LTR-CDME-05-30-NP (NON-PROPRIETARY)

W* Integrity Evaluation for Salem Unit 2 Limited SG Tube RPC Examination Based on WCAP-14797, Revision 2, "Generic W* Tube Plugging Criteria for 51 Series Steam Generator Tubesheet Region WEXTEX Expansions.

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1.0 Introduction

PSEG Nuclear LLC (PSEG) is proposing to modify the Salem Unit 2 Technical Specification's section on "Steam Generators" to change the scope of the steam generator (SG) tube sheet inspections required in the SG tubesheet region using a modified application of the W* methodology[1]. Specifically, the proposed change will revise the Unit 2 Technical Specification definition for steam generator tube inspection included in Salem Technical Specification (TS) Surveillance Requirement (SR) to revise the definition to exclude the portion of the tube within the tubesheet below the W* distance. The proposed change will also revise the SR on steam generator tube repair criteria, add a SR to require a 100 percent sample inspection of the hot leg tubesheet W* distance using an inspection probe qualified for detection of the expected degradation modes, add new W* terminology definitions in the TS, and add new reporting criteria for W* inspection information. The Salem Unit 2 proposed change requires that any tube identified with service induced degradation in the W* distance or less than eight inches below the top of tube sheet (TTS), which ever is greater, must be repaired. Since Salem proposes to repair any service induced degradation within the W* distance, this proposal is a conservative limited scope application of the complete W* methodology as described in WCAP-14797, Revision 2.

As a consequence of implementation, any degradation occurring below the W* distance may remain in service regardless of its axial or circumferential extent. The amendment will be based on portions of WCAP-14797-P, Revision 2, entitled "Generic W* Tube Plugging Criteria for 51 Series Steam Generator Tubesheet Region WEXTEX Expansions," Reference 1, and the following information developed herein. The W* analysis accounts for the reinforcing effect that the tubesheet has on an external surface of the steam generator tubes within the tubesheet region.

This amendment is requested to address NRC GL 2004-01, Reference 14, with respect to defined tube inspection depth below the top of the tubesheet using supplemental inspection techniques qualified for flaw detection in expanded tubesheet conditions, such as RPC (rotating probe coil) or array probes.

2.0 Summary & Conclusions

The information in this report demonstrates:

1) The information developed for the generic application of W*, Reference 1, is applicable to the SGs at Salem Unit 2.
2) The total leak rate from postulating all tubes in the bundle to have undetected indications that are throughwall for an extent of 360° at an elevation of 12 inches below the top of the tubesheet would be bounded by 0.3 gpm.

3) The number of undetected indications in the range of 8 to 12 inches below the top of the tubesheet can be conservatively estimated base on the number of indications detected in the range of zero to 8 inches.

4) The number of undetected indications in the range of 8 to 12 inches below the top of the tubesheet is expected to be very small.

5) The total leak rate from undetected indications in the range of 8 to 12 inches below the top of the tubesheet can be conservatively bounded by multiplying the number of predicted tubes with such indications by 0.0028 gpm per tube.

6) The total leak rate from axial circumferential and volumetric indications in the range of 0 to 8 inches below the top of the tubesheet can be conservatively estimated for the Condition Monitoring evaluation by applying available flaw depth estimation techniques and calculating the leak rate using the models described herein for leak rate from constrained axial cracks for those eddy current indications judged to represent a 100% throughwall (TW) degraded condition.

Performing an RPC inspection of the tubes in the Salem SGs to a depth of 8 inches is sufficient to assure the structural and leak rate integrity of the tube bundle in accord with industry and regulatory requirements.

3.0 W* Description

Existing plant Technical Specification tube repair/plugging criteria apply throughout the tube length and do not take into account the reinforcing effect of the tubesheet on the external surface of an expanded tube. The presence of the tubesheet constrains the tube and complements tube integrity in that region by essentially precluding tube deformation beyond the expanded outside diameter. The resistance to both tube rupture and tube collapse is significantly enhanced by the tubesheet. In addition, the proximity of the tubesheet in the expanded region significantly reduces the leakage of throughwall tube cracks. Based on these considerations, the establishment of alternate repair criteria to the portion of tubing expanded by Westinghouse explosive tube expansion (WEXTEX) process is supported by testing and analysis results included in Reference 1.

For Westinghouse Model 51 Series steam generators with WEXTEX expansions at Salem Unit 2, the full depth tube-to-tubesheet expansion can be defined as follows. From the lower tube end and extending upward for a length of approximately 2.75 inches is a region expanded by a tube rolling expansion process. From the top of the rolled expansion region to the vicinity of the top of the tubesheet (TTS), the expansion joint was produced by the WEXTEX process. The resulting full depth tube-to-tubesheet expansion can be considered as four distinct areas. These are described in Reference 1 as:

1. The Roll Region – The region of tube which has been expanded by the tube rolling process. This region extends from the bottom of the tube to approximately 2.75 inches above the bottom of the tube.

[1] W* is defined in WCAP-14797, Revision 2, Reference 1.

2. The Roll Transition – The portion of the tube which extends from the roll expanded region of the tube to the initially unexpanded region, and which is subsequently expanded by the WEXTEX process.
3. The WEXTEX Region – The portion of the tube expanded by the explosive expansion process to be in contact with the tubesheet. This region starts at the roll transition and extends to the WEXTEX transition in the vicinity of the top of the tubesheet.
4. The WEXTEX Transition – The portion of the tube which acts as a juncture between the WEXTEX region and the unexpanded region of the tube. The region starts at the top of the explosively expanded region and extends for approximately 0.25 inches.

The alternate SG tube repair criteria referred to as W* were developed by Westinghouse (and has been licensed to varying extents at another plants) to permit tubes with predominantly axially oriented primary water stress corrosion cracking in the WEXTEX and hardroll regions to remain in service. The W* analysis determined the W* length as measured from the bottom of the tube explosive expansion transition that would permit flaws below that length to remain in service and based on the assurance that adequate strength is available to resist the axial pullout loads experienced within the tubesheet during all plant conditions.

The following definitions apply with regard to describing the W* criteria:

BWT – The bottom of the WEXTEX Transition is defined in WCAP-14797, Rev. 2, as approximately 0.25 inches from the top of the tubesheet.

W* length – The maximum length of tubing below the bottom of the WEXTEX transition (BWT) which must be demonstrated to be non-degraded and is defined in WCAP-14797, Rev. 2, Section 4.0 as 7.0 inches below the bottom of the WEXTEX transition on the hot leg side.

W* distance – The distance from the top of the tubesheet to the bottom of the W* length including the distance from the top of the tubesheet to the BWT and measurement uncertainties.

The W* analysis provides the basis for tubes with any form of degradation below the W* length to remain in service. The presence of the surrounding tubesheet prevents tube rupture and provides resistance against axial pullout loads during normal and accident conditions as discussed in Reference 1. In addition, any primary to secondary leakage from tube degradation below the W* length is determined to be acceptably low as discussed in Section 8.0 of this report. Both steam generator tube structural and leakage integrity will be shown to meet the required performance criteria of Reference 2 and, thus, the necessary regulatory criteria as defined below.

General design criteria (GDC) 1, 2, 4, 14, 30, 31, and 32 of 10 CFR 50, Reference 3, Appendix A, define requirements for the reactor coolant pressure boundary (RCPB) with respect to structural and leakage integrity.

General design criterion (GDC) 19 of 10 CFR 50, Appendix A, defines requirements for the control room and for the radiation protection of the operators working within it. Accidents involving the leakage or burst of SG tubing comprise a challenge to the habitability of the control room.

10 CFR 50, Appendix B, establishes quality assurance requirements for the design, construction and operation of safety related components. The pertinent requirements of this appendix apply to all activities affecting the safety related functions of these components; these include, in part, inspecting, testing, operating and maintaining Criteria IX, XI and XVI of Appendix B as applied to the SG tube integrity program defined by NEI 97-06, Rev. 1 "Steam Generator Program Guidelines," Reference 2.

10 CFR 100, Reference 4, specify criteria to be used with respect to establishing a reactor site with regard to the risk of public exposure to the release of radioactive fission products. Accidents involving leakage or burst of SG tubing may compromise a challenge to containment and therefore involve an increased risk of radioactive release. Salem Unit 2 is licensed for the use of an alternate source term in accordance with 10 CFR 50.67 for some design basis accidents.

Under 10 CFR 50.65, the Maintenance Rule, licensees classify steam generators as risk significant components because they are relied upon to remain functional during and after design basis events. SGs are to be monitored under 10 CFR 50.65 (a) (2) against industry established performance criteria. Meeting the performance criteria of NEI 97-06, Rev. 1, Reference 2, provides reasonable assurance that the SG tubing remains capable of fulfilling its specific safety function of maintaining the reactor coolant pressure boundary.

The SG performance criteria as defined in NEI 97-06, Rev. 1, Reference 2, identify the standards against which performance is to be measured.

As discussed in more detail in Section 4.0 of this report, the generic W* analysis contained in Reference 1, is applicable to the Salem Unit 2 SGs and defines the maximum hot leg W* length for pullout resistance as 7.0 inches below the bottom of the WEXTEX transition. Seven (7.0 inches) is for Zone B or B1[2]. Note that although Zone A, for tubes located at a large radius from the center of the tubesheet, is 5.2 inches, 7.0 inches is applied throughout. The maximum nondestructive examination (NDE) uncertainty on the W* distance in Reference 1 is 0.12 inch. Therefore, the required Technical Specification inspection distance below the top of the tubesheet, or bottom of the WEXTEX transition, whichever is lower, is 7.12 inches.

[2] Zone B was the designation for a radius of about 2.3 inches for pullout analysis and Zone B1 was the designation for the same radius for leak rate analyses. Hence, the designations are interchangeable.

4.0 Applicability of WCAP-14797, Rev. 2, to Salem Unit 2

4.1 Background Information

As previously noted, the W* is the length of sound engagement of the tube within the tubesheet such that the force resisting expulsion from the tubesheet balances the force applied to the end section of a presumed severed tube. The value of W* is determined using applicable performance criteria relative to tube burst, expulsion from the tubesheet in this case, and relative to allowable leakage, as may be established for alternate repair criteria (ARC). The structural performance criteria are that tube burst will not occur with a margin of 3 during normal operation and 1.4 during the most severe faulted event, a postulated steam line break event (SLB) for Salem Unit 2 per Reference 1, conservatively bounded by using 2650 psid.

Applied Load

The applied force comes from the internal pressure in the tube. At the U-bend there is a component of the primary-to-secondary differential pressure acting in the axial direction. For the development of the criteria it is also assumed that the tube is severed in the tubesheet so that the differential pressure acts on the entire cross section area of the tube as calculated using the expanded outside diameter (OD) of the tube. The applied force, F_A, is determined from the applied pressure, ΔP, area, A, and the outside diameter, D_o, as,

$$F_A = \Delta P A \textit{ where, } \mathrm{A} = \frac{\pi}{4} D_o^2 \tag{1}$$

Here, ΔP is the difference between the primary, P_P, and secondary pressure, P_S, at the top of the tubesheet, i.e., $P_P - P_S$.

Reaction Load

The reaction load in developing the W* length arises from friction between the tube and the tubesheet within the tubesheet hole. The friction force is the product of the normal force between the tube and the tubesheet and coefficient of friction between the tube and the tubesheet. The normal force arises or is affected by four sources:

1. The residual preload from the expansion process,
2. Differential thermal expansion between the tube and the tubesheet,
3. Resultant pressure in the tube within the tubesheet, and
4. Dilation of the tubesheet holes from bowing of the tubesheet.

The first three items result in a compressive normal force between the OD of the tube and the ID of the tubesheet hole. The last item results in a reduction of the normal force near the top of the tubesheet and an increase in the normal force below the tubesheet neutral axis. It is noted that a lateral load applied to the center of the tube span above the TTS would tend to result in a slight lateral contraction in the axial direction. An analysis of the geometry of deflection shows that the axial contraction is a small fraction of the lateral deflection and the bending load that would be developed at the top of the tubesheet would act to bind the tube tighter in the tubesheet hole. On this basis, the action of lateral flow loads can be neglected from further consideration.

