,c} inch, and a general corrosion on the outside of the tube is assumed to be [ ]^{a,c} inch.

2.2 Overall Tube Bundle Integrity Requirements

These requirements are based on the assumption that removal of tubes from service does not impair the structural and functional capability of the overall tube bundle. In the event of extensive tube plugging, plant derating and/or re-analyses associated with functional requirement verification may be necessary. However, re-analysis for the verification of the structural integrity of the tube bundle as a whole will not be required, since the deactivated tubes would physically remain in the tube bundle, thus maintaining the structural characteristics of the tube bundle practically intact. Removal of an isolated tube for inspection purposes would have an insignificant effect on the overall bundle response.

2.3 Locally-Degraded Tube Integrity Requirements

As previously indicated, the potential for localized tube wall degradation may exist at certain locations in the tube bundle. Even though such localized degradation has generally been confined to a small portion of the tubing (and hence of no adverse consequence to the structural capability of the bundle), it is to be assessed from the viewpoint of a potential tube burst, if the associated depth of penetration is relatively large. Therefore, to show that there are no safety consequences as a result of a random tube burst, a conservative bound on acceptable degradation for continued operation must be established along with the in-service inspection and leakage monitoring requirements for the detection of degraded tubes. Guidelines in US NRC Regulatory Guide 1.83 for EC inspection and US NRC Regulatory Guide 1.121 for tube repair limit calculations provide the bases for determining the limiting safe condition of a locally-degraded tube. For tube degradation in excess of the established repair limit, it is required that the tube be repaired or removed from service in order to provide continued safe operation.

The intent of US NRC Regulatory Guide 1.121, as applicable to this analysis, is as follows:

- In the case of tube thinning due to mechanical and chemical wastage, and generalized intergranular attack, stresses in the remaining tube wall must be capable of meeting the applicable requirements with adequate allowance for the EC measurement uncertainties and assumed continued degradation until the next scheduled outage. The strength requirements are specified in terms of allowable primary stress limits and margins against burst during normal operation and collapse following a LOCA.

- For tube cracking due to fatigue and/or stress corrosion, a specification on maximum allowable leak rate during normal operation must be established such that a reasonable likelihood that "leak before break" would be achieved. If the leak rate exceeds the specification, the plant must be shut down and corrective actions taken to restore integrity of the unit. The EPRI PWR Primary-to-Secondary Leak Guidelines, Reference 4, form the basis of the plant's operational leakage program. These guidelines define several monitoring and action level conditions, depending on the amount of leakage and the rate of leakage increase. Once the primary-to-secondary leakage exceeds 75 gallons per day (gpd) for a period of one hour or longer, the utility must begin action to move to Mode 3 (hot standby) operation within twenty-four hours. If the primary-to-secondary leakage exceeds 75 gpd with an increasing leak rate of ≥ 30 gpd/hr, the utility must ramp to 50% power within one hour and to Mode 3 operation within two hours. Finally, if the primary-to-secondary leak rate exceeds 150 gpd, regardless of the rate of increase, the utility must move to Mode 3 operation within the next six hours.

2.4 Tube Stress Classification

In order to evaluate the tube stresses, the stresses must be classified consistent with the definitions in the ASME Code. There are two general considerations that must be accounted for in determining the classification of stresses, namely the location in the structure and the nature of the loading.

The tube stress classification for various locations in the tube bundle under the different types of loadings is summarized in Table 1. The notation "P_m" refers to general primary membrane stress, "P_b" refers to primary bending stress and "Q" refers to secondary stress.

[

]a,c

[

]a,c

2.5 Criteria and Stress Limits

The allowable stress limits are established using the ASME Code minimum strength properties in Reference 13. A summary of the corresponding tube strength properties is provided in Table 2. Note that elevated temperature values for Alloy 600 ultimate strength, S_u, are not provided in the Code Case. However, the value can be inferred from the specified value for S_m. Appendix III, Paragraph III-2110 (b) of the ASME Code specifies four criteria for establishing S_m. S_m is the lessor of the following criteria.

2/3 S_y at Room Temperature
90% S_y at Temperature
1/3 S_u at Room Temperature
1/3 S_u at Temperature

For an S_m value of 80 ksi, the limiting criteria would be 1/3 S_u, and 3 x 26.6 ksi is 79.8 ksi, which rounds to 80 ksi. Note that the analysis is performed based on the properties at 600°F.

It should be noted that in performing the analysis to assess primary-to-secondary leak limits, where the EPRI PWR Primary-to-Secondary Leak Guidelines are used, the tube burst strength is calculated based on expected strength properties, as taken from Reference 5. The yield and ultimate strengths for 7/8" Alloy 600 Thermally Treated tubing at 650°F are [ ]^{a,c}, respectively.

Level A and B Service Conditions

The limits on primary stress, P_m, for a primary-to-secondary pressure differential ΔP_i, are as follows:

$$\text{Normal Operation: } P_m < S_u/3$$

$$\text{Transient Conditions: } P_m < S_y$$

Level D (Postulated Accident) Service Conditions

Loadings associated with a primary LOCA or a loss of secondary side pressure (LSP) blowdown, concurrent with the DBE, are evaluated against the stress limits specified for Level D Service Conditions in Appendix F of the Code.[1] Since the tube has a circular cross-section, the shape factor K is introduced in determining the allowable membrane plus bending stress.

$$P_m < \text{smaller of } 2.4\ S_m,\ 0.7\ S_u$$

$$P_m + P_b < K \times (\text{Limit on } S_m)$$

The shape factor K, is the ratio of the moment to cause yielding of the full cross-section, assuming elastic-plastic material behavior, to the moment to cause yielding of the tube outer fiber. For a circular cross-section, the shape factor, K, has the following relationship.

$$K = \frac{16R_o}{3\pi}\left(\frac{R_o^{\,3} - R_i^{\,3}}{R_o^{\,4} - R_i^{\,4}}\right)$$

where,

$$R_o = \text{Tube outside radius}$$
$$R_i = \text{Tube inside radius}$$

For two-sided AVB wear, the shape factor, K, has the following relationship for in-plane bending. Recall that out-of-plane bending is secondary for localized tube wear.

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1 The 1965 / Summer 66 edition of the Code does not provide stress limits for faulted conditions. Therefore, the applicable criteria are taken from Appendix F of the Code as found in 1974 and later editions of the Code.

$$K = \frac{16R_o}{3}\left(\frac{R_o^3 - R_i^3}{\pi\left(R_o^4 - R_i^4\right) - 8I_s}\right) - \frac{8R_0\left(R_o d^2 - \frac{1}{3}d^3\right)}{\pi\left(R_o^4 - R_i^4\right) - 8I_s}$$

where,

$$I_s = \frac{AR_o^2}{4}\left\{1 - \frac{2}{3}\left[\frac{\sin^3\alpha\cos\alpha}{\alpha - \sin\alpha\cos\alpha}\right]\right\}$$

$$A = \frac{R_o^2}{2}(2\alpha - \sin 2\alpha)$$

$$\alpha = \cos^{-1}\left(\frac{R_o - d}{R_o}\right)$$

and,

R_o = Tube outside radius
R_i = Tube inside radius
d = Depth of thinning

Table 3 and Table 4 provide summaries of the shape factor K versus depth of thinning for uniform and two-sided wear, respectively.

A summary of the allowable stresses for the various operating conditions is provided in Table 5. Once preliminary values are established for the minimum cross-sections, then allowable stresses are calculated for the locally degraded cross-sections, as appropriate, and the minimum cross-sections are evaluated against those allowables.

As far as the consideration of the secondary and peak stresses in the evaluation of a locally-thinned tube is concerned, it is noted that the effects of these stresses will be manifested in ratcheting, fatigue and/or corrosion-fatigue type of mechanisms associated with tube cracking if that should occur. In that case, the validation of leak-before-break would implicitly safeguard against the effects of the secondary and peak stresses.

3.0 PRIMARY LOADS FOR TUBE ANALYSIS

In establishing the safe limiting condition of a tube in terms of its remaining wall thickness, the effects of loadings during both normal operation and the postulated accident conditions must be evaluated. The applicable stress criteria are in terms of allowables for the primary membrane and membrane-plus-bending stress intensities. Hence, only the primary loads (loads necessary for equilibrium) need be considered.

[

]a,c

This analysis considers the tube / support plate intersections to be in the unlocked condition. With broached stainless steel support plates, such as exist for the Indian Point Unit 2 replacement steam generators, there has not been any occurrence of corrosion products building up in the broached tube intersections in any of the operating units. Thus, there is no reason to expect such a condition to develop at Indian Point Unit 2.

3.1 Normal Operation and Level A / Level B Service Conditions

The limiting stresses during Level A and Level B service conditions are the primary membrane stresses due to the primary-to-secondary pressure differential ΔPi across the tube wall. Two sets of conditions are evaluated that bound the operating parameters corresponding to the current operating conditions. They are referred to as "high T_{ave}" and "low T_{ave}" in the discussions to follow. A summary of the normal operation (100% Power) parameters corresponding to high T_{ave} and low T_{ave} is provided in Table 6. Summaries of the corresponding transient parameters are provided in Table 7 through Table 8 for high T_{ave} and low T_{ave}, conditions, respectively.