*Determination of W**

The calculation performed is to find the length, W*, that makes the following equality true between the resisting force on the left and the applied force on the right,

$$\mu(N_X + N_T + N_P + N_D) = \Delta P\,A \tag{2}$$

where
N_X = The residual normal force from the expansion process,
N_T = The normal force from the differential thermal expansion,
N_P = The normal force due to the resultant pressure in the tube,
N_D = The normal force resulting from dilation of the tubesheet hole,
μ = The coefficient of friction between the tube and the tubesheet.

The resisting forces are due to the interface pressure between the tube and the tubesheet. The actual force is the product of the interface pressure times the effective area of contact, the circumference of the tube times the length of contact. Conservative uncertainty adjustments are then made to the length of contact to determine W*. The diameter of the tube is constant, so an expression for the force per unit length is used and solved for the length, *L*. This means that each force term must be replaced by force per unit length term.

The solution for W* is then,

$$W = \frac{\Delta P\,A}{\mu(F_X + F_T + F_P + F_D)} \tag{3}$$

where *W* stands for the W* length and the letter *F* stands for the force per unit length of engagement. Each force per unit length term is then replaced by a corresponding pressure times circumference term, i.e.,

$$W = \frac{\Delta P\,A}{\mu(P_X + P_T + P_P + P_D)\pi D_o} \tag{4}$$

where D_o is the outside diameter of the expanded tube. Substituting for the cross section area yields,

$$W = \frac{\Delta P\,D_O}{4\mu(P_X + P_T + P_P + P_D)} \tag{5}$$

for the determination of *W*, without adjustments for uncertainties in measurement and end effects where the assumption of a severed tube has been made. The following points are to be noted:

1. The applied load term, the numerator is affected by changes in the operation of the plant. The value used for the generic document is the same as that for the plant specific

application at Salem Unit 2, hence the W* length would be expected to be the same as that for the generic application.

2. The residual expansion pressure, P_X, is not affected by changes in the operation of the plant.
3. The thermal expansion term, P_T, is affected by changes in the hot leg temperature, T_{hot}. The hot leg temperature at Salem Unit 2 is greater than the value used for the generic determination, hence the value of W* for use at Salem Unit 2 should be less than the generic value.
4. The differential pressure term, P_P, is affected by changes in the primary and/or secondary pressure. The differential pressure term used for the Salem Unit 2 analysis is less than the generic analysis; therefore, the value of W* for use at Salem Unit 2 should be less than the generic value.
5. The dilation term, P_D, is also affected by changes in the primary and/or secondary pressure. The differential pressure acting across the tube sheet is the same as in the generic report. It is noted that different differential pressure conditions were used for the determination of the different contributing load terms for the analysis of the generic report. This is an acceptable approach since the structure remains elastic when the terms are superimposed and is discussed in the following section.

4.2 Application of WCAP-14797-P, Rev. 2, To Salem Unit 2

The determination of the non-degraded tube length considers the residual preload capability of the tube expansion process, the thermal tightening effects due to thermal expansion coefficient differences between the tube and the tubesheet material, pressure tightening effects, and loss of preload due to tubesheet bow effects. The residual preload inherent in the expansion in the expansion process is independent of differences between analysis and plant conditions. The generic analysis uses a hot leg temperature of 590°F, whereas the limiting Salem Unit 2 hot leg operating temperature is approximately 602°F (or more), thus the generic analysis results are based on less thermal tightening than actually occurs in the steam generators. The generic analysis uses a secondary side steam pressure of 900 psia for evaluation of pressure tightening effects whereas the minimum steam pressure just prior to the 2R14 outage was about 784 psia. When the pressure loss between the sensing location and the SG outlet of about 10 psi is included, the steam pressure at the SG outlet is at least 793 psia (the normal operation primary-to-secondary pressure differential is about 1457 psi). This steam pressure results in a smaller primary to secondary pressure differential for the generic analysis condition compared to the Salem Unit 2 condition. Therefore, the generic analysis considers about 7.3% less pressure tightening contribution than the actual condition within the Salem Unit 2 steam generators. The generic analyses also used a steam pressure of 760 psia (differential pressure of 1490 psi across the tubesheet) for the evaluation of tubesheet bow effects during normal operation whereas the current Salem Unit 2 differential pressure across the tubesheet is 1457 psi, thus the generic analysis is about 2.3% more hole dilation than the current Salem Unit 2 conditions. Assumed normal operating steam pressure also influences the analysis with regard to defining the applied end cap load that acts to push the postulated separated tube out of the tubesheet hole. The generic analysis uses a steam pressure of 760 psia for a differential pressure of 1490 psi which also is conservative compared to the current Salem Unit 2 condition. Moreover, the internal steam pressure losses due to moisture separation will result in a slightly higher pressure within the steam generator. Therefore, the generic analysis includes greater end cap loading compared to the actual conditions within the Salem Unit 2 steam generators. This end cap load must be reacted by the net residual contact load. As the end cap load is reduced, the non-degraded tube length is also reduced compared to the generic analysis.

Based on the above, it is expected that the Salem Unit 2 specific W* should be less than the generic value because of the net effect of the changes. The independent considerations lead to the results similar to those presented in Reference 1. A comparison of the Salem Unit 2 operating parameters to those considered in the generic report is provided in Table 1.

4.3 Salem Unit 2 Conclusions

The determination of the W* lengths of 5.2 and 7.0 inches for Zones A and B1 respectively in Reference 1 for the application to the Salem Unit 2 SGs is considered to be valid. The differences in length required for the two zones are based on a variance in the tubesheet bow between peripheral and center regions of the tubesheet. The differences between the Salem Unit 2 specific and the generic calculation values is the result of the conservative assumptions associated with performing a generic calculation, e.g., extremely low secondary side pressure (which increases the applied load and the dilation of the tubesheet holes), additional pressure considered in the crevice, and the use of a lower bound residual expansion pressure. Nevertheless, the application of W* to the Salem Unit 2 Nuclear plant SG tubes per the Reference 2 guidance is considered to be justified.

5.0 W* Applications Background

Knowledge of the background is necessary to facilitate and understanding of why a bounding analysis approach is being proposed for application in the Salem 2 SGs instead of that developed in Reference 1. The alternate tube repair criteria (ARC) designated as W* described in Reference 1 were approved for use to disposition tube indications occurring within the tubesheets of the steam generators (SGs) at Pacific Gas & Electric (PG&E) Company's the Diablo Canyon Nuclear Power Plant (DCPP) in 1999. The safety evaluation (SE) performed by the staff in supporting the approval of the license modification was documented in Reference 6. Again, the W* criteria state that indications (e.g., cracks) of any magnitude can be tolerated below a specified depth within the tubesheet, designated as W*, and that tube indications that are essentially axial above that depth may remain in service if the predicted leakage from those indications is less than an amount permitted for the specific plant's SGs. The calculation of predicted leak rates is performed using a Westinghouse computer code named DENTFLO. The description of indications of any magnitude includes circumferential indications with an extent up to 360°, i.e., severing of the tube within the tubesheet, although the number of circumferential indications was not expected to be significant at the time of development of the criteria and is consistent with ongoing inspection results. The use of the W* criteria required that PG&E obtain an amendment to the operating license for the DCPP units. In approving the license amendment, the NRC staff stipulated that the criteria performance be monitored, that in situ leak rate testing of significant tube indications be performed, and that the license be periodically renewed.

A request for a license amendment to permit the application of a subset of the W* criteria for use in disposition of potential indications in the SG tubes at the Beaver Valley Power Station was submitted to the NRC staff for approval in the summer of 2004 by the FirstEnergy Nuclear Operating Company (FENOC), Reference 7. The proposed change requested a revision to the SG tube inspection scope to limit the use of bobbin or rotating probe coil (RPC) inspection technology to a depth of 8 inches below the top of the tubesheet, but not to implement the portions of the W* criteria that permit indications within the W* length to remain in service. The background for the request was associated with a deficiency in the detection capabilities of using the bobbin coil probe for performing the nondestructive examination (NDE) of the tubes. The use of an RPC probe is indicated when it is suspected that circumferential degradation might be present. The Reference 7 change submittal stipulated that any tube with service-induced degradation within the tubesheet in the W* length, i.e., eight inches from the top of the tubesheet (TTS), would be repaired. The request for Beaver Valley was also based on application for one cycle of operation (the last before SG replacement) which featured in the staffs response, Reference 8, and is discussed later. It was also noted in the SE that the staff had concerns regarding the use of the crevice leakage model that were associated with an understanding of the nature of the tube-to-tubesheet contact pressure within the crevice. It was apparent that a key element of the approval for application at Beaver Valley was the commitment to plug or repair tubes with indications within the W* length.

A Tennessee Valley Authority (TVA) submittal for a like application of the W* criteria subset to the SG tubes at the Sequoyah 2 power plant was transmitted to the NRC for approval in December 2004, Reference 9. There were two elements of the TVA request that were different from that for Beaver Valley, limiting the inspection depth to 7 inches as justified in the Reference 1 WCAP instead of eight as implemented at Beaver Valley, and application for multiple cycles of operation without requiring renewal. Engineering support for the license amendment similar to that developed for Beaver Valley was documented in Reference 10; a series of RAIs (requests for additional information) were sent to the utility in response to the license amendment request by Reference 11. The evaluation of potential primary-to-secondary leakage was solely based on the results of the tube-to-tubesheet crevice tests as was done for Beaver Valley. The approval of the amendment request was transmitted to TVA via Reference 12.

The need to renew the license agreement with regard to the future application of the W* ARC to SG tube inspections at the DCPP Units 1 & 2 sites led to discussions between PG&E and the NRC Staff in late December 2004, to examine a potential course of action. The criteria had been applied per the description in Reference 1 since the 1999 Reference 6 approval on the basis of renewing the NRC concurrence with technical specification changes on a two-cycle basis to minimize the number of tubes affected by primary water stress corrosion cracking and to minimize the risk for cracks to propagate into the freespan above the top of the tubesheet. Axial indications within the W* length were permitted to remain in service as long as their potential leakage was accounted for (using the DENTFLO code). There were three main elements to the discussion:

1. Effecting a permanent license renewal instead of a two-cycle extension, favored by PG&E.

2. Terminating the performance of the *in situ* tests of tube crack-like indications within the tubesheet that were originally required by the NRC staff because none of the tests have ever resulted in measurable leakage.
3. Implementing a modified calculation algorithm that would account for leakage from throughwall tube cracks located below the W* distance from the top of the tubesheet to address concerns associated with the Beaver Valley approval.

The NRC staff also appeared to be in favor of a permanent implementation of the license amendment and also judged that the *in situ* testing was not providing meaningful results and probably could be terminated. It was also apparent that there remained staff concerns associated with the use of the original leakage model. Thus, further dialogue concentrated on the third element of the discussion. The concern the staff considered to be unresolved was with regard to the accuracy of the Reference 1 leak rate model that accounted for leakage through a tube crack in series with the tube-to-tubesheet joint crevice[3]. Tests were performed relating flow through an axial crack in which deformation of the flanks was constrained by the inside diameter (ID) of the tubesheet and separate tests were performed to characterize the leak rate of flow through the crevice, i.e., interference fit, between the tube and the tubesheet. There were no tests performed that used specimens which mimicked the actual SG geometry consisting of a crack in the tube in series with the tube-to-tubesheet crevice. The Reference 1 information indicates that such testing is not necessary based on the theoretical basis of integrating the two empirical models. That is, the two flow restricting elements of the joint are in series and the analysis method involves satisfying conservation of mass and the constraint that the pressure at the outlet of the crack must be a match to the pressure at the inlet to the crevice. The interpreted staff position was that the concern is not with the model theory, but that the accuracy has never been established by test, i.e., there has been no benchmarking of predicted leak rates relative to measured values, thus, leading to the speculation that the leak rate being assigned to indications above a 12 inch depth into the tubesheet might be nonconservative.

In order to address the expressed concern, another leak rate model was developed for Diablo Canyon which was based solely on the use of the constrained crack data. This was necessitated by PG&E desiring to use a criterion that would continue to allow specified axial cracks to remain in service within the W* length. A subsequent PG&E discussion with the staff in January 2005, following transmittal of information describing the constrained crack model, led to the following feedback:

1) Subject to final staff review, it would probably be acceptable to use the constrained crack model at a 95% confidence level to calculate ARC condition monitoring (CM) and operational assessment (OA) leak rates[4] and it was noted that it would be acceptable to determine each leak rate as a function of specific tubesheet zone, i.e., the radial location of the tube hole since that was a feature reviewed and accepted in the Reference 1 approach.

[3] The WEXTEX tube expansion process results in a residual interference fit that is also present during normal operation and postulated accident conditions, a small amount of primary-to-secondary leakage is predicted to occur based on the results of testing and analysis models.

[4] The constrained crack model is discussed in detail in Section 9.0 of this report.

2) In order to apply the W* DENTFLO leak rate model, a comparison of the constrained crack versus DENTFLO leak rates would have to be performed at the same confidence levels. In addition, the staff would have to evaluate the leak rate reduction factor effect of the crevice, and thus would need additional information for its review.

3) More information would be needed to justify assigning the DENTFLO leak rate to undetected circumferential tube cracks between 8 and 12 inches deep in the tubesheet. It was also noted that no leak rate needs to be assigned to circumferential cracks that are being plugged on detection, as long as they are not throughwall. Finally, the staff agreed that it would be conservative to assume that every uninspected tube in the 8 to 12 inch range had a circumferential crack, however, they were not certain that assigning the DENTFLO leak model would provide conservative results.

Consideration of the outcome led to the development of an application subset of the W* criteria for the disposition of tube indications within the tubesheet at Salem 2 is identical in philosophy to that utilized by Beaver Valley, i.e., all indications found within a W* length of 8 inches will be plugged. A bounding leak rate is to be applied to account for leakage from projected indications in a range of 8 to 12 inches below the top of the tubesheet, and a bounding leak rate will be applied to all tubes that are not inspected below 12 inches from the top of the tubesheet. The application of the leak rate model for more that one cycle of operation is justified because of the conservatism afforded by using only the constrained crack test data, thereby ignoring the added resistance of the tube-to-tubesheet crevice, which is at least on the order of that for constrained cracks.

Each of the NRC staff concerns are addressed for implementation of the subset of the W* criteria at Salem 2. The technical elements of the implementation are as follows:

(1) *Leak Rate from Indications Less Than 8 Inches from the TTS* — If indications are found that are estimated to be throughwall, the leak rate for the condition monitoring evaluation can be calculated using the constrained crack leak rate correlation at a 95% confidence level based on the location of the tube within the tube bundle as provided herein.

(2) *Leak Rate from Cracks Between 8 and 12 Inches from the TTS* — Estimate the number of indications that could be present using data above 8 inches and calculate the potential leak rate using the constrained crack bounding model. This is a feature from the Diablo Canyon evaluation to use the constrained crack model to calculate the leak rate from indications in the range of 8 to 12 inches below the top of the tubesheet.

(3) *Leak Rate from Cracks Below 12 Inches from the TTS* — Assume that all of the tubes in the bundle are cracked and estimate the total leak rate from the indications using the bounding crevice model.

The emphasis of this report is on the leak rate characteristics of tube indications found within the tube sheet. The strength of the tube-to-tubesheet joint was well established by the results of pullout tests as documented in Reference 1, and has been accepted by the NRC staff as documented in

References 6, 8, and 13 for Diablo Canyon Units 1 & 2, Beaver Valley Unit 1, and Sequoyah Unit 2 respectively.

6.0 Primary-to-Secondary Leak Path

The primary-to-secondary potential leak path for throughwall tube cracks within the tubesheet is through the crack and then through the interface between the tube and the tubesheet. Recall that the interface is commonly referred to as the tube-to-tubesheet crevice in spite of the fact that an interference fit with a positive contact pressure is present over most, and frequently all, of the length of the tube within the tubesheet. The term crevice in this report refers to the tube-to-tubesheet interface in the same respect. To develop the leak rate model for application in operating SGs, Westinghouse performed tests using two distinct types of specimens as follows:

1. Crevice test specimens fabricated so that there would be no resistance to primary water entering the crevice between the tube and the tubesheet. The results from the tests would then be typical of those that would be expected if a tube were to become severed that the severed faces separated within the tubesheet.
2. Constrained crack test specimens which were axially cracked and installed in tubesheet simulating collars such that the upper tip of the crack was located at the entrance to an open channel to the top of the collar. The tested configuration simulated an axial crack within the tubesheet for which there was no crevice resistance above the uppermost tip of the crack.

The physical situation within a SG tubesheet would predominantly be that of an axial crack like the second series of tests where the fluid would then enter the crevice simulated by the first series of tests. In both cases the resistance to flow was characterized. The DENTFLO code was developed to integrate the two models into a unified model for the flow such that predictions could be made for operating SGs. As such, the pressure drop through the crack was calculated based on satisfying the law of conservation of mass flow and used as the driving potential for flow through the crack. The remaining pressure drop was then used as the driving potential for flow through the crevice.

Owing to unresolved concerns on the part of the NRC staff related to the accuracy of the model since the integrated configuration had not been tested, the original approvals for usage were limited to two cycles of operation and also required the performance of in situ testing in an attempt to obtain confirmatory data. References 6 and 13 provide information related to the conditions under which approvals of license amendments were granted.

In order to address the staff's concerns regarding the accuracy of the integrated model, a bounding approach to estimating the leak rate based on using only the data from the crevice tests was developed as described in Reference 7. The FENOC submittal was based on repairing all tubes with indications within the W* length, thus avoiding consideration of the potential leak rate from such indications. A subsequent submittal was developed by the Tennessee Valley Authority utilizing the same model and approach to repairing tubes at Sequoyah Unit 2. However, the request for Beaver Valley entailed only one cycle of operation following implementation while that a Sequoyah would involve multiple cycles of operation. An alternate approach based on using only the data from the constrained axial crack tests was subsequently developed to support the application for Diablo

Canyon for multiple cycles of operation because a bounding model for potential leakage from axial indications within the W* length for tubes remaining in service was needed. This latter model ignores the resistance to leakage provided by the crevice. In both cases, the entire pressure drop is assumed to provide the driving potential for primary-to-secondary flow. The analysis of the data from the crevice tests is discussed in Section 8.0 of this report and the analysis of data from the constrained crack tests is discussed in Section 9.0. The results from the crevice leak rate tests have been used to establish a bounding leak rate for indications located below 12 inches from the top of the tubesheet, while the results from both the crevice and constrained crack tests have been used to establish a bounding leak rate for indications located from 8 to 12 inches below the top of the tubesheet.

7.0 Circumferential Cracks

The NRC staff recently approved a one-cycle license amendment for the application of a subset of the W* criteria for application to inspection for indications in the SG tubes at the Beaver Valley Unit 1 SGs, Reference 8. The approval was based on the results from a bounding leak rate estimation approach using only the data from the crevice test specimens, i.e., Table 6.2-3 of Reference 1. The values from these specimens represent the expected leakage from a tube which has been cracked throughwall over 360° within the tubesheet and the two sections of the tube parted so that the crack itself presents no resistance to leakage. In other words, the data are bounding for circumferentially cracked tubes. In approving the license amendment the staff noted that there was still concern when comparing the average contact pressure for the nominal 1.25 inch crevice depth leak test samples to contact pressures for indications located approximately 8 inches below the TTS. "According to the data presented in WCAP-14797, the contact pressure at approximately 8 inches below the TTS is less than 100 psi greater than the averaged contact pressure from the test samples. If the maximum contact pressure, rather than the average contact pressure, is the dominant factor that determines leak rate, the NRC staff can not verify that 1.25-inch crevice depth sample leak rates based on average contact pressures are conservative for indications located 8 inches below the TTS in the SG." The staff concurred with the application for one cycle of operation based on additional conservatisms in the analysis and the fact that the leak rate at a depth of 8 inches would be applied over the range from 8 to 12 inches and contact pressure increases with depth.

The Tennessee Valley Authority (TVA) submitted a similar license amendment request for the Sequoyah Nuclear plant for application for multiple cycles of operation. The following is the text of an electronic mail sent from the NRC staff to the TVA with regard to that request.

> "The issue is the leak rate assigned to degradation located between 8 and 12 inches within the tubesheet region. The concern is that the licensee used an average contact pressure to relate the test conditions to the field conditions. In the staff's SE approving the Beaver Valley W* amendment, we raised a concern about this; however, we concluded it was acceptable for one cycle of operation given the other conservatisms in the analysis. The licensee for Sequoyah attempts to address this issue by explaining that there are many conservatisms in the analyses and therefore the leak rate they are using is acceptable. They also provide another assessment that correlates the leak rate to both the crevice length and the contact pressure (presumably

the average contact pressure). We agree that many of the assumptions in the analyses are conservative. It is difficult to quantitatively conclude that these conservatisms will ensure that the leak rate applied to degradation between 8 and 12 inches below the top of the tubesheet is conservative.

"As a result, does the licensee have any more quantitative information to support their case? For example, have they quantitatively assessed what the effect on the maximum and average contact pressure of the test specimens would be if they consistently accounted for the secondary side pressure in determining the contact pressure in the test and in the field (for the field they assumed a crevice pressure of 800 psi, for the test they assumed there was no pressure within the crevice)? Additionally, do they have any insights into the relative roles of maximum contact pressure and average contact pressure on the leak rate?"

The information provided above is similar to the opinions expressed during telephone discussions with members of the staff, however, it also states that there is a concern regarding the interpretation of the test data from the crevice leak test program. The concern was originally documented in the structural evaluation (SE) for Beaver Valley, quoted above, and relates to the use of average versus maximum contact pressure over the length of contact of the test specimen. If the average contact pressure is the dominant factor in controlling the leak rate, then increasing the length of the joint must decrease the potential leak rate. If however, the maximum contact pressure is the dominant factor, the staff has opined that simply increasing the length of the joint may not result in a proportional reduction in the leak rate. The implication is that without additional test data or some compelling rebuttal argument the staff will not concur with the application for an amendment to the technical specification for the plant.

The evaluation to resolve the expressed concern is based on noting that the analysis performed for the Beaver Valley 1 plant SGs, leading to the Reference 8 SE, conservatively utilized the contact pressures from Table 4.3-9 of Reference 1. These values were originally developed for the analysis of pullout loads for Zones B and A for 4-loop plants for bounding faulted conditions. Data developed for leak rate analyses were presented in Table 4.3-11 of Reference 1 for Zones B1 through B4 and A based on the discussion of Section 4.3.3 of that reference. (Note that Table 4.3-11 of Reference 1 contains a typographical error in that the contact pressure in Zone B4 at a depth of 2 inches should read 198 instead of -198.) There are subtle differences in the results which affected the NRC staff's conclusion regarding the contact pressure margin being less than 100 psi. For example, the Table 4.3-11 contact pressure at a depth of 8 inches into the tubesheet ranges from 1823 to 2108 psi, without the residual installation contact pressure, depending on the zone being analyzed. The average contact pressure for the test specimens of the comparison was 1352 psi. Thus, the contact pressure at a depth of 8 inches ranges from about 470 to 760 psi greater than the average of the test specimens. The difference is illustrated on Figure 9. Examination of the Table 6.2-3 data reveals that the minimum contact pressure at a depth of 8 inches per the finite element analysis matches the maximum contact pressure of the tested specimens, i.e., about 1820 psi. It should also be noted that the actual length of contact of the test specimens ranged from 0.59 to 0.62 inch although the nominal distance from the drilled holes to the top of the tubesheet collar was 1.25 inches. The average specimen contact pressure is matched by the finite element zone with the minimum contact pressure at a depth of 6.8 inches. Thus, every 0.6

inch length starting at a depth of 6.8 inches has a contact pressure that exceeds the average of the test data. For example, the average contact pressure from 6.8 to 7.4 inches below the top of the tubesheet is greater than 1352 psi, actually 1471 psi or more than 100 psi greater that that of the test specimens. The minimum contact pressures in Zone B2 are more than 100 psi greater than those in Zone B1, and correspond to the maximum difference in Zone B1, which involves a small number of tubes.