3.2 Accident Condition Loads

For the Faulted plant condition evaluation, the postulated Level D Service Condition events are: Loss-of-Coolant Accident (LOCA), Loss of Secondary Pressure (LSP) and Design Basis Earthquake (DBE). The tube integrity evaluation is performed for the blowdown loads in conjunction with the DBE loads, i.e.: LOCA + DBE and LSP + DBE. The tube loadings are maximized by assuming these events to initiate when the plant is operating at the 100% full power condition.

3.2.1 Loss of Coolant Accident Loads

LOCA loads are developed as a result of transient flow and pressure fluctuations following a postulated main coolant pipe break. Based on the prior qualification of the Indian Point Unit 2 steam generators for leak before break requirements for the primary piping, the limiting LOCA event is one of the branch line breaks. As a result of a LOCA, the steam generator tubing is subjected to three distinct types of loading mechanisms:

1) Primary fluid rarefaction wave loads,
2) Steam generator shaking loads due to the coolant loop motion and,
3) External hydrostatic pressure loads as the primary side blows down to the atmospheric pressure.

The first two loading mechanisms occur simultaneously during the course of LOCA and result predominantly in bending stresses in the tube U-bends at the top TSP. In contrast, the maximum secondary-to-primary pressure differential occurs during the quasi steady-state portion of the transient and, therefore, its effects on tube integrity can be evaluated independently of the first two loads. The main concern with this loading is tube collapse potential and consequent increase in the primary flow resistance to the extent that the core cooldown rate is affected.

In regards to LOCA shaking, for large pipe break events, that are assumed to occur immediately adjacent to the primary piping inlet or outlet, the pipe break event results in shaking of the overall steam generator. However, as noted above, under leak before break conditions, small pipe break events are considered in this analysis. Since these events are remote to the steam generator and of a much reduced pipe size, the potential for shaking loads being introduced to the steam generator is significantly reduced. Even for large pipe break events, the tube stresses resulting from shaking of the steam generator are small compared to the rarefaction wave loads. Due to the remoteness of the small pipe breaks and reduced size of the pipe failure, it is judged that LOCA shaking loads for the small pipe break events will not result in any significant tube loads. As such, no further consideration is given to the LOCA shaking conditions for this analysis.

The LOCA rarefaction wave initiates at the postulated break location and travels around the tube U-bends. A differential pressure is created across the two legs of the tubes that causes an in-plane horizontal motion of the U-bend.

The pressure-time history input to the structural analysis is obtained from a transient thermal-hydraulic (T/H) analysis using the MULTIFLEX computer code, Reference 6. A break opening time of 1.0 msec of full flow area, simulating an instantaneous double-ended rupture is assumed to obtain conservative hydraulic loads. Pressure time histories are calculated for three tube radii, identified as the minimum, average and maximum radius tubes. A plot showing the tube representation in the T/H model is provided in Figure 2.

Using "leak before break" criteria, the most severe LOCA loadings for the Indian Point Unit 2 steam generators are the Pressurizer Line and the Accumulator Line breaks. A summary of the maximum hot-to-cold leg pressure drops for the Pressurizer Line break and the Accumulator

Line break is provided in Table 9. Plots of the hot-to-cold leg pressure drop for the maximum radius tube are shown in Figure 3 for the Pressurizer Line break and in Figure 4 for the Accumulator Line break.

For the rarefaction wave induced loadings, the predominant motion of the U-bends is in the plane of the U-bend. Thus, the anti-vibration bars do not couple the individual tube motions. Also, only the U-bend region is subjected to high bending stresses. Therefore, the structural analysis is performed using single tube models limited to the U-bend and the straight-leg region over the top two TSP's. A schematic of the tube structural model is shown in Figure 5. The model consists of five tubes corresponding to approximately Row 2 (R=3.82 inches2), Row 23 (R=29.34 inches), Row 30 (R=37.99 inches), Row 36 (R=45.39 inches), and Row 45 (R=56.50 inches). After results were obtained for the initial three tube radii, it was concluded that the limiting tube had likely not been considered. Thus, two additional tubes were considered having radii of 37.99 inches and 45.39 inches. The applied loads for the additional tubes are based on the pressure time history for the Row 23 tube was scaled upwards to account for the variation in the amplitude of the loads due to the increased tube radius. The mass inertia is input as effective material density and includes the weight of the tube, weight of the primary fluid inside the tube and the hydrodynamic mass effects of the secondary fluid. Damping coefficients are defined to realize a maximum damping of 1% at the lowest and highest significant frequencies of the structure.

3.2.2 Loss of Secondary Pressure (LSP) Loads

During the postulated Loss of Secondary Pressure accident, the predominant primary tube stresses result from the ΔPi loading. The secondary side of the faulted steam generator blows down to the ambient pressure. A peak transient pressure differential of [ ]^{a,c} psi is defined for the LSP transient.

In addition to the primary pressure loads, bending of the tube may occur as a result of flow-induced vibration. As noted earlier, stresses due to flow-induced vibration are not evaluated specifically since they are enveloped by the in-plane U-bend stresses from LOCA + DBE, and since they are axial bending stresses which would not propagate an axially oriented crack. As a result, flow-induced vibration stresses do not significantly influence the burst pressure of a cracked or thinned tube.

3.2.3 Design Basis Earthquake (DBE) Loads

Seismic (DBE) loads are developed as a result of the motion of the ground during an earthquake. The steam generator may be subjected to earthquake forces in the horizontal and vertical directions equal to 0.37g and 0.25g, respectively, applied at the center of gravity.

2 The tube radius of 3.82 inches does not correspond exactly to tube Row 2.

The maximum stresses will result from the seismic forces due to 0.37g horizontal acceleration in a tube with the largest U-bend radius. The tube is modeled as a beam, fixed at the secondary side tubesheet surface and simply supported at all the baffle/tube support plates. For conservatism, the U-bend region of the tube is assumed as overhanging from the top tube support plate. The U-bend region is modeled as a straight beam of length equal to the distance of center of gravity of the U-bend from the top tube support plate. The loading on the tube model is applied as an uniformly distributed force over the portion between the tubesheet and top tube support plate and the total force acting on the overhang portion.

The seismic analysis statically determined a maximum tube bending stress of [ ][a,c].

4.0 TUBE EVALUATION: OVERALL BUNDLE INTEGRITY

4.1 Functional Integrity Evaluation

The overall tube bundle integrity is evaluated to show that the tube primary stresses are within the specified acceptance limits. The tubes are evaluated for primary membrane stresses resulting from seismic, dead weight, and through wall pressure. For primary membrane plus bending stresses, the tubes are evaluated for LOCA + DBE and LSP + DBE.

4.1.1 LOCA + DBE

The maximum seismic bending stress is [ ]a,c. The membrane stresses are assumed to be negligible. The maximum seismic bending stress is assumed to occur on all tube rows.

A summary of the maximum and minimum bending stresses for the Pressurizer Line and Accumulator Line breaks for the top tube support plate and U-bend locations are shown in Table 10. Based on the analysis results, the limiting location for combined LOCA + DBE stresses is the U-bend region of the tube. Recall that in-plane bending stresses at the top TSP are secondary and do not need to be evaluated for primary stress limits.

For the U-bend region of the tube, where both the in-plane and out-of-plane stresses are classified as primary for the nominal tube, it is necessary to determine the tube stress as a function of the azimuthal position around the tube circumference. At any given angle around the tube circumference, the combined LOCA + DBE membrane + bending stress is calculated as follows:

$$\sigma_a = \{[\sigma_b(\text{DBE-In-Plane}) \cos\theta + \sigma_b(\text{DBE-Out-of-Plane}) \sin\theta + \sigma_m(\text{DBE})]^2 + [\sigma_b(\text{LOCA-In-Plane}) \cos\theta]^2\}^{1/2}$$

The combined LOCA + DBE membrane + bending stresses for the U-bend region are shown in Table 11. The membrane stress in Table 11 corresponds to the through-wall pressure induced stresses. Similarly, a summary of the combined LOCA + DBE membrane + bending stresses at the top tube support plate are shown in Table 12.

Through-wall pressure stresses are calculated using the following closed form solutions.

$$\sigma_h = \sigma_{hoop} = \frac{P_i R_i - P_o R_o}{t}$$

$$\sigma_a = \sigma_{axial} = \frac{P_i R_i^2 - P_o R_o^2}{R_o^2 - R_i^2}$$

For the LOCA + DBE case, the through-wall pressure stresses are conservatively calculated for full power operating conditions, which correspond to the transient initial conditions. As a result of the break, the primary side de-pressurizes, resulting in a decrease in the primary-to-secondary pressure drop from the transient initial conditions. Stresses are calculated for both the high T_{ave} and low T_{ave} conditions. The low T_{ave} conditions are conservatively used for the functional integrity evaluation. For the LSP transient, the through-wall pressure stresses are calculated for the maximum primary to secondary ΔP loading. A summary of the resulting tube stresses for through-wall pressure gradients corresponding to Full Power and LSP conditions is provided in Table 13.