A more accurate comparison can be made between the specimens tested with a nominal crevice length of 2.0 inches from the drilled holes to the top of the tubesheet collar. The average length of contact was actually 1.28 inches and the contact pressures ranged from 1864 to 2257 psi with an average value of 2019 psi. The corresponding contact pressures from the finite element analysis range from 1823 to 2108 psi with an average value of 1971 psi. This means that the expected leak rate for circumferential indications at a depth of 8 inches would be expected to be bounded by the leak rate from the nominal 2 inch engagement test specimens, about a factor of 3 less than the value conservatively used in the leak rate analysis. That is, the contact pressure in the worst zone of the tubesheet for a distance of 1.3 inches above a depth of 8 inches is greater than or equal to that that of the tested specimens, thus the leak rate from a severed and separated tube would be expected to be the same. In reality, the crack itself would present a significant leak resistance upstream of the crevice and the leak rate would be expected to be meaningfully less. This means that the constrained crack model presented for the consideration of indications below the W* depth and above a depth of 12 inches is appropriately conservative and valid for the purpose for which it was intended.

Leak Rate from Indications Below 12 Inches from the TTS

The total anticipated leak rate from indications located below a depth of 12 inches into the tubesheet is based on considering all of the tubes to be cracked at that elevation. This is the same approach considered to be acceptable in References 6 and 8. No leakage would be expected from indications greater than 12 inches below the TTS due to the substantial contact pressure below that depth, e.g., the expected Zone B1 contact pressure at 4200 seconds into the SLB event is about 3000 psi. However, conservative estimate of leakage for indications at greater than 12 inches below the TTS can be made by using the upper 90% prediction leak rate at 2650 psid for the 3 inch nominal crevice data of $8.7 \cdot 10^{-5}$ gpm. Figure 11 provides a graphical illustration of the value for the actual contact length of 2.25 inches. The contact pressure for the 3 inch nominal crevice samples, 2273 psi, is approximately equal to that at about 9 inches below the TTS and increase at a rate of about 400 psi per inch of depth, see Figure 9. If all of the approximately 3300 the tubes in the affected SG, regardless of plugging, were assumed to be severed at a depth of 12 inches into the tubesheet, the calculated SLB leakage would be on the order of 0.3 gpm. Zones B2, B3, B4 and A contact pressures as a function of depth below the top of the tubesheet are higher than for Zone B1 to a depth of about 11 inches. Zone A tubes have a positive contact pressure for almost the entire crevice length which is expected to result in a substantially decreased leak rate during a postulated SLB event.

7.1 Severed Tube Model for Circumferential Cracking & Postulated Volumetric Indications

As previously noted, there is a NRC staff concern associated with the use of average contact pressure over the crevice length as opposed to the maximum contact pressure over a short length. The purpose of this discussion is to present a development of the physical model of the interface, that is, a torturous path between contacting rough surface asperities that must be present in order to explain the observed phenomenon of leakage. The model assumes a complete circumferential separation of the tube and thus presents a bounding approach that addresses all observed and postulated degradation orientations within the expanded tubesheet. Testing has demonstrated that water can be forced between the mating tube and tubesheet surfaces when the internal pressure is less than the contact pressure from the interference fit, hence, there must be a path for the flow when the net contact pressure is greater than zero. In order for flow to occur, a finite area flow path must exist between the outside surface of the tube and the inside surface of the tubesheet.

Both the tube and tubesheet can be characterized as having rough surfaces on a microscopic scale with the OD of the tube being much smoother than that of the ID of the tubesheet hole. The physical nature must be that of two rough surfaces being pressed together so that 100% intimate material contact does not occur until unusually high contact pressures are reached. The leak path is then between irregular mating of the surface asperities. If the tube and tubesheet surfaces were perfectly smooth and in intimate contact there could be no flow through the interface because there would be no flow area. This would be true even in the event that the pressure internal to the tube was greater than the contact pressure. For example, flat rubber stoppers in open drains prevent flow effectively simply due to the weight of the water pressing on the upper surface. Leakage is prevented because the material of the stopper comes into intimate contact with the material of the sink and the rubber deforms to fill any superficial irregularities. When the smooth tube is forced into contact with the rougher tubesheet, the tube material does not flow to fill the gaps between asperities. This physical model explains the leakage phenomenon and is why the Darcy model for the flow was selected initially to quantify the calculation of the leak rate. Because there is an inhomogeneous physical interface between the tube and the tubesheet that is in contact, it is to be expected that there would be a meaningful relationship between the resistance to flow and the contact pressure. Consideration of the effect of the geometry of the interface leads to the expectation of a nonlinear microscopic deformation behavior that could be described using a logarithmic scale. The force needed to close off the crevice gaps would be expected to increase disproportionately and the resulting relationship on a logarithmic scale could be weak. That is, as the contact pressure increases, the resistance to further deformation at the interface also increases at the same time as the reduction in flow area decreases. Such a relationship was observed in plotting the loss coefficient against the contact pressure in Reference 1. Hence, the a model implies that the resistance to flow would be significant over the length of the leak path and not be limited by any limited extent location of maximum contact pressure.

However, there are outcomes that could be also expected if the maximum contact pressure was the dominant factor in determining the magnitude of the resistance to flow. Specifically, the frequency of occurrence of maxima of the contact pressure would be expected to increase with an increase in length of the joint. For example, the frequency of occurrence of a local contact pressure matching the maximum over a specified length of joint would be expected to double on average if the joint length doubled. This means that the resistance to leakage would still be expected to be significantly dependent on the total length of the joint, a phenomenon which is evident from the test data.

8.0 Leak Rate Through the Tube-to-Tubesheet Crevice

The NRC Staff has recently questioned the validity of the original conclusion from Reference 1 that postulated circumferential cracking below W* would not produce meaningful leakage at SLB conditions. The evaluation of this and the following sections establishes the bases supporting the argument that meaningful leakage would not result from degradation below the W* elevation. SG leakage events have been attributed to outside diameter stress corrosion cracking (ODSCC) in the freespan and at TSP intersections, primary water stress corrosion cracking (PWSCC) at U-bends, at tack roll transitions of non-expanded tubes, and due to loose parts, a.k.a. foreign objects. Since no operating plant leakage has been associated with postulated circumferential degradation below W*, it is reasonable to assume that the potential for such indications to leak is unlikely. Another interpretation is that the inherent leakage resistance of at least 7 inches of sound WEXTEX expansion (based on a nominal 8 inch below the TTS inspection distance when the expansion transition distance is ignored) at the TTS is sufficient to preclude reportable leakage (i.e., in the range of less than 2 gpd or $1.4 \cdot 10^{-4}$ gpm).

Two sets of leakage data support the W* criteria. The first set of data was prepared by tack rolling a 7/8 inch OD by 0.050 inch wall thickness Alloy 600 tube into a carbon steel collar. The tube was seal welded to the collar and subsequently WEXTEX expanded. Ten (10) 0.125 inch diameter holes were drilled through the collar and tube at elevations referenced from the top of the collar to permit water to enter the interface between the tube and the tubesheet. The diameter of the holes may have been increased to 0.25 inch and the number reduced to eight at the discretion of the test engineer. The second set of leakage tests were performed to examine the effect of the tube-to-tubesheet contact pressure on the leak rate from axial cracks with flanks constrained from radial deflection and is discussed in Section 9.0. The resistance to flow from the constrained crack tests is of the same order of magnitude as that from the crevice tests. Thus, the overall leak rate predicted by either set of data alone must be conservative by about a factor of two.

8.1 Tube-to-Tubesheet Crevice Leak Rate Testing Description

The first series of tests that are discussed is referred to as crevice or drilled-hole leak tests interchangeably. Each of four typical WEXTEX expanded tube specimens was tested with the leak path holes drilled through the tube at 3, 2, and 1.25 inches from the top of the collar in sequence, see Reference 1. Each of the specimen configurations was tested at differential pressures of 1620, 2000, and 2650 psi, at 600°F and at room temperature for the lowest differential pressure. Following drilling of the holes through the collar and tube, the holes in the carbon steel collar were drilled to a larger diameter and the OD of the tube deformed inward (i.e., staked) to assure that there was no resistance to water entering the tube-to-tubesheet crevice. The cumulative diameter of the holes drilled in the tubes was greater than or equal to 3.93 inches, greater than the OD circumference of the expanded tube, 0.890 inch. The staking operation deformed the OD of the tube away from the ID of the collar, maximizing the flow path upstream of the crevice entrance. The staking operation also had the effect of reducing the contact length of the crevice by about

0.23 inch for each tested configuration. Following completion of the 3 inch nominal crevice length tests, a second set of holes was drilled at 2 inches from the top of the test collar. The process was repeated for a third set of holes drilled at a nominal distance of 1.25 inches from the top of the collar. The tube holes were not plugged after completion of testing at the 3 and 2 inch nominal crevice length tests[5]. Leak rates increased as the nominal distance to the top of the collar decreased. Calculations were performed to estimate the actual crevice length associated with each of the test specimens based on accounting for the staking operation and the geometry of the expansion transition at the top of the crevice. The results reported in Reference 1 were that for the nominal length of 3 inches at 2650 psid at 600°F the actual crevice lengths were 2.37, 2.29, 2.37, and 2.1 inches, for an average of 2.28 inches. The average actual crevice length for the 2 and 1.25 inch nominal crevice length specimens was 1.28 and 0.61 inches respectively. The added contact length due to pressure inside of the tube is reduced at lower pressures and the actual crevice length is likewise slightly less.

8.2 Correlation of Leak Rate to Crevice Length

The first set of crevice tests were performed with the drilled holes located at 3 inches from the end of the test collar. The leak rate results are listed in Table 6.2-3 of Reference 1. The leak rate results from the tests performed at a differential pressure of 2650 psi at 600°F are listed in Table 3 and illustrated on Figure 1. A linear first order regression model of the logarithm of the leak rate, Q, on the crevice length, L, was fitted as,

$$\log(Q) = b_0 + b_1 L + \varepsilon \tag{1}$$

where b_0 and b_1 are the regression coefficients and ε is a random error about the regression line with a mean of zero and a standard deviation of s. An upper 90% prediction bound for the regression model was calculated as,

$$\log(Q) = b_0 + b_1 L + t_{0.9,n-2}\, s\sqrt{1 + \frac{1}{n} + \frac{(L - L_m)^2}{SSL}} \tag{2}$$

where n is the number of data points in the regression, L_m is the mean length tested, and SSL is the corrected sum-of-squares of the lengths tested, i.e.,

$$SSL = \sum_{i=1}^{n} (L_i - L_m)^2, \tag{3}$$

and t is the 90th percentile value of the Student-t distribution for n-2 degrees of freedom. It is noted that the observation of leakage from the specimens at the equivalent of normal operating conditions, i.e., differential pressure of 1620 psi at a temperature of 600°F, is different from the experience of plant experience where no leakage has been attributed to indications within the

[5] The effect of holes at lower elevations would be negligible for the 1.25 and 2 inch nominal tests because of the lack of a pressure drop between the holes.

tubesheet, either the samples yield conservative leakage estimates or such degradation is not present in operating units.

Additional regression analyses were performed using all of the data. The results from performing linear first order regression analyses for the leak rate data for differential pressures of 1620, 2000 and 2650 psi at 600°F respectively are and presented on Figure 2. It is noted that the leak rate data are independent of the test pressure for the lengths tested since fitting separate regression lines yields similar slopes and intercepts. Comparison tests were performed on the results of the analyses and it was found that there were no statistically meaningful differences between the intercepts or the slopes. Thus, the attendant increase in contact pressure compensated for the increase in pressure difference by reducing the area available for the leakage flow, or the flow in the test specimen crevices was at choke conditions. Regardless, the conclusion is that all of the leak rate data, i.e., those for 1620, 2000 and 2650 psid, could be included on the same plot and a regression analysis performed of the lumped data set. Performance of this analysis results in a regression line similar to that for the 2650 psi differential pressure test data that also predicts slightly lower median flow rates. The other consequence of including all of the data is a reduction in the standard error of the regression and a reduction of the leak rate values from the upper prediction bound, about a factor of two or slightly greater over the range of interest of about 0.6 to 2.3 inches. Thus, predictions based on the use of only the 2650 psi differential pressure leak rate data are conservative relative to those from the entire data set.

8.3 Determination of Bounding Leak Rates

The leak rate from postulated severed tubes can be bounded by the leak rate from the crevice test specimens as long as the elevation of the sever is conservatively below the location in the tubesheet where the contact pressure matches that of the test specimens. The results from the finite element analyses of the tube-to-tubesheet joint[6] were used to determine equivalent depths below the top of the tubesheet in the SG based on matching the contact pressures to use the predictions from the test data for actual crevice lengths in the range of 0.6 to 2.3 inches. The contact pressures as a function of depth into the tubesheet for Zones B1 and A are shown on Figure 3, conservatively taken from the values developed for the pullout load analyses as listed in Table 4.3-9 of Reference 1. The average contact pressures for the specimens tested at a differential pressure of 2650 psi are also illustrated using their actual crevice lengths. The contact pressures from the test specimens are matched by tubes in Zone B1 at depths of 7.7, 9.5, and 10.3 inches below the TTS respectively. When the same comparison is made using the contact pressures developed for SLB leak rate analyses and presented in Table 4.3-11 of Reference 1, the equivalent depths are about 1 inch less than those listed above, or, for the same depths in the tubesheet, the leak rate analysis contact pressures are about 500 psi greater than those developed for the pullout analysis. These comparisons are made without including the residual WEXTEX expansion contact pressure because that was the basis for the reported the leak rates in Table 6.2-3 of Reference 1. The corresponding 90th percentile upper bound regression model leak rates at the minimum and maximum average specimen depths, i.e., those bounded by depths of 8.3 and 12.6 inches into the tubesheet are $4.5 \cdot 10^{-3}$ and $8.7 \cdot 10^{-5}$ gpm respectively. The use of the latter values assures that the

[6] See Tables 4.3-9 and 4.3-11 for tube pullout and leak rate analyses respectively,

contact pressure is greater than that of the tested specimens over the entire actual length of the crevices tested. The regression analysis used the test results from those specimens that leaked, however, two of the specimens with a 3 inch nominal crevice length did not leak. If an average or best estimate leak rate is included in the analysis for the specimens that did not leak, the upper 90% prediction leak rate is reduced by a factor of 1.3 from that shown on Figure 1. If the correlation of the leak rate on the crevice depth as shown on Figure 1 is projected to greater depths within the tubesheet, the expected leak rate from indications below 12 inches would be reduced significantly.

The total positive radial contact pressure as a function of depth below top of the tubesheet due to thermal expansion, pressure expansion, and WEXTEX expansion is reported in Reference 1. The reduction in contact pressure due to tubesheet bow is included to develop resultant radial contact pressure as a function of depth below the top of the tubesheet. Figure 3 presents a plot of resultant radial contact pressure as a function of depth below top of the tubesheet for the Zone A and B1 regions. If the Zone B1 data is conservatively applied to the entire tubesheet, at approximately 9.1 inches below the TTS, the resultant radial contact pressure is 2500 psi. The Figure 3 data are based on the plant response at 4200 seconds into the SLB event.

When the equivalent depths are calculated, most of the length of the crevice above the equivalent depth is ignored. For example, the actual crevice length of the 1.25 inches nominal crevice length test specimens was about 0.6 inch. The corresponding Zone B1 tube would have a total crevice length of almost 8 inches, of which 4 inches is calculated to have a positive contact pressure. Thus, the use of the drilled hole specimen data is conservative because the actual length of contact, and hence flow resistance, is greater than the length tested. The fact that there is a smaller contact pressure over most of the interface length does not mean that the flow resistance is zero.

Since the contact pressure reduction due to hole dilation was not included, a conservative estimate of potential leak rate for a postulated circumferentially separated tube below the W* inspection distance of 8 inches below the TTS would be to use the predicted leak rates. At this crevice depth (equivalent to leakage specimens with actual crevice depth of 0.61 inch), the predicted leak rate is $1.9 \cdot 10^{-3}$ gpm using the mean (arithmetic average) regression of the leak rate as a function of actual crevice depth and $4.5 \cdot 10^{-3}$ gpm at the upper 90% prediction bound, see Figure 1. Thus, the SLB condition conservative leak rate applied to a circumferentially separated tube between 8.0 and 12 inches below the TTS is $4.5 \cdot 10^{-3}$ gpm. For a postulated circumferentially separated tube at > 12 inches below the TTS, substantial contact pressure and crevice lengths would exist above this location, resulting in a no leakage condition. However, a conservative leakage allowance will be included.

As no 100% TW, 360° circumferentially separated tubes are anticipated to be present between 8 and 12 inches below the TTS, application of the W* alternate repair criteria could be such as to not involve leakage from postulated indications below W*. No leakage would be expected due to the substantial contact pressure at greater than 12 inches below the top of the tubesheet. However, for practical purposes an estimate can be made and is discussed in developing a conservative estimate of the potential leakage as follows:

1) For example, if it is assumed that all 48 postulated indications between 8 and 12 inches below the TTS at the end of cycle 2R14 are circumferentially oriented and that the tubes are severed, the leakage associated with these indications is 0.13 gpm using the 90^{th} percentile leak rate corresponding to a test specimen crevice length of 0.61 inch, which has a contact pressure similar to that in the SG at a depth of ~8 inches, and would be dispersed over 4 SGs.

2) A conservative estimate of leakage for indications at greater than 12 inches below the TTS can be accomplished by applying the upper 90^{th} percentile prediction leak rate at 2650 psid for the 3 inch nominal crevice data of $8.7 \cdot 10^{-5}$ gpm. The contact pressure for the 3 inch nominal crevice samples is approximately equal to a Zone B at 10 inches below the TTS. At 12 inches below the top of the tubesheet, the expected Zone B contact pressure at 4200 seconds into the SLB event is approximately 2900 psi, about 600 psi greater than for the average of 2273 psi for the 3 inch nominal crevice length leakage specimens.

   If all remaining active tubes in the least plugged SG are assumed to contain a circumferential separation at 12 inches below the TTS, the SLB leakage contribution would be approximately 0.27 gpm (3150 tubes times $8.7 \cdot 10^{-5}$ gpm per tube). Note that 2 of the 4 samples had no leakage at 2650 psid and the constrained crack leak test data suggest that no leakage could be expected, regardless of the indication orientation at a contact pressure of greater than 2500 psi.

   Zone A contact pressures as a function of depth below the top of the tubesheet are higher than for Zone B to a depth of about 11 inches. The increase in contact pressure above that depth can have a significant effect on the leak rate, however, this has been conservatively neglected in the leak rate analysis. Zone A tubes retain positive resultant contact pressure for almost the entire crevice length. The added length with positive contact pressure is expected to provide a substantially increased resistance to leakage during a postulated event. It should also be noted that the assumption that all tubes contain a circumferential separation at > 12 inches below the TTS is an extreme conservatism.

Combining the upper 90% prediction leak rate with the assumption that all tubes are separated is even more conservative, and may be so conservative that the predicted value is unrealistic. For a large number of samples, i.e., assuming all tubes are separated, any postulated SLB condition leakage would be expected to migrate to the mean leak rate. The mean, i.e., arithmetic average, leak rate regression for the 3 inch nominal crevice length specimens is on the order of $1.6 \cdot 10^{-5}$ gpm per tube, and for the conservative assumption of all tubes separated, the expected leak rate would then be about 20% of the value of 0.27 gpm calculated above.

Summarizing the example, for an end-of-cycle 2R14 nominal inspection distance of 8 inches below the TTS, total SLB leakage from indications below the inspection distance could be 0.40 gpm, with 0.13 gpm attributed to indications between 8 and 12 inches below the TTS and 0.27 gpm attributed to indications at greater than 12 inches below the TTS.

Predicted leak rate as a function of contact pressure was also considered, however it was determined that the leak rate prediction is best accomplished using the specimen crevice depth. This determination was based on a comparison of the statistical goodness-of-fit between the two sets of data. At equal probability levels, the estimation of leakage using crevice depth provides for a conservative total leakage prediction compared to estimation of leakage using contact pressure.

Additional conservatism is present in the above described leakage prediction since all indications below the 2R13 planned inspection depth of 8 inches below the TTS are assumed to be circumferentially separated. As stated above, only 10% of the total historical indication count are circumferentially oriented. Leakage estimation from axial PWSCC is substantially less than the model used for circumferentially oriented PWSCC.

8.4 Correlation of Leak Rate to Crevice Length & Contact Pressure

In addition, finally, additional calculations were performed to obtain linear regression coefficients for the logarithm of the leak rate as a function of the crevice length and the calculated contact pressure. The regression results were then used to estimate the 90th percentile prediction bound relative to the predictions based on the regression on crevice length alone. The results indicated that neglecting the contact pressure leads to over predictions on the order of 4 to 20 relative to that from using the combined data set. In conclusion, the bounding calculation results reported could be about an order of magnitude greater than would be obtained from a refinement of the analysis.

In order to partially quantify the conservatism associated with the first order linear regression analysis approach involving only the crevice length, a subsequent analysis was performed which included the contact pressure as a second variable. The analysis also considered all of the data in establishing the regression line. The regression model for the analysis of the leak rate, Q, as a function of the crevice length, L, and the contact pressure, P_c, for a differential pressure of 2560 psi at a temperature of 600°F is,

$$\ln(Q) = a_0 + a_1 L + a_2 P_c + \varepsilon. \tag{4}$$

Here, a_0 through a_2 are the coefficients of the least squares regression analysis, and ε represents a random normally distributed error about the regression line. Note that an interaction between the crevice length and the contact pressure was not anticipated and an interaction term is not included in the model. Letting ln(Q) be represented by the variable Y, L by X_1 and P_c by X_2 a series of equations can be formed for each of the sets of test data up to the total number of tests N. For example, the lengths $L_1 \ldots L_N$ are represented by $X_{11} \ldots X_{1N}$, the contact pressures $P_1 \ldots P_N$ are represented by $X_{21} \ldots X_{2N}$, so the set of simultaneous equations to be solved for the coefficients is represented by,

$$\begin{bmatrix} 1 & X_{11} & X_{21} \\ 1 & X_{12} & X_{22} \\ \vdots & \vdots & \vdots \\ 1 & X_{1N} & X_{2N} \end{bmatrix} \begin{Bmatrix} a_0 \\ a_1 \\ a_2 \end{Bmatrix} = \begin{Bmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_N \end{Bmatrix}. \tag{5}$$

The shorthand notation for the above equation is [X]{a}={Y} where brackets are used for matrices and braces are used for vectors. The maximum likelihood or least squares solution for the coefficients is found as,

$$\{a\}=\left[X^T X\right]^{-1}[X]^T\{Y\} \tag{6}$$

where the superscripts T and -1 denote the transpose and inverse of the matrix respectively. Once the coefficients have been obtained from the regression analysis, the prediction of a new values of the logarithm of the leak rate, Y, for a given crevice length, X_1 and contact pressure X_2 is obtained from,

$$Y=\lfloor 1 \quad X_1 \quad X_2 \rfloor \begin{Bmatrix} a_0 \\ a_1 \\ a_2 \end{Bmatrix}=\lfloor X_h \rfloor \{a\}. \tag{7}$$

An upper prediction bound for the value of the logarithm of the leak rate, $\ln(Q)$ or Y, is found from the relation,

$$\ln(Q)=a_0+a_1 L+a_2 P_c+t_{1-\alpha,N-p}\, s\sqrt{1+\lfloor X_h \rfloor\left[X^T X\right]^{-1}\lfloor X_h \rfloor^T} \tag{8}$$

where,
s = the standard error of the regression equation,
$1-\alpha$ = prediction portion to be bounded, e.g., 90%,
N = the number of data sets used in the regression analysis,
p = the number of coefficients in the regression equation, and,
t = the upper Student's t distribution variate for $1-\alpha$ and $N-p$ degrees of freedom.