The combined LOCA + DBE stresses are shown in Table 14 for the U-bend region and in Table 15 for the top TSP. Summaries of the tube stress intensities for the LOCA + DBE conditions are provided in Table 16 and Table 17 for the U-bend and top TSP, respectively. The maximum stress intensity has a value of [ ]^{a,c} ksi.

4.1.2 LSP + DBE

The applicable pressure drop for the LSP loading is [ ]^{a,c} psi. The tube stresses resulting from the through-wall pressure gradient are summarized in Table 13. The seismic stresses are combined with the LSP stresses using the same methodology as for the LOCA + DBE load combination. The combined LSP + DBE stresses are summarized in Table 18. Summaries of the corresponding tube stress intensities for the LSP + DBE conditions are provided Table 19. The maximum stress intensity has a value of [ ]^{a,c} ksi.

4.1.3 Combined Stress – End-of-Life Condition

To account for the loss of material due to general erosion and corrosion, the maximum stress intensity is conservatively scaled upward by the ratio of the area moments of inertia for the nominal and reduced cross-sections, 1.06. The maximum stress intensity for the reduced cross-section is [ ]^{a,c}, which is less than the allowable value of 75.44 ksi.

5.0 TUBE EVALUATION: DEGRADED TUBE CONDITIONS

5.1 Analysis Overview

This section establishes the minimum wall requirement for the tubes and compares stresses in the degraded tube against the appropriate structural limits. Calculations are performed to establish the minimum wall requirements for uniform tube wear and for wear over limited axial extent at the tube support plate and AVB intersections. The degraded tube is also evaluated relative to requirements for margin to burst, collapse loads, and leak-before-break requirements.

5.2 Uniform Tube Wear

5.2.1 Minimum Wall Requirement

In accordance with the stress classification in Table 1, the tubes are subject to primary stress limits for both membrane and bending stresses. [

]^{a,c}

For computing t_{min}, the pressure stress equation shown below is used. That is,

$$t_{min} = \frac{\Delta P R_i}{P_m - 0.5\Delta P}$$

where,

ΔP = through-wall pressure gradient
R_i = tube inside radius
P_m = allowable primary membrane stress intensity

Using the above formulation, calculations are performed to determine the minimum acceptable wall thickness for uniform wall thinning. A summary of the minimum required wall thicknesses for high T_{ave} and low T_{ave} conditions is provided in Table 20.

5.2.2 Uniform Thinning Over Limited Axial Extent

For locations having uniform degradation over a limited axial distance, such as for AVB locations, a reduced t_{min} is established by accounting for the strengthening effect of the remainder of the tube in terms of burst strength capability. It has been documented in Reference 7 that tubing with degradation over a limited axial length has higher burst strength capability than tubing with an equivalent amount of degradation over an unlimited length. A ratio of the burst pressure for a degraded tube to the burst pressure for an undegraded tube as taken from Reference 7 is shown below,

$$\frac{\Delta P}{\Delta P^{o}} = (1 - h/t)^{\left[1 - e^{-0.13L/\sqrt{R_i(t-h)}}\right]}$$

where,

ΔP = thinned tube burst pressure
ΔP_o = unthinned tube burst pressure

h = depth of thinning
t = nominal wall thickness
R_i = inside tube radius
L = length of thinned region

Using this relationship, a ratio is obtained for burst pressure for a tube having an unlimited length of degradation, which is effectively defined to be 1.5 inches in Reference 7, to the burst pressure for a tube having degradation over a limited length. The minimum required wall thickness is then scaled using this ratio.

Utilizing the relationship for locally-degraded regions, reduced t_{min} requirements are established for the tube support plate (TSP), flow distribution baffle (FDB), and anit-vibration bar (AVB) intersections. Degraded lengths of [ ]^{a,c} inches are considered. The [ ]^{a,c} inch lengths correspond to the FDB and TSP, respectively, and the [ ]^{a,c} inch length corresponds to the AVB intersections for rows 14 and higher. Note that the AVB dimension on the side next to the tubes is [ ]^{a,c}. The AVB to tube contact area is larger for tube Rows 1 to 13, thus the repair limits for the [ ]^{a,c} inch FDB can be used for AVB wear scars in these inner rows. A summary of the minimum required wall thicknesses is provided in Table 21.

5.2.3 Primary Stress Limit Evaluation for Degraded Section

The locally degraded tube must also be evaluated against the stress limit for primary membrane plus bending (in-plane) stress intensity in the U-bend region, namely the AVB intersections. The tube stresses at the degraded locations are calculated by scaling the stresses for the non-degraded tube by the ratio of the corresponding section properties of the nominal and locally degraded tubes. The minimum value for t_{min} in Table 21 at the AVB intersections is [ ]^{a,c}. The corresponding ratios for A_{nom}/A_{min} and $(c/I_{min})/(c/I_{nom})$ are [ ]^{a,c}, respectively. The seismic stresses for the locally degraded tube are [ ]^{a,c} psi. The LOCA bending stresses for the locally degraded tube are summarized in Table 22. The combined LOCA + DBE stresses are shown in Table 23. Summaries of the corresponding tube stress intensities for the LOCA + DBE conditions are provided in Table 24. The maximum stress intensity has a value of [ ]^{a,c}.

A summary of the combined LSP + DBE stresses is provided in Table 25. Note that for the two-sided AVB wear, the maximum in-plane seismic stresses occur in the undegraded portion of the tube wall away from the AVB wear location. Thus the hoop stresses associated with the LSP load are calculated for the full tube cross-section. The axial stresses associated with the LSP load account for the reduced cross-section resulting from the wear. Summaries of the LSP + DBE tube stress intensities are provided in Table 26. The maximum stress intensity has a value of [ ]^{a,c} ksi.

Based on the values in Table 4, the shape factor K has a value of [ ]^{a,c} for two-sided AVB thinning with a [ ]^{a,c} inch wall thickness (wear depth = [ ]^{a,c} inch). The corresponding allowable membrane plus bending stress limit is 73.68 ksi. The maximum stress intensity of [ ]^{a,c} ksi satisfies the applicable stress limit.

5.3 Margin to Burst Under Normal Operating ΔP_i

The fundamental premise of the RG 1.121 criteria is that all tubes should retain margins of safety against burst consistent with the safety factor margins implicit in the stress limit criteria of the ASME Code as referenced in 10 CFR 50.55a, for all service level loadings. Satisfaction of these criteria means that all tubes have been determined to retain the required margin against gross failure or burst under Level A service conditions. In addition, all tubes have been determined to retain a margin of safety against gross failure or burst consistent with the margin of safety determined by the stress limits in the ASME Code under postulated accidents concurrent with a Design Basis earthquake. Since the tube min-wall (t_{min}) values calculated in Section 5.2.1 are based on stress limit criteria consistent with the ASME Code criteria, the required margin to burst is satisfied.

5.4 Tube Collapse Evaluation

In addition to the primary stress limits, there is an additional requirement that the degraded region of the tubing withstand the external pressure loading from LOCA without collapse with a margin consistent with the Code criterion. That is,

$$0.9\, P_c \geq \Delta P_o$$

where:

P_c = collapse pressure of the degraded tubing, and

ΔP_o = external pressure loading due to the secondary-to-primary pressure gradient

For verifying the integrity of the thinned tube, the maximum secondary-to-primary ΔP_o occurs during the LOCA event. Based on Reference 8, the maximum secondary to primary pressure gradient is [ ]^{a,c} psi. Hence, in accordance with the ASME Code criterion, the minimum required collapse pressure is [ ]^{a,c}.

The collapse pressure is significantly affected by tube ovality. A number of correlations using limit analysis theory have been developed to predict collapse strength of ovalized tubes. The analytical correlation shown below, provided in Reference 9, has been found to be quite accurate for the thermally-treated (or stress relieved) tubing, believed to be due to its less anisotropic yield properties, compared to that of as-manufactured tubing.

$$P_c = \frac{2S_y t}{\rho\left[2+e\left(1+\frac{8\rho}{3t}\right)+\frac{4e^2\rho}{3t}\right]}$$

where,

$\rho = R_m$,

S_y = tube yield strength,

t = tube wall thickness,

and,

e = tube ovality

The validity and conservatism of this analytical correlation was verified against the results of room temperature collapse pressure tests on mill-annealed 0.75 inch OD x 0.043 inch t, and 0.875 inch OD x 0.050 inch t oval tubes. The comparison of analytically predicted (normalized) collapse pressures with those obtained from the tests is shown in Figure 6.