The results of the analysis are presented on Figure 4. The 90th percentile leak rate for a crevice depth of 0.61 inch is $5.4\cdot10^{-4}$, corresponding to the value of $4.4\cdot10^{-3}$ from the single variable analysis, a difference of a factor of 8. Likewise, the bounding leak rate for a crevice length of 2.28 inches was calculated to be $1.26\cdot10^{-5}$, a factor of 6.5 less than the corresponding value from the single variable analysis using the crevice data.

Application of these results to the previous analyses leads to the expectation that the 0.13 gpm total leak rate from indications in the range of 8 to 12 inches below the TTS would be reduced to 0.018 gpm by increasing the complexity of the crevice data analysis. Similarly, the 0.27 gpm leak rate for 3,150 postulated separated tubes at a depth of 12 inches would be reduced to 0.04 gpm, with the total expected leak rate being about 0.058 gpm instead of the considered 0.40 gpm using the constrained crack data for the 8 to 12 inch depth and crevice data for greater than 12 inches below the top of the tubesheet. The calculated median leak rate per tube used with the assumption that all of the tubes in the SG are severed is reduced from $4\cdot10^{-6}$ to $4.3\cdot10^{-7}$ gpm per tube. And, again, the use of the crevice data conservatively omits the resistance of the crack and the use of the constrained crack data conservatively omits the resistance of the crevice.

9.0 Leak Rate Through Constrained Axial Cracks

An analysis of the potential leak rate from the W* axial indications in the Unit 2 SG tubes was performed using a prediction methodology based only on the data from the constrained crack tests as presented in Table 6.3-3 of Reference 1. By using only the constrained crack data, the predictions omit consideration of the resistance to the leak rate from the crevice, i.e., interference fit, between the tube and the tubesheet, and therefore, may be expected to be significantly conservative. A review of the raw test data was performed before starting the analysis because the data presented in Table 6.3-3 of Reference 1 were rounded to provide a summary of the original results. In addition, the contact pressures reported as zero in that table were really for cases where there was a physical gap between the tube and the tubesheet and a negative contact pressure to represent the magnitude of the actual gap had to be calculated. It was found that two of the leak rates for Collar A, with a tighter clearance, at a nominal pressure difference of 2650 psi at 600°F were lower than listed in Table 6.3-3 of Reference 1. The leak rates for specimens WP-008 and WP-012 should have been reported as 4.58E-05 and 1.28E-04 gpm respectively. These values are factors of 0.6 and 0.3 relative to the originally reported values respectively and result because the fluid collection times were actually greater than in the data summary. All other data values were confirmed to be accurate. The discovered changes are not meaningful to the overall W* analysis and do not affect any prior plant analyses. Moreover, the originally reported leak rate values were greater than actually obtained, i.e., conservative, and would result in overestimating, albeit very slightly, the leakage from plant indications.

The data were analyzed to prepare two figures relating the leak rate to the contact pressure and the depth in the tubesheet during a postulated accident event. Figure 5 presents the leak rate from the constrained crack specimens as a function of contact pressure within the test collar. The contact pressure was varied by using two different diameter tubesheet collars and by changing the temperature and internal pressure of the tube. Slightly negative contact pressures represent small clearances between the tube and tubesheet collar. These are the positive diametral gap values in Table 6.3-3 of Reference 1 for collar B. The median and average logarithm of the leak rate as a function of the contact pressure is given by the relation,

$$\ln(Q) = a_0 + a_1 P_c + \varepsilon \tag{9}$$

where ε is a statistical error about the regression line. The value of ε will be somewhat constant over the range of the data and is to be calculated at a one-sided 95% simultaneous confidence level. A prediction of the average logarithm of the leak rate, $\ln(Q_i)$, at a 95% confidence level for any indication, i, with a contact pressure P_{ci} can be calculated as,

$$\ln(Q_i) = a_0 + a_1 P_{ci} + \left(2F_{2,n-2,\alpha}\right)^{1/2} s\sqrt{\frac{1}{n} + \frac{\left(P_{ci} - P_{cm}\right)^2}{SSP_c}} \tag{10}$$

where a_0 and a_1 are coefficients obtained from performing a regression analysis of the data, P_{cm} is the mean value of the test contact pressures and SSP_c is the corrected sum of squares of the contact pressures found as,

$$SSP_c = \sum_{i=1}^{n} (P_{ci} - P_{cm})^2 , \tag{11}$$

n is the number of data used to obtain the coefficients of the regression equation, s is the standard deviation of the regression errors, and F is the variate from the F-distribution for n and n-2 degrees of freedom with α being the percentile in the upper tail, e.g., a 95th percentile corresponds to an α of 5%. Since various lengths of the cracks were tested, the variance of the regression errors includes the effect of different lengths of throughwall indications. The 95th percentile value of the F distribution term for 2 regression coefficients and 36 data pair is 2.221. The use of the F-distribution is necessary because the confidence bound curve is to be applicable to all values of the contact pressure simultaneously, i.e., all indications in the detected population. The average of the logarithm of the leak rate corresponds to the median leak rate, but not the average, a.k.a. arithmetic average, leak rate. To obtain the average leak rate, the exponential is taken of the logarithm of the leak rate plus 1/2 of the variance of the prediction errors, s^2, of the logarithm of the leak rate. Therefore, a simultaneous one-sided 95% confidence on the expected or average value of the leak rate is given by the following where α is 0.05,

$$Q_i = \exp\left[a_0 + a_1 P_{ci} + \left(2F_{2,n-2,\alpha}\right)^{1/2} s \sqrt{\frac{1}{n} + \frac{(P_{ci} - P_{cm})^2}{SSP_c}} + \frac{1}{2} s^2 \right]. \tag{12}$$

In order to apply this prediction to estimate the total leak rate from several indications in the tubesheet, relations for the contact pressure as a function of depth and radius from the center of the tubesheet were developed from the results of the finite element analysis discussed in Reference 1. The tubesheet has been divided into five zones for which the contact pressure as a function of depth was determined for use in leak rate calculations and reported in Table 4.3-11 of Reference 1. Table 5 lists the intercept, b_0, and slope, b_1, parameters for the contact pressure as a function of depth, L, in the tubesheet for the five zones, i.e., B1 through B4 and A (also see Table 6.4-1 of Reference 1 for the radii for the zones). The relationships are all of the form,

$$P_c = b_0 + b_1 L \tag{13}$$

where the coefficients b_0 and b_1 vary as a function of the zone of the tubesheet for the tube with the indication. A plot of the contact pressures for each zone is provided as Figure 6. The analysis was further refined by examining the relationship between the intercept and slope of the prediction equations as a function of tube location radius. It was found that second order polynomial expressions could be used to describe the parameters almost exactly, i.e., with negligible error, confirming that the analyses could be performed by using contact pressure relation parameters calculated for each affected tube. In summary, the finite element model results for contact pressure as a function of radius can be described by second order polynomial curve fits. Table 6 provides the polynomial coefficients that were then used to determine the values of b_0 and b_1 for any given radius from the center of the tubesheet. A plot of the intercept and slope coefficients as a function of tube location radius is provided on Figure 7. Here, the following relationships are depicted,

$$\begin{aligned} b_o &= g_0 + g_1 R + g_2 R^2 \quad \text{(Intercept)} \\ b_1 &= h_0 + h_1 R + h_2 R^2 \quad \text{(Slope)} \end{aligned} \tag{14}$$

The results from converting the contact pressures to elevation depths for leak rate calculations using the finite element analysis results for Zone B1 are shown on Figure 8 to illustrate the relationship. Zone B1 is characterized as having the most severe tubesheet bow effects associated with Zones B1 through B4 on Figure 8.2-1 of Reference 1.

Constrained crack leak rate calculations were performed considering cracks at a depth of 8 inches into the tubesheet at each of the 5 zone radii resulting in estimates of 0.0022 to 0.0028 gpm at contact pressures ranging from 2834 to 2557 psi respectively. Thus, a bounding leak rate that can be applied to all indications in the range from 8 to 12 inches into the tubesheet is 0.0028 gpm. This is also evident from examination of the information on Figure 6 regarding FEA contact pressures and Figure 10 illustrating the 95% simultaneous confidence bound for the leak rate as a function of contact pressure. Recall that the constrained crack leak rate data were presented as a function of total contact pressure, thus the total contact pressure during SG operation, including the residual installation contact pressure, must be used.

A final consideration was made with regard to the potential expansion taper at the bottom of the WEXTEX transition in some of the tubes in the Diablo Canyon SGs. The cause for consideration is that the presence of taper could signify a reduction in the residual contact pressure in the region of the taper. An examination of the profiles of the tubes in the Diablo Canyon SGs reveals that 95% do not have any expansion taper. However, the presence of the taper can only influence the predictions from the model if the tip of the crack is within the taper. That is, the taper is irrelevant because the model is based on considering that the tube does not exist above the tip of the crack for all practical purposes. This means that the model does not have to consider the potential influence of taper in the expansion if the tip of the crack is located below the bottom of the tapered region. It is recommended that any tube that is both tapered and has an axial crack with the upper tip of the crack within the taper be plugged. Since both the taper and the crack are detectable by eddy current, the 95th percentile confidence limit on the location of the tip of the crack does not have to be applied, all you have to do is make sure that the tip can be differentiated as being below the bottom of the taper. Alternatively, a model could be developed to account for the loss in contact pressure due to the presence of the taper and the leak rate calculated accordingly. Since the likelihood of both cracking and a tapered expansion being in the same tube, and the tip to being above the bottom of the taper is judged to be very small, it is likely that the need for such a model will not manifest itself.

9.1 Constrained Crack Model Validation

The results from the analysis of the indications in SG 1 at Diablo Canyon Unit 2 at refueling outage 12 demonstrated the leak rates from the constrained crack correlation at a simultaneous 95% confidence limit to be about three to five time those from the W* condition monitoring analysis (CM). The measured elevation of the upper tip of each crack (UCT) was increased by 0.22 inch, the 95% upper bound on the Plus Point™ NDE uncertainty associated with locating the UCT relative to the TTS per Table 8.3-1 of Reference 1. Corresponding comparisons were made for the operational assessment (OA) calculations using growth rates for each of the indications at a 95th percentile value. The OA leak rates from the correlation were found to be about three to six times the W* leak rate calculation values. It is expected that the results should be significantly greater than the W* model predictions simply because the resistance provided by the tube-to-tubesheet interference fit is neglected. For each of the SGs, the estimated total leak rate was found to be about a factor of 3 greater than that from the model that includes the crevice resistance.

Similar calculations were performed for the tube indications in the Diablo Canyon Unit 1 SGs. The constrained crack leak rate ratios relative to the DENTFLO calculations were factors of about 2 to 5, except for SG 11 where the constrained crack leak rate was less. The difference is minor and reflects the fact that the constrained crack leak rates are based on contact pressures as a function of the individual tube row and column numbers. The difference was due the result for a single tube for which the constrained crack model estimate of the leak rate was negligible due to its radial position on the periphery and resulting high contact pressures.

10.0 Comparison of Severed Tube and Constrained Crack Leak Rates

A comparison of the constrained crack and crevice leak tests was performed in order to directly address the staff's concern regarding the leak rate from circumferential cracks. In other words, an evaluation based on data as opposed to comparative analyses. Two subsets of each test series were considered. The differential pressure for each was on the order of 2650 psi at a temperature of 600°F. The data for tests of specimens with actual crevice lengths of approximately 0.6 and 1.3 inches were compared to the constrained axial crack test results for the designated close and tight collars, identified as B and A respectively. The basis for the selection of the test data with which to make the comparison was the contact pressure. The constrained crack results reported in Table 6.3-3 of Reference 1 are absolute in the sense that there was no residual installation pressure. The data in Table 6.2-3 do not include the residual contact pressure from the installation process and a value of 693 psi, consistent with prior analyses, was added to each contact pressure in order to make a direct comparison between specimen types. The results are illustrated on Figure 10. The axial cracks ranged from about 0.33 to 0.59 inch long. The equivalent length of the entrance to the crevice for the tubes with the drilled holes was about 2.8 inches (equivalent at least to the circumference of the expanded tube). The implication from observing similar leak rates from greater crack lengths is that the resistance to flow of the crevice is significantly greater than that of the restrained crack. This is consistent with the observation that the predicted leak rates for the Diablo Canyon SGs using the constrained crack model are more than twice the values obtained from the DENTFLO analyses.

In practice it has been found that the leak rate from freespan circumferential cracks is significantly less than that from freespan axial cracks with the same length. The difference is associated with the flexibility of the crack flanks and it is easy to demonstrate that axial cracks would be expected to have a greater crack opening area (COA) for the same internal pressure. The restriction of the tubesheet would prevent the flanks of an axial crack from deforming radially outward and provide a meaningful compressive hoop stress so that axial and circumferential cracks with similar lengths could be expected to exhibit similar leak rates under conditions of the same differential pressure and temperature. This anecdotally reinforces the conclusion that the constrained crack model results would be expected to be more than two multiples of the DENTFLO model results. It also provides support for the use of the constrained crack model for the evaluation of circumferential cracks. The confidence bound for the leak rate is also shown on Figure 10, illustrating the significant margin between the evaluation curve and the test data.

The DENTFLO analysis is based on solving for the crevice conditions that result in satisfying two constraints, the principle of conservation of mass from fluid dynamics and the fact that the pressure of the fluid exiting the crack must be equal to the pressure of the fluid entering the crevice at the elevation of the crack. The problem being solved is one in which the resistance of the crack is in series with the resistance of the crevice. The DENTFLO code employs routines from another code, named CRACKFLO, to calculate the flow through the crack. The CRACKFLO code was originally developed to model the flow through axial cracks in freespan tube locations. In order to adapt the calculations to the flow through a crack in the tubesheet where the radial deformation of the flanks is prevented and the hoop crack opening is severely restricted, an effective crack length was defined as the freespan crack length providing the same flow as observed in the constrained crack tests. Figure 6.3-8 of Reference 1 illustrates the concept of the effective crack length as a function of the tube-to-tubesheet contact pressure, presenting data for a variety of test crack lengths. The data indicate that the effective length is independent of the actual crack length. In summary, the crevice resistance is characterized by a parameter referred to as the loss coefficient and the crack resistance is characterized by a parameter referred to as the effective crack length. Both are treated as functions of the contact pressure between the tube and the tubesheet. Since the loss coefficient is a function of the contact pressure and the contact pressure varies from the elevation of the crack to the top of the tubesheet, the loss coefficient per unit length is integrated to obtain a weighted average for use in the leakage calculations.

In performing the leak rate calculations the DENTFLO code utilizes two bounding type relations presented in Reference 1, a 95% single-sided lower confidence bound for the loss coefficient, i.e., resistance per unit length, and a one-sided 95% upper prediction bound for the effective crack length, both as a function of the contact pressure between the tube and the tubesheet. The use of the added prediction bound for the crack length increases the difficulty of making a direct comparison between the models. Regardless, the calculations for circumferential cracks and volumetric indications based on the constrained crack model would be expected to be more conservative that those using the DENTFLO code because the crevice resistance is ignored in the constrained crack model.

11.0 Conclusions Regarding the Leak Rate Testing

The WEXTEX drilled hole leakage testing indicates the following characteristics for a WEXTEX expanded tube with a postulated circumferential separation below the W* inspection distance.

1. Comparison of the room temperature and elevated temperature tests indicates that elevated temperature leak rates were approximately 100 times less than room temperature leak rates.

2. Comparison of the elevated temperature test data for 1620 and 2650 psi pressure differential shows the leak rates are essential constant for both pressure differential conditions suggesting that pressure expansion has a limited effect on leak rates.
3. Based on the observations of items 1 and 2, contact pressure is seen as the most significant factor for restricting leak rate.
4. For the 1.25" nominal crevice test case, the contact pressure is approximately equal to the contact pressure of an expanded tube at 7.7" below the TTS while for the 3" nominal crevice test case, the contact pressure is approximately equal to the contact pressure of an expanded tubes at 10.3 inches below the TTS. The contact pressure reduction in the test samples was more rapid (per unit length) than in the actual tube. Contact pressures in the leakage specimens did not account for pressure within the tube to tubesheet crevice, and results in a conservative estimate of contact pressure. Contact pressures for the SG tube (Figure 4.8) include a crevice pressure of 800 psi for a leakage condition.
5. The accumulation of the leakage effects of the holes at 2 and 3 inch below the TTS can be seen as a representation of the postulated case where the tube is separated at 7.7, 9.5, and 10.3 inch below the TTS. The leak rate determined for the 1.25 inches nominal crevice tests is a conservative estimate of leakage for a tube with a postulated circumferential separation below the W* inspection distance.
6. Evaluation of the reported flaw elevations for Salem shows that indications were reported as deep as 9.8 inches below the TTS. Therefore, a number of tubes were inspected to depths exceeding the nominal inspection depth for 2R12 of 8 inches below the TTS. Therefore, the likelihood of any postulated circumferentially separated tube at or below 8 inches below the TTS is exceptionally small.

Zone B1 tubes were used for estimation of SLB condition leak rates. The Zone A tubes retain positive resultant contact pressure over the entire crevice length, and this increased length is expected to represent a significant decrease in SLB condition leak rates compared to Zone B1.

12.0 Distribution and Number of Tube Indications in the Salem 2 Tubesheets

An evaluation of the primary water stress corrosion cracking (PWSCC) history of the Salem Unit 2 SG tubes resulted in the conclusion that the most likely point of initiation is at the top of the tubesheet, and that the potential for PWSCC cracks to initiate below the top of the tubesheet decreases dramatically with depth into the tubesheet. This finding is the same as that from evaluations performed for other plants with WEXTEX tube-to-tubesheet joints. The evaluation of the Salem specific data indicates that the likelihood for a circumferentially separated tube to exist below the current +Point™, a.k.a. +Pt, coil inspection distance of 8 inches below the TTS is exceptionally small. The purpose of performing the evaluation is to estimate the number of indications in the range of 8 to 12 inches below the TTS in order to assign a conservative leak rate for use in demonstrating compliance with the allowable value during postulated faulted events.

12.1 Distribution of Indications

An estimate of the number of indications in service below the current tubesheet region inspection distance of 8 inches is based on an examination of the historical inspection data as listed in Table 7. Data available through 2R10 (Salem Unit 2 Refueling Outage number 10) were based on inspections to a depth of 3 inches from the top of the tubesheet. At 2R11 the nominal inspection depth was increased to 5 inches and at 2R12 the depth was increased to 8 inches. Thus, cumulative indication distribution information is available as a function of depth into the tubesheet. For example, the indications found between 5 and 8 inches at 2R12 are the entire population of indications that developed since the first operation of the plant. These can be compared to the number from 0 to 3 inches and from 3 to 5 inches in order to characterize the propensity for indications to form as a function of depth into the tubesheet by comparing the actual number found to expectations calculated on the basis of assuming that the formation of indications is random relative to depth.

PWSCC was first reported at the 2R06 in the fall of 1991; one axial PWSCC indication was reported at the explosive expansion transition just below the top of the tubesheet. Axial PWSCC indications in the tubes at the top of or within the tubesheet have been reported at each subsequent outage. Circumferential PWSCC indications were first reported at the 2R09 outage in the spring of 1995; three circumferential and two volumetric (likely circumferential and considered as such in this report) PWSCC indications were reported at the expansion transition just below the top of the tubesheet. The 2R09 inspection was the first large scale application of +Pt inspection technology for the tubesheet region of the tubes. The top of the tubesheet RPC examination depths have varied by outage. A summary of the nominal inspection depths are presented in Table 7, along with number of reported axial and circumferential indications, and the lowest reported flaw elevation.

A total of 239 axial PWSCC indications in 203 tubes and 9 circumferential PWSCC indications in 8 tubes were reported through the 2R10 inspection when the inspection depth was limited to 3 inches below the TTS, with the exception of SG24 at 2R10, corresponding to an average density of roughly 83 indications per inch of depth. If the indication initiation distribution was uniform over the entire length of the tube in the tubesheet, about 166 indications would have been expected to have been reported at the 2R11 inspection in the range between 3 and 5 inches below the TTS; however, only 15 axial indications were reported. The implication of the finding is clear, the distribution of indications is not uniform within the tubesheet and the density of indications is skewed with the highest density near the top of the tubesheet. This is not unexpected because the same trend has been observed at several other plants, discussed later.

The depth of inspection during the 2R11 inspection of the SG tubes was 5 inches for SGs 21, 23 and 24, and 7 inches for SG 22. A cumulative total of 321 indications were reported through 2R11 as indicated in Table 7. Consideration of a uniform flaw density would lead to the expectation of 64 indications per inch, and the prediction of about 192 indications in the 3 inch span between 5 and 8 inches below the TTS for the 2R12 inspection. A total of 27 indications were found at 2R12 with only 7 of those located more than 5 inches below the TTS. In summary, increasing the inspection depth below the TTS shows that the number of indications decreases dramatically with distance from the TTS. A cumulative of 166 indications were expected at 2R11 in the range of 3 to 5 inches below the TTS with only 15 actually reported, and a cumulative of 192 indications were expected at 2R12 in the range of 5 to 8 inches with only 7 reported. For the ranges of 3 to 5 and 5 to 8 inches respectively, the actual number of indications present were 9 and 3.6% of those expected based on the assumption of a uniform distribution for the potential for indications to be present.

The 2R12 and 2R13 data can also be used to examine the potential for the initiation of new indications deeper within the tubesheet. For both outages the nominal inspection depth was 8 inches below the TTS. At 2R13, 15 axial indications were reported, 13 within 3 inches and two at greater than 8 inches below the TTS. There were no new indications within the 3 to 8 inch span below the TTS. Again, the previous conclusion that both the distribution of and potential for new indications is skewed with the highest number occurring near the TTS is verified.

The inspection distance applied to the 2R14 outage was 8 inches below the TTS, consistent with the 2R12 and 2R13 inspections. A total of 41 axially oriented indications in 37 tubes was reported. No circumferentially oriented PWSCC was reported at the 2R14 inspection. Of the 41 reported indications, 39 were located within 3 inches of the TTS, one was located in the range from 3 to 8 inches below TTS (-6.71 inches actual elevation reported), and one was located at greater than 8 inches below TTS (-9.38 inches actual elevation reported). The 2R14 inspection data are consistent with the previous outages in that this data shows the potential for development of indications is reduced with increasing depth below TTS.

The distribution of all PWSCC indications reported at Salem and other plants with Series 51 SGs with WEXTEX tube-to-tubesheet joints as a function of elevation within the tubesheet is shown on Figure 12[7]. The chart clearly illustrates that the initiation of PWSCC indications is significantly greater for the region of the tube near the top of the tubesheet and decreases rapidly at the deeper elevations. Recall that for the 2R10 and all early outages, the +Pt inspection distance below the TTS was 3 inches while for the 2R11, 2R12, and 2R13 outages the +Pt inspection distances below the TTS were 5, 8, and 8 inches respectively. It is also clear from the information on Figure 12 that the potential for the initiation of tube PWSCC indications monotonically decreases with depth into the tubesheet.

The elevation distributions for all data and the 2R12 and 2R13 data are quite similar, further supporting the argument that PWSCC initiation potential below the transition region is far less than for the transition region. Note that for the charts presented herein, indications in the elevation range from 0.00 and 0.99 inch below the top of the tubesheet are found in the 0 inch bin and so forth. The Salem cumulative elevation distribution was compared against that of other plants with Model 51 SGs. The distributions for all plants are quite similar. Figure 12 also includes the Diablo Canyon Power Plant and Beaver Valley Power Station distributions which are seen to be quite similar to those in the Salem SGs.

[7] The cumulative distribution of tube PWSCC indications as a function of elevation for the 2R11, 2R12, and 2R13 outages only is also presented.