Using the above algorithm, calculations to determine collapse pressure for a 0.875" OD x 0.050" t inch tube as a function of tube ovality are provided in Table 27, and shown plotted in Figure 7. The maximum permissible tube ovalities are [ ]^{a,c} % in the tube straight leg and [ ]^{a,c} % in the U-bend region. Based on the results in Table 27, the predicted tube collapse pressures for a nominal tube are [ ]^{a,c} psi for the straight leg and [ ]^{a,c} psi for the U-bend region.

In terms of establishing the tube collapse potential for the degraded tube, the assumption of uniform thinning over the entire length of the tube is overly conservative. Degradation in the straight leg region of the tube is generally in the form of pits, short cracks, outside diameter stress corrosion cracking, or the result of wear with a loose part or a single axial crack (scratch) from the tube installation process. Each of these degradation configurations can be approximated, for the purpose of evaluating tube collapse, as one or two-sided wear. This same geometry is also applicable to wear at tube / AVB intersections.

Data from collapse tests performed for tubes with machined flats similar to AVB wear, documented in Reference 10, are used. The tests utilized thirteen 7/8 inch x 0.050 inch thickness tubes with simulated penetrations in three basic configurations (A, BI, and B2) as shown in Figure 8 and Figure 9. The difference between the B1 and B2 configurations is the depth of thinning, with the B1 configuration being thinned by 75% (25% remaining wall), and the B2 configuration being thinned by 50% (50% remaining wall).

The test arrangement allowed the installation of a check valve that would allow controlled collapse so that local collapse could be determined. The upper end of the tube was attached to the check valve that was open to the atmosphere through a small hole in the vessel head. A sudden high velocity jet of water from this hole easily detected local collapse. Simultaneous pressure readings were taken from a panel-mounted gage. Wall thicknesses were determined indirectly by taking external micrometer measurements across the flats (or flat) and the round portion of the tube.

The test results are summarized in Table 28. A plot of collapse pressure as a function of percent thinning is provided in Figure 10. The results fall essentially into two general classes. The first class is a very local collapse of the flat thinned section only, and the second case is a more general "total local" collapse which involves the entire tube circumference in the vicinity of the milled flat. It is the case of total collapse that is of interest here, as a small local collapse immediately adjacent to the wear scar will not result in a significant reduction in flow area for the tube. The data corresponding to the total collapse case can be approximated using the following exponential curve.

$$y = a\,e^{bx},$$

where,

y = Collapse pressure
a = [ ]a,c
b = [ ]a,c
x = Percent thinning

A plot showing the above curve fit to the data is shown in Figure 11. By adjusting the curve downward [ ]a,c psi, a lower bound curve approximating the collapse pressure for two-sided AVB wear is obtained. The lower bound curve and corresponding exponential expression are also shown on Figure 11.

Calculations to determine the tube collapse pressure for the tube straight leg are summarized in Table 29. Referring to Table 29, the [

]a,c % in the bottom of the table. The resulting tube collapse pressure for a tube with [ ]a,c % ovality and two-sided wear with a remaining wall thickness of [ ]a,c psi. This is higher than the required collapse pressure of [ ]a,c

For the tube / AVB intersection, the minimum wall thickness is [ ]^{a,c} wall thinning. Also, the maximum ovality in the U-bend is [ ]^{a,c} %. Following the same procedure as for the straight leg, the calculated collapse pressure is [ ]^{a,c}. Since the expected collapse pressure of [ ]^{a,c} psi is higher than the required minimum of [ ]^{a,c}, the minimum tube wall thickness of [ ]^{a,c} inch is acceptable.

Due to the broached geometry of the tube support plate holes, tube wear inside the TSP will have an irregular geometry. For purposes of the collapse evaluation, as with the evaluation for the tube minimum wall requirement, the tube wear inside the broached tube support plates will be treated as uniform thinning over the height of the tube support plate. A series of collapse tests have been run for uniform thinning with varying lengths and depth of thinning. The test results, documented in Reference 7, show that, in general, the longer and deeper the defect, the lower the collapse pressure. A summary of the data is provided in Table 30. The uniform thinning collapse tests were performed on 0.875 x 0.050 tubing at a temperature of 600°F. The approximate yield strength of the tubing used in the tests at 600°F is [ ]^{a,c}.

The results in Table 21 show the minimum required wall thickness in the TSP intersection to be [ ]^{a,c}. Based on the test results in, a conservative estimate of the uniform thinning collapse pressure is [ ]^{a,c}. Scaling this result for yield strength differences using the formulation below, the predicted collapse pressure is calculated to be [ ]^{a,c} psi.

$$\frac{(P_c)_{Tube}}{(P_c)_{Test}} = \frac{\left[S_y\left(t/R_m\right)\right]_{Tube}}{\left[S_y\left(t/R_m\right)\right]_{Test}}$$

$$(P_c)_{Tube} = \frac{\left[S_y\left(t/R_m\right)\right]_{Tube}}{\left[S_y\left(t/R_m\right)\right]_{Test}}(P_c)_{Test}$$

Assuming that the uniformly thinned section inside the TSP has the same maximum ovality as the straight leg thinning, then based on the results shown in Table 30, the collapse pressure for the thinned section is [ ]^{a,c} times the collapse pressure for a round tube. Thus, the collapse pressure for the tube / TSP intersection assuming uniform thinning and maximum ovality is [ ]^{a,c}. Since the expected collapse pressure of [ ]^{a,c} is higher than the required minimum of [ ]^{a,c}, the minimum tube wall thickness of [ ]^{a,c} at the tube / TSP intersection is acceptable. Note that the above calculations for the tube / TSP interface have conservatively ignored any stiffening effect that may be provided by the TSP in resisting tube collapse. The amount of stiffening is a function of the orientation of the tube collapse inside the broached hole.

5.5 Tube Leakage Limits

The operating leak rate limits provide a defense in depth added margin against tube rupture. As a defense in depth measure, operating leakage limits are targeted toward obtaining a significant probability that a single indication causing the leakage will have a burst pressure exceeding the limiting accident condition pressure differential. The objective for the normal operating leak rate limit is to establish a reasonable likelihood that the plant is shut down before a tube could rupture under either normal or faulted conditions (i.e., "leak before break"). Normal operating leak rates from corrosion induced through-wall cracks can be highly variable. As a consequence, "leak before break" cannot be assured for an established operating leakage limit. However, establishing the operating leakage limit under the assumption of a uniform through wall crack length provides a technical basis for obtaining a reasonable likelihood that "leak before break" would be achieved.

The EPRI PWR Primary-to-Secondary Leak Guidelines, Reference 4, form the basis of the plant's operational leakage program. These guidelines define several increased monitoring and action level conditions, depending on the amount of leakage and the rate of leakage increase. Once the primary-to-secondary leakage exceeds 75 gallons per day (gpd) for a period of one hour or longer, the utility must begin action to move to Mode 3 operation within twenty-four hours. If the primary-to-secondary leakage exceeds 75 gpd with an increasing leak rate of ≥ 30 gpd/hr, the utility must ramp to 50% power within one hour and to Mode 3 operation within two hours. Finally, if the primary-to-secondary leak rate exceeds 150 gpd, regardless of the rate of increase, the utility must move to Mode 3 operation within the next six hours. This analysis is performed to show that the EPRI PWR Primary-to-Secondary Leak Guidelines result in a significant probability that a single indication causing the leakage will have a burst pressure exceeding the limiting accident condition pressure differential.

The basic process is to:

1) Calculate the estimated leak rate as a function of crack length using the Westinghouse computer code CRACKFLO.
2) Calculate the expected leak rate as a function of the CRACKFLO leak rate using the correlation developed for the PWSCC program (Reference 11) between the expected leak rate and the estimated leak rate.
3) Calculate the burst pressure as a function of the crack length.
4) Relate the burst pressure to the expected leak rate.

<u>Estimated Leak Rate as a Function of Crack Length</u>

The largest permissible crack length based on leakage considerations is determined using computer program CRACKFLO which has been developed for predicting leak rates through axially oriented cracks in a steam generator tube. CRACKFLO calculates a crack opening area based on the primary to secondary pressure differential acting on a tube with a given crack length and material properties. Fluid mechanics relations are applied to the pressure opened crack and assumed crack surface geometry such as roughness and tortuosity of the crack flow path. The CRACKFLO leakage model has been developed for single axial cracks and compared with leak rate test results from pulled tube and laboratory specimens.

Leak rates for the tubes are a function of tube geometry, material strength properties, and several operating parameters. The operating properties of significance are the primary and secondary side pressures and the primary side temperature (at 100% Power). A summary of the baseline operating parameters is provided in Table 6. Based on calculations that have been performed to determine the sensitivity of leak rate to operating parameters, the limiting set of conditions is the highest secondary side pressure combined with the highest value for T_{hot}. For this analysis, therefore, a secondary side pressure of 758 psia is used, along with a value for T_{hot} of 611.7 °F.

Comparison of primary side stress corrosion cracks (PWSCC) and outside diameter stress corrosion cracks (ODSCC) has shown that ODSCC cracks are typically the most irregular in shape. Because the conditions leading to reduced leakage are conservative for this analysis, calculations are performed for ODSCC cracks. A summary of the calculated leakage as a function of crack length is provided in Table 31. Note that in the last column of Table 31, the leakage flow at operating conditions is converted to leakage flow collected and condensed to ambient conditions, the reference conditions for leakage acceptance limits.

A plot of the resulting predicted leakage using CRACKFLO as a function of crack length is shown in Figure 12. Using these results, a regression analysis is performed on the log-log relationship for the two straight-line segments shown in Figure 12. Results of the regression analysis are summarized in Table 32. The resulting expression for the crack length as a function of leakage is as follows.

$$\log(L) = b_0 + b_1 \log(Q) \,,$$

As a check of the regression analysis parameters, check calculations are performed in the lower right portion of Table 32, and shown plotted in Figure 12. The results show the regression line to accurately predict the crack length as a function of CRACKFLO leakage.

Expected Leak Rate as a Function of Calculated Leak Rate

Based on the study performed in Reference 11, a correlation was developed between the measured leak rate, Q_E, from a throughwall crack in a tube and the value predicted by the computer code CRACKFLO, Q_C.

$$\log(Q_E) = -0.62158 + 0.62527 \log(Q_C)$$

Converting the correlation from units of gallons per minute, used in Reference 11, to gallons per day results in the following:

$$\log(Q_E) = 0.561944 + 0.62527 \log(Q_C)$$

Calculate Burst Pressure as a Function of Crack Length

Burst pressure is often presented in the form of a relationship between a normalized burst pressure, P_N, and a normalized crack length, λ. The normalized burst pressure is simply the actual burst pressure non-dimensionalized by the flow stress of the material, and adjusted for the size of the tubing by the ratio of the mean radius to the thickness. This provides a ratio of a membrane stress in the tube to the strength of the material, and allows for the correlation to be applicable to multiple tube sizes. The flow stress of the material is usually taken as a linear function of the yield stress, S_y, and the ultimate tensile stress, S_u, of the material. Acceptable correlations for Alloy 690 tubes have been obtained using a fraction of the sum of the two properties as the flow stress.

For a tube with a mean radius of R_m and a thickness t, the normalized burst pressure as a function of the actual burst pressure, PB, is defined as

$$P_N = \frac{P_B R_m}{(S_y + S_u)t}.$$

The normalizing parameter, λ, for the crack length, a, is defined as

$$\lambda = \frac{a}{\sqrt{R_m t}},$$

The burst pressure as a function of axial crack length for a specific tube size is then easily obtained from the non-dimensionalized relationship.

A series of regression analyses, summarized in Reference 12, were performed for available burst data, considering a variety of linear and non-linear functions. The function that was concluded to provide the best fit of the burst data is,

$$P_N = 0.06132 + 0.5365 e^{-0.2778\lambda}$$

A plot comparing the predicted normalized burst pressure as a function of normalized crack length to the corresponding test data is provided in Figure 13. For a given value of length, a random value of the normalized burst pressure is found as:

$$P_N = 0.06132 + 0.5365 e^{-0.2778\lambda} + ZS_P$$

where Z is a random deviate from the standardized normal distribution.

Relate the Burst Pressure to the Expected Leak Rate

In order to determine the crack length associated with a 75 gpd leak rate, a Monte Carlo simulation of 1000 random samples is performed. Variables included in the simulation include uncertainties in the slope, intercept and data about the $\log(Q_E)$ / $\log(Q_C)$ relationship, uncertainties in the relationship for normalized burst, and uncertainties in the tube strength properties. A variance reduction technique known as Latin Hypercube sampling is employed because of the limited number of simulations performed. A sample of the simulation results is documented in Table 33. Referring to Table 33, initially, a random value is calculated for the log of the predicted leakage from CRACKFLO for the prescribed leak rate, 75 gpd in this case. The predicted leakage is then used to calculate the corresponding crack length. Using the expression shown above, the crack length is converted to a non-dimensionalized length, λ. Knowing the non-dimensionalized crack length, λ, the non-dimensionalized burst pressure is then calculated.

Once the normalized burst pressure is known, the actual tube burst pressure can be calculated as:

$$P_B = P_N \left(\frac{t}{R_m}\right)(S_Y + S_U + ZS_s),$$

where S_s is the standard deviation of the sum of the yield and tensile strengths of the material.

Selection of the Burst Pressure Array Element

Selection of the element of the ordered array is based on using a normal approximation for the binomial distribution. The binomial distribution can be approximated by a normal distribution with a mean of n·p and a variance of n·p·(1-p). If r is the element of the array for a given probability (percentile, p) and confidence level, C, then r is calculated as follows:

$$r = np - Z\sqrt{np(1-p)}$$

For the 5th percentile (95% probability), p, of n =1000 simulations, with a 95% confidence, r is the 39th element of the ordered array (ordered from lowest to highest burst pressure). Where Z is 1.645. The resulting burst pressure for a 95% probability with 95% confidence for a 75 gpd leak rate is 2,566 psi. The peak LSP pressure differential, as defined in Section 3.2.2 is 2,485 psi. Since this is less than the 2,485 psi burst pressure predicted above, the 75 gpd leak rate limit will result in a significant probability that a single indication causing the leakage will have a burst pressure exceeding the limiting accident condition pressure differential.

The EPRI Primary-to-Secondary Leakage Guidelines allow for spikes in the leakage of up to 150 gpd for a duration of less than one hour without any reduction in power. Thus calculations are also performed for a leak rate of 150 gpd. Results of the calculations are summarized in Table 34. Because the leak rates are of short duration, a probability is established for meeting both the limiting accident condition pressure and the full power operating pressure. As shown in Table 34, there is an 89% probability with a 50% confidence that a tube with a 150 gpd leakage will not burst under the limiting accident condition loading. When compared to the limiting full power operating primary-to-secondary pressure drop of 1,600 psi, it is shown that for the short term pressure spikes up to 150 gpd that there is at least a 95% probability with a 95% confidence that a tube with a 150 gpd leakage will not burst under normal operating conditions.

Overall, it is concluded that leakage monitoring using the EPRI PWR Primary-to-Secondary Leak Guidelines provides a reasonable likelihood that the plant can be shut down before the single tube postulated to be leaking would rupture under either normal or accident conditions.

6.0 SUMMARY OF TUBE STRUCTURAL LIMITS

The minimum acceptable wall thickness and other recommended practices in Regulatory Guide 1.121 are used to determine a repair limit for the tube. The Regulatory Guide was written to provide guidance for the determination of a repair limit for steam generator tubes undergoing localized tube wear. Tubes that are determined to have indications of degradation in excess of the repair limit would have to be repaired or removed from service.

As recommended in paragraph C.2.b. of the Regulatory Guide, an additional thickness degradation allowance must be added to the minimum acceptable tube wall thickness to establish the operational tube thickness acceptable for continued service. Paragraph C.3.f. of the Regulatory Guide specifies that the basis used in setting the operational degradation allowance include the method and data used in predicting the continuing degradation and consideration of eddy current measurement errors and other significant eddy current testing parameters. A summary of the tube structural limits as determined by this analysis is provided in Table 35. The corresponding repair limits are established by subtracting from the structural limits an allowance for eddy current uncertainty and continued growth. It is the responsibility of the utility to incorporate appropriate values for these quantities to define corresponding repair limits.

Finally, the analysis results show that leakage monitoring using the *EPRI PWR Primary-to-Secondary Leak Guidelines* provides a reasonable likelihood that the plant can be shut down before the single tube postulated to be leaking would rupture under either normal or accident conditions.

7.0 REFERENCES

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2. USNRC Regulatory Guide 1.83, Rev. 1, "In-Service Inspection of Pressurized Water Reactor Steam Generator Tubes," 7/75.
3. USNRC Regulatory Guide 1.121, "Bases for Plugging Degraded PWR Steam Generator Tubes (for comment)," 8/76.
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10. WCAP-8429, "Analytical and Experimental Evaluation of the Mechanical Integrity of Steam Generator Tubing," 6/81.
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12. EPRI Report TR-105505, "Burst Pressure Correlation for Steam Generator Tubes With Throughwall Axial Cracks," EPRI, Palo Alto, CA: 1997.
13. "ASME Boiler and Pressure Vessel Code," Section III, 1989, Code Case N-20-3.

Table 1
Tube Stress Classification

a,c

Table 2
Tube Strength Properties
Thermally-Treated Alloy 600
0.875" OD x 0.050" t

Temperature (^{o}F)	S_y (1) (ksi)	S_u (2) (ksi)	S_m (1) (ksi)
100	40.0	80.0	26.6
200	38.2	80.0	26.6
300	37.3	80.0	26.6
400	36.3	80.0	26.6
500	35.7	80.0	26.6
600	35.3	80.0	26.6
700	35.0	80.0	26.6

(1) Values based on Code Case N-20-3 (Reference 13)

(2) Values for S_u at elevated temperatures inferred from criteria in the ASME Code Appendix III-2110 (b) for S_m, and minimum tensile strength specified in Code Case N-20-3

Table 3
Calculation of Tube Shape Factor (K) as a Function of Thinning
Case of Uniform Thinning

a,c

Table 4

Calculation of Tube Shape Factor (K) as a Function of Thinning

Two-Sided AVB Wear: In-Plane

a,c

Table 5
Summary of Allowable Stresses

a,c

Table 6
Summary of Full Power Operating Parameters
Uprating Conditions

a,c

Table 7
Summary of Transient Parameters
High T_{ave} Conditions – 25% Plugging

a,c

Table 8
Summary of Transient Parameters
Low T_{ave} Conditions – 25% Plugging

a,c

Table 9
Summary of Maximum Hot-to-Cold Pressure Drops

a,c

Table 10
Summary of LOCA Rarefaction Stresses
In-Plane Bending

a,c

Table 11
Summary of Combined Membrane + Bending Stresses
LOCA + DBE Loading Conditions
Nominal Tube Geometry
U-Bend Region

a,c

Table 12
Summary of Combined Membrane + Bending Stresses
LOCA + DBE Loading Conditions
Nominal Tube Geometry
Top TSP

a,c

Table 13
Summary of Through-Wall Pressure Stresses

a,c

Table 14
Summary of Combined / Principal Stresses
LOCA + DBE Loading Conditions
Nominal Tube Geometry
U-Bend Region

a,c

Table 15
Summary of Combined / Principal Stresses
LOCA + DBE Loading Conditions
Nominal Tube Geometry
Top TSP

a,c

Table 16
Summary of Tube Stress Intensities
LOCA + DBE Loading Conditions
Nominal Tube Geometry
U-Bend Region

a,c

Table 17
Summary of Tube Stress Intensities
LOCA + DBE Loading Conditions
Nominal Tube Geometry
Top TSP

a,c

[ ]

Table 18
Summary of Combined / Principal Stresses
LSP + DBE Loading Conditions
Nominal Tube Geometry
U-Bend and Top TSP Regions

a,c

Table 19
Summary of Tube Stress Intensities
LSP + DBE Loading Conditions
Nominal Tube Geometry
U-Bend and Top TSP Regions

a,c

[ ]

Table 20
Summary of Minimum Acceptable Wall Thicknesses (t_{min})

a,c

Table 21
Summary of Minimum Acceptable Wall Thickness (t_{min})
Limited Length Degradation

a,c

Table 22
Summary of LOCA Rarefaction Bending Stresses
Degraded Tube

a,c

Table 23
Summary of Combined / Principal Stresses
LOCA + DBE Loading Conditions
Degraded Tube
U-Bend Region

a,c

Table 24
Summary of Tube Stress Intensities
LOCA + DBE Loading Conditions
Degraded Tube Geometry
U-Bend Region

a,c

Table 25
Summary of Combined / Principal Stresses
LSP + DBE Loading Conditions
Degraded Tube
U-Bend Region

a,c

Table 26
Summary of Tube Stress Intensities
LSP + DBE Loading Conditions
Degraded Tube Geometry
U-Bend Region

a,c

[ ]

Table 27
Tube Collapse Pressure as a Function of Tube Ovality
t_{min} = 0.050 inch

a,c

Table 28
Collapse Pressures for Straight 7/8 – 0.05 Alloy 600 Tube With Simulated Wall Thinning

a,c

Table 29
Summary of Tube Collapse Pressure Calculations
Tube Straight Leg – Free Span Area

a,c

Table 30
Summary of Tube Collapse Data
Uniform Wall Thinning

Specimen Number	Maximum Depth (inch)	Minimum Wall (inch)	Defect Length (inch)	Percent Thinning (%)	Collapse Pressure (psi)
B-42-7	0.039	0.0522	0.184	74.7	4980
B-56-3	0.013	0.0514	0.370	25.3	4720
B-03-7	0.014	0.0052	0.370	26.9	4850
B-29-3	0.029	0.0528	0.370	54.9	4320
B-75-9	0 028	0 0518	0.375	54.1	4240
B-42-9	0.039	0.0522	0.378	74.7	4990
B-04-7	0.039	0.0518	0.399	75.3	2380
B-06-1	0.028	0.0514	0.750	54.5	2990
B-28-3	0.014	0.0514	0.755	27.2	4670
B-70-7	0.038	0.0518	0.755	73.4	1760
B-48-5	0.039	0.0518	0.760	75.3	4980
B-32-7	0.014	0.0518	0 765	27.0	4770
B-18-9	0.029	0.0518	0.775	56.0	3080
B-70-5	0.038	0.0518	0.875	73 4	2160
B0-8-5	0.038	0 0514	1.496	73.9	3840
B-40-1	0.038	0.0518	1.500	75.0	2980
B-56-9	0.014	0.0514	1.550	27.2	4250
B-12-1	0.029	0 0514	1.560	56.5	2840
B-39-7	0 013	0.0518	1.580	25.1	4470
B-23-7	0.029	0.0518	1.580	56.0	2580

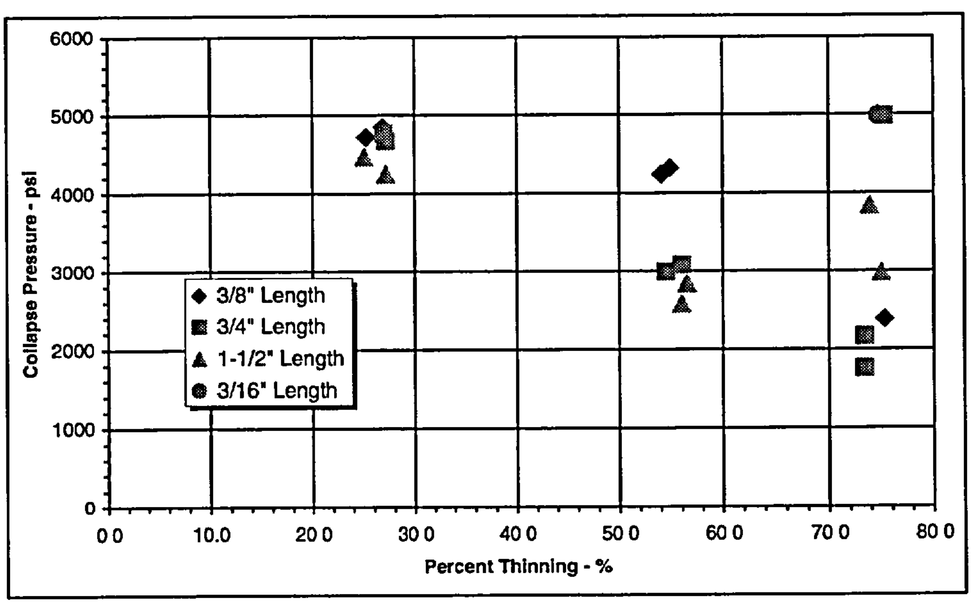

Table 31
Summary of CRACKFLO Results

a,c

Table 32
Summary of Leak Rate Correlation Results

a,c

Table 33
Summary of Leak Rate Simulation Results

a,c

Table 34
Summary of Results to Determine Probability of Burst

a,c

Table 35
Summary of Tube Structural Limits

a,c

a,c

Figure 1
Schematic of a Model 44F Steam Generator

a,c

Figure 2
Thermal / Hydraulic Model
LOCA Rarefaction Analysis

a,c

Figure 3
Plot of LOCA Pressure Time Histories
Hot-to-Cold Leg Pressure Gradient
Maximum Radius Tube
Pressurizer Line Break

a,c

Figure 4
Plot of LOCA Pressure Time Histories
Hot-to-Cold Leg Pressure Gradient
Maximum Radius Tube
Accumulator Line Break

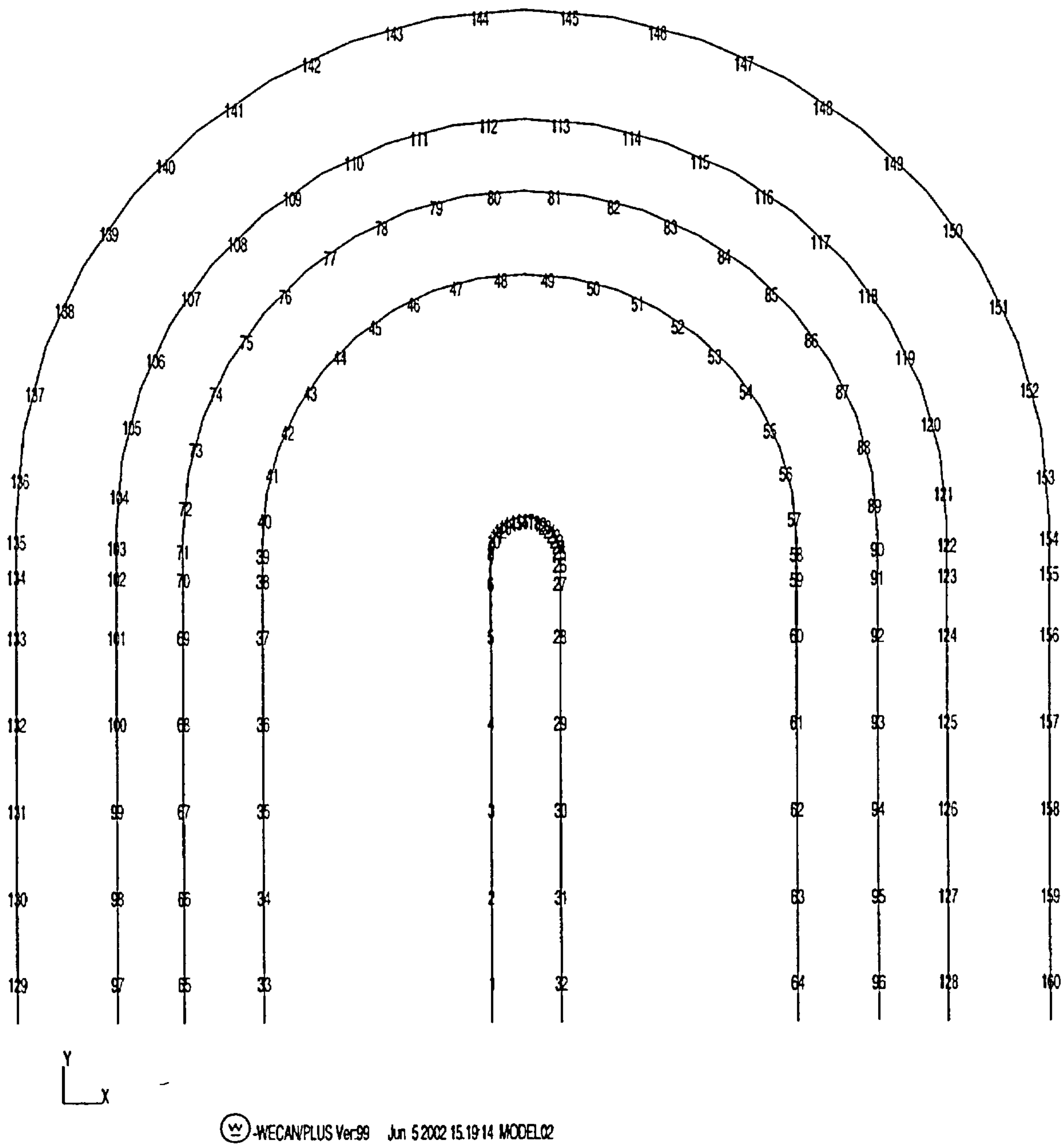

Figure 5
Tube Finite Element Model- Node Numbers
LOCA Rarefaction Wave Analysis

a, c

Figure 6
Correlation Between Tube Ovality and Collapse Pressure

a,c

Figure 7
Tube Collapse Pressure as a Function of Tube Ovality
t_{min} = 0.050 inch

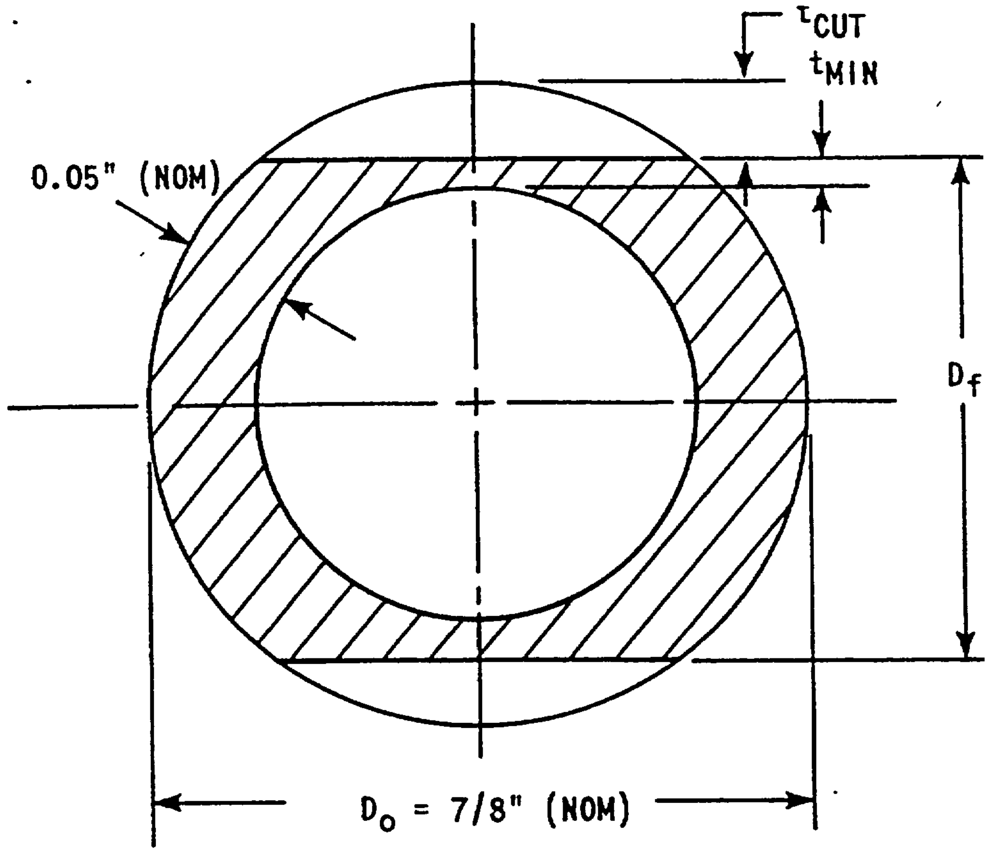

Figure 8
Thinned Tube Cross Section for Collapse Tests
Type A Configuration

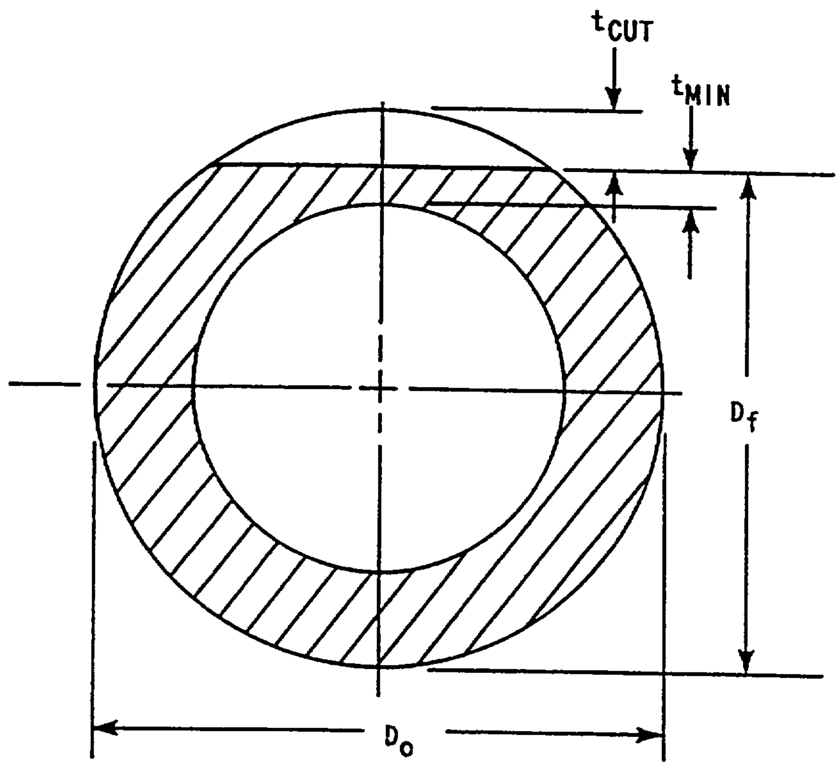

Figure 9
Thinned Tube Cross Section for Collapse Tests
Types B1 and B2 Configurations

a,c

Figure 10
Collapse Pressures for Straight 7/8 x 0.05 Inconel Tubes With Simulated Wall Thinning

a,c

Figure 11
Collapse Pressures for Straight 7/8 x 0.05 Inconel Tubes
With Simulated Wall Thinning
Exponential Curve Fit of Total Collapse Data

a,c

Figure 12
CRACKFLO Predicted Leakage Results

a,c

Figure 13
Normalized Burst Pressure Versus Normalized Crack Length
Alloy 600 Steam Generator Tubes

ATTACHMENT 5 TO NL-02-112

Westinghouse letter dated August 6, 2002 (CAW-02-1544)

Application for Withholding Proprietary Information from Public Disclosure

Entergy Nuclear Operations, Inc.
Indian Point Unit No. 2
Docket No. 50-247

Westinghouse

Westinghouse Electric Company
Nuclear Services
P.O Box 355
Pittsburgh, Pennsylvania 15230-0355
USA

Document Control Desk
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001

Direct tel: (412) 374-5282
Direct fax: (412) 374-4011
e-mail: Sepp1ha@westinghouse.com

Attention: Mr. Samuel J. Collins

Our ref CAW-02-1544

August 6, 2002

APPLICATION FOR WITHHOLDING PROPRIETARY
INFORMATION FROM PUBLIC DISCLOSURE

Subject: WCAP-15909-P, "Regulatory Guide 1.121 Analysis for the Indian Point Unit 2 Replacement Steam Generators" (Proprietary)

Dear Mr. Collins:

The proprietary information for which withholding is being requested in the above-referenced report is further identified in Affidavit CAW-02-1544 signed by the owner of the proprietary information, Westinghouse Electric Company LLC. The affidavit, which accompanies this letter, sets forth the basis on which the information may be withheld from public disclosure by the Commission and addresses with specificity the considerations listed in paragraph (b)(4) of 10 CFR Section 2.790 of the Commission's regulations.

Accordingly, this letter authorizes the utilization of the accompanying Affidavit by Entergy Nuclear Northeast.

Correspondence with respect to the proprietary aspects of the application for withholding or the Westinghouse affidavit should reference this letter, CAW-02-1544 and should be addressed to the undersigned.

Very truly yours,

H. A. Sepp, Manager
Regulatory and Licensing Engineering

Enclosures

Cc: G. Shukla/NRR

CAW-02-1544

AFFIDAVIT

COMMONWEALTH OF PENNSYLVANIA:

ss

COUNTY OF ALLEGHENY:

Before me, the undersigned authority, personally appeared H. A. Sepp, who, being by me duly sworn according to law, deposes and says that he is authorized to execute this Affidavit on behalf of Westinghouse Electric Company LLC ("Westinghouse"), and that the averments of fact set forth in this Affidavit are true and correct to the best of his knowledge, information, and belief:

MARGARET L. GOFANO COMMONWEALTH OF PENNSYLVANIA NOTARY PUBLIC

H. A. Sepp, Manager
Regulatory and Licensing Engineering

Sworn to and subscribed
before me this 6th day
of August, 2002

Margaret L. Gonano
Notary Public

Notarial Seal
Margaret L. Gonano, Notary Public
Monroeville Boro, Allegheny County
My Commission Expires Jan. 3, 2006
Member, Pennsylvania Association Of Notaries

(1) I am Manager, Regulatory and Licensing Engineering, in Nuclear Services, Westinghouse Electric Company LLC ("Westinghouse"), and as such, I have been specifically delegated the function of reviewing the proprietary information sought to be withheld from public disclosure in connection with nuclear power plant licensing and rule making proceedings, and am authorized to apply for its withholding on behalf of the Westinghouse Electric Company LLC.

(2) I am making this Affidavit in conformance with the provisions of 10CFR Section 2.790 of the Commission's regulations and in conjunction with the Westinghouse application for withholding accompanying this Affidavit.

(3) I have personal knowledge of the criteria and procedures utilized by the Westinghouse Electric Company LLC in designating information as a trade secret, privileged or as confidential commercial or financial information.

(4) Pursuant to the provisions of paragraph (b)(4) of Section 2.790 of the Commission's regulations, the following is furnished for consideration by the Commission in determining whether the information sought to be withheld from public disclosure should be withheld.

(i) The information sought to be withheld from public disclosure is owned and has been held in confidence by Westinghouse.

(ii) The information is of a type customarily held in confidence by Westinghouse and not customarily disclosed to the public. Westinghouse has a rational basis for determining the types of information customarily held in confidence by it and, in that connection, utilizes a system to determine when and whether to hold certain types of information in confidence. The application of that system and the substance of that system constitutes Westinghouse policy and provides the rational basis required.

Under that system, information is held in confidence if it falls in one or more of several types, the release of which might result in the loss of an existing or potential competitive advantage, as follows:

(a) The information reveals the distinguishing aspects of a process (or component, structure, tool, method, etc.) where prevention of its use by any of

Westinghouse's competitors without license from Westinghouse constitutes a competitive economic advantage over other companies.

(b) It consists of supporting data, including test data, relative to a process (or component, structure, tool, method, etc.), the application of which data secures a competitive economic advantage, e.g., by optimization or improved marketability.

(c) Its use by a competitor would reduce his expenditure of resources or improve his competitive position in the design, manufacture, shipment, installation, assurance of quality, or licensing a similar product.

(d) It reveals cost or price information, production capacities, budget levels, or commercial strategies of Westinghouse, its customers or suppliers.

(e) It reveals aspects of past, present, or future Westinghouse or customer funded development plans and programs of potential commercial value to Westinghouse.

(f) It contains patentable ideas, for which patent protection may be desirable.

There are sound policy reasons behind the Westinghouse system which include the following:

(a) The use of such information by Westinghouse gives Westinghouse a competitive advantage over its competitors. It is, therefore, withheld from disclosure to protect the Westinghouse competitive position.

(b) It is information that is marketable in many ways. The extent to which such information is available to competitors diminishes the Westinghouse ability to sell products and services involving the use of the information.

(c) Use by our competitor would put Westinghouse at a competitive disadvantage by reducing his expenditure of resources at our expense.

(d) Each component of proprietary information pertinent to a particular competitive advantage is potentially as valuable as the total competitive advantage. If competitors acquire components of proprietary information, any one component may be the key to the entire puzzle, thereby depriving Westinghouse of a competitive advantage.

(e) Unrestricted disclosure would jeopardize the position of prominence of Westinghouse in the world market, and thereby give a market advantage to the competition of those countries.

(f) The Westinghouse capacity to invest corporate assets in research and development depends upon the success in obtaining and maintaining a competitive advantage.

(iii) The information is being transmitted to the Commission in confidence and, under the provisions of 10CFR Section 2.790, it is to be received in confidence by the Commission.

(iv) The information sought to be protected is not available in public sources or available information has not been previously employed in the same original manner or method to the best of our knowledge and belief.

(v) The proprietary information sought to be withheld in this submittal is that which is appropriately marked in WCAP-15909-P, Rev. 0, "Regulatory Guide 1.121 Analysis for the Indian Point Unit 2 Replacement Steam Generators" (Proprietary), dated August 2002, being transmitted by Entergy Nuclear Northeast letter and Application for Withholding Proprietary Information from Public Disclosure, to the Document Control Desk, Attention Mr. Samuel J. Collins. The proprietary information as submitted for use by Westinghouse Electric Company LLC for Indian Point Unit 2 is expected to be applicable for other licensee submittals in performing Regulatory Guide 1.121 analyses for steam generators.

This information is part of that which will enable Westinghouse to:

(a) Provide a response to NRC questions on the Indian Point Unit 2 steam generators.

(b) Provide a quantitative technical justification for the Regulatory Guide 1.121 Analysis for Indian Point Unit 2 Steam Generators.

(c) Assist Entergy Nuclear Northeast in obtaining a license amendment for the Regulatory Guide 1.121 Analysis.

Further this information has substantial commercial value as follows:

(a) Westinghouse plans to sell the use of similar information to its customers for purposes of establishing Regulatory Guide 1.121 analyses.

(b) Westinghouse can sell support and defense of Regulatory Guide 1.121 analyses.

(c) The information requested to be withheld reveals the distinguishing aspects of a methodology which was developed by Westinghouse.

Public disclosure of this proprietary information is likely to cause substantial harm to the competitive position of Westinghouse because it would enhance the ability of competitors to provide similar calculations and licensing defense services for commercial power reactors without commensurate expenses. Also, public disclosure of the information would enable others to use the information to meet NRC requirements for licensing documentation without purchasing the right to use the information.

The development of the technology described in part by the information is the result of applying the results of many years of experience in an intensive Westinghouse effort and the expenditure of a considerable sum of money.

In order for competitors of Westinghouse to duplicate this information, similar technical programs would have to be performed and a significant manpower effort, having the requisite talent and experience, would have to be expended.

Further the deponent sayeth not.

CAW-02-1544

PROPRIETARY INFORMATION NOTICE

Transmitted herewith are proprietary and/or non-proprietary versions of documents furnished to the NRC in connection with requests for generic and/or plant-specific review and approval.

In order to conform to the requirements of 10 CFR 2.790 of the Commission's regulations concerning the protection of proprietary information so submitted to the NRC, the information which is proprietary in the proprietary versions is contained within brackets, and where the proprietary information has been deleted in the non-proprietary versions, only the brackets remain (the information that was contained within the brackets in the proprietary versions having been deleted). The justification for claiming the information so designated as proprietary is indicated in both versions by means of lower case letters (a) through (f) contained within parentheses located as a superscript immediately following the brackets enclosing each item of information being identified as proprietary or in the margin opposite such information. These lower case letters refer to the types of information Westinghouse customarily holds in confidence identified in Sections (4)(ii)(a) through (4)(ii)(f) of the affidavit accompanying this transmittal pursuant to 10 CFR 2.790(b)(1).

CAW-02-1544

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