12.2 Prediction of Indications to a Depth of 8 Inches

The inspection transient effect of the 2R11 and 2R12 outages, i.e., the increase of inspection depth to examine tube locations that were not previously inspected with RPC technology shows that the total number of indications is approximately 4 to 5 times the number of indications in regions that were not inspected using the RPC technique. In summary, the evidence is overwhelming that the historical indication counts can be used to reliably estimate the number of non-detected indications below the specified RPC inspection distance from the TTS.

For the 2R11 outage with a +Pt inspection distance of 5 inches below the TTS in SGs 21, 23, and 24, and 7 inches below the TTS in SG 22, 73 PWSCC indications were reported; 58 were reported within a previously inspected distance. Including 2R11, 321 indications were reported, and only 15 (about 4.7%) of the cumulative total were reported at elevations previously not inspected using RPC technology, i.e., in the range of 3 to 5 inches from the TTS. For the 2R12 outage with a +Pt inspection distance of 8 inches below the TTS in all SGs, 27 indications were reported; 20 were reported within a previously inspected distance. Including 2R12, 348 indications were reported, and only 7 (about 2%) of the cumulative population were reported at elevations never before inspected, i.e., in the range of 5 to 8 inches from the TTS.

The cumulative indication totals by outage through 2R13 are illustrated on Figure 13. The trend of the cumulative number of indications is linear for the last several outages, in essence for the time period that the +Pt coil has been the inspection of record for the tubesheet region. Based on the cumulative data through 2R13, between 23 and 56 indications would be predicted at 2R14 from the regression lines, depending upon whether the data used are from the last 3, 4, or 5 outages. The largest 2R14 predicted indication is obtained using the 2R09 through 2R13 data. As the recent (2R09 through 2R13) trending shows a decreasing indication count, and use of the cumulative data is conservative compared to the per outage data, a projected value equal to the limiting value from those from the last 3, 4 and 5 outages can be used, that is, approximately 56 indications. Therefore, the cumulative number of indications including the 2R14 projection would be expected to be a maximum of no more than 417 (361 plus 56) for the Salem 2 SGs. As noted, the actual indication count for 2R14 was 41, thus good agreement between prediction and actual was obtained. Of the 41 indications, recall that 39 were located within the TTS to 3 inches below range, one was located in the 3 to 8 inch below TTS range, and one was located at greater than 8 inches below TTS. Applying a similar methodology to the 2R14 data results in a prediction of between 25 and 50 indications at 2R15 from the regression lines, depending upon whether the data used are from the last 4, 5, or 6 outages. Figure 14 presents the cumulative indication totals by outage through 2R14 and includes the regressions to the last 4, 5, and 6 outages for prediction of indication counts for future outages.

12.3 Prediction of Indications Between 8 and 12 Inches

Previous W* application evaluations have used the historical elevation distribution to develop a bounding estimate of indications in the greater than 8 inches depth below the TTS. This has been performed by using the indication totals in the zero to 4 and 4 to 8 inch ranges below the TTS, with indications reported at more than 8 inches below the TTS accumulated into the 4 to 8 inch span. A total of 402 indications have been reported to date with 370 located within 4 inches of the TTS. That is, 92.04% of the indications have been found within and only 7.96% deeper than 4 inches from the TTS. Even though the elevation distribution shows a decreasing trend with increasing depth below the TTS, the density of indications in the range of 4 to 8 inches below the TTS is conservatively applied to the range of 8 to 12 inches below the TTS.

To date, 32 indications (7.96%) of the historical indication count have been reported at more than 4 inches below the TTS. Thus, the expected indication count between 8 and 12 inches below the TTS can be conservatively estimated by applying this percentage to the cumulative 2R14 indication count of 402, or about 32 indications. Previous W* applications have conservatively increased the percentage for making projections to future inspections. A 99% confidence bound on the potential number of indications in future samples would be 12%. Thus, 12% of the combined historical plus 2R14 new indications in the range of 4 to 8 inches, or 48 indications can be ascribed to the range of 8 to 12 inches below the TTS. Since the projection methodology for the range between 8 and 12 inches below the TTS includes the assumption that an equal number of indications are found in this range as for the range from 4 to 8 inches below TTS, provided no more than 48 indications are reported for the 4 to 8 inches below TTS range through future outages the projection of indications and associated leak rate for the 8 to 12 inch below TTS range remains valid. The limiting cumulative indication trend line indicates that approximately 500 total indications may be reported through the 2R16 outage, with approximately 40 total indications, i.e., 8%, in the 4 to 8 inches below the TTS range. Thus, the assumption of up to 48 indications in the limiting SG in the 8 to 12 inches below the TTS range is expected to remain valid through the service life of the original Salem 2 SGs (until replacement).

A very small number of these 48 postulated indications between 8 and 12 inches below the TTS would be expected to have all of the following characteristics;

1. be circumferentially oriented (To date, 363 total indications on 309 tubes have been reported, only 11, or 3%, of which were circumferentially oriented.),
2. have a depth of 100% throughwall (TW), and,
3. be circumferential with an extent of 360°.

At the 2R12 inspection in 2001, which was the first inspection to 8 inches below the TTS, two circumferential indications were reported both of which were in the range of 0 to 4 inches below the TTS (2 and 4 inches respectively). The maximum reported +Pt amplitude of the two circumferential indications was 0.9 volt, indicative of shallow maximum and average depths. For the 2R12 and 2R13 inspections the largest +Pt flaw amplitude at about 5 inches below the TTS was only 1.33 volts, which is also indicative of shallow depth.

The above data were developed using the nominal inspection distance below the TTS of 3 to 8 inches, based on the chronology of the outages. In practice, the inspection distance applied to each tube exceeds the specified value; this is purposely done during the data collection process to ensure that the appropriate distance is examined. This is shown by the deepest reported indications which reside at about 11 inches below the TTS, see Table 7. A plot of the binned PWSCC elevation data for all historical indications with and without the expansion transition indications is presented on Figure 16. Exclusion of the expansion transition indications would be expected to provide the best dataset for estimating indications at deeper depths because of the significantly higher residual surface stresses associated with the expansion transition. A best fit regression of the data with the expansion transition excluded is also shown the Figure 16. The data show that the predicted number of indications in each bin is only 1 for each of the one-inch increment bins greater than 8 inches below the TTS. Indication totals for the 1 through 7 inch bins below the TTS were used for the regression analysis as this range excludes the expansion transition effect on initiation and considers all historical indications in the applied nominal +Pt inspection program of 8 inches below TTS. Note that the 1 inch below the TTS bin of the x-axis on Figure 16 represents the elevation range from -1.00 to -1.99 inches below the TTS.

An upper 95% prediction bound for the data is also shown on Figure 16. Estimates using the 95% prediction curve indicate that approximately 18 indications would be expected in the 8 to 12 inch range below the TTS at the 2R14 inspection. The 18 indications for the upper 95% prediction represent the sum of the predictions for the 8, 9, 10, and 11 inch bins and represents the elevation range from -8.00 to -11.99 inches below TTS. For conservatism, the previously established value of 48 will be applied for the leak rate analysis of the Salem 2 SG indications. The binned indication count data for the 2R12 and 2R13 outages shows the largest number of indications in any 1 inch bin between 4 and 8 inches below the TTS was only 3. Therefore, as the initiation potential is decreased with increasing depth below the TTS, there is no basis to assume that large numbers of indications are present below the nominal inspection depth of 8 inches below the TTS.

Note that this analysis was performed to estimate the number of indications between 8 and 12 inches below the TTS using the data through 2R14. Subsequent outage inspection data can be evaluated in the same manner to more accurately estimate the potential non-detected number of indications between 8 and 12 inches below the TTS in order to assign a leak rate contribution during a postulated faulted event. However, the methodology applied, which assumes equal initiation potential for the 4 to 8 inch below TTS range as for the 8 to 12 inch below TTS range provides sufficient margin that a reevaluation of the regression is not considered relevant until at least 48 total indications are reported for the 4 to 8 inch below TTS range, or about the 2R18 timeframe. In order to estimate the number of indications in the 8 to 12 inch range below TTS at future points, the cumulative probability distribution of indication elevations was held constant and the indication counts increased to arrive at 48 indications in the 4 to 8 inch below TTS range. The total number of indications (TTS to -8 inches) at this point in time would be expected to be on the order of approximately 700. Using the upper 95% prediction developed for this assumed dataset, the estimated number of indications in the 8 to 12 inch range below TTS would be 31, well below the assigned value of 48. A second case was evaluated in which the indication count in the 4 to 8 inch below TTS range was again set at 48, however the total indication count was limited to 500. This represents a shift in the historical indication trending as it accounts for a much higher indication ratio in the 4 to 8 inch range compared to the total count. For this case the upper 95% prediction for the 8 to 12 inch below TTS range gives 43 indications, again bounded by the assigned value of 48.

Previous evaluations of the residual stress distribution in hydraulically expanded tube-in-tubesheet joints indicates that the residual surface stresses below the expansion transition are likely compressive in nature. Therefore, PWSCC initiation is likely associated with a localized geometry discontinuities resulting from the tubesheet hole drilling process (e.g., associated with variations in coolant flow and the longer path for chip removal with depth). As all tubesheet holes were drilled from the primary face, the frequency of tube hole abnormalities would be expected to increase as the secondary side face of the tubesheet is approached. The data of Figure 12 supports this argument. Furthermore, the circumferential extent of these abnormalities would be expected to be limited. The inspection data that shows the largest circumferential arc extent is 51° for indications below the TTS also supports this assumption.

12.4 Planar Distribution of the Tube Indications Within the Tubesheet

A tubesheet map or chart of all Unit 2 PWSCC indications reported through 2R13 is provided on Figure 15. A total of 128 of the 361 indications in the reported population were in the outboard region, designated as Zone A, which is the zone with the lesser amount of tubesheet deflection during operating or faulted conditions. In fact, from the Reference 1 designation of zones for leak rate analysis, any zone larger than that designated as Zone B1 would be expected to exhibit a leak rate significantly less than predicted from the Zone B, synonymous with B1 for leak rate calculations.

13.0 Conclusions

The analysis of the potential leak rate from tube indications within the tubesheet in the Diablo Canyon SGs (the original application of W*) using very conservative approximate methods confirmed the W* approaches taken to originally deal with those indications were effective. During the time since the original implementation of the W* methodology, the NRC staff raised concerns regarding the potential for leakage from such indications. The approximate methods have been demonstrated to be adequately bounding of the test data to alleviate those concerns.

In conclusion, the RPC (rotating probe coil) inspection for Salem 2 can be performed to a depth of 8 inches from the top of the tubesheet with confidence that the potential leak rate from indications in the region from 8 to 12 inches can be conservatively estimated. For the application of W* to the Salem 2 SGs, tubes with detected axial and circumferential indications within the W* distance will be plugged. The leak rate from detected and undetected indications can be calculated as delineated in Table 2. In summary,

1) The leak rate for axial indications within 12 inches from the top of the tubesheet can be conservatively calculated using the constrained crack model. The leak resistance from the interface is at least as great as that of the crack, thus omitting the resistance of the crevice means that the rates are overestimated by a factor of at least 2 in addition to the other bounding considerations.

2) A bounding leak rate of $9{\cdot}10^{-5}$ gpm from the crevice model can be assigned to all tubes not inspected below 12 inches to account for any level of degradation that may be present.

This means that an approximate level of 0.3 gpm will be added to the leak rate for all tubes in the affected SG.

3) The leak rate for circumferential and volumetric indications within 12 inches from the top of the tubesheet can be conservatively calculated using the constrained crack model for axial indications.

4) A bounding leak rate of $2.8 \cdot 10^{-3}$ gpm per estimated indication can be used to conservatively estimate the total leak rate from postulated undetected indications located between 8 and 12 inches below the top of the tubesheet.

5) A total of 48 indications with a maximum possible leak rate of 0.13 gpm could be postulated in the range of 8 to 12 inches below the top of the tubesheet based on considering all of the indications from all four SGs to be in the single affected SG.

6) Consideration of the distribution of indications on a per SG basis would reduce the number significantly as would calculation of the location specific leak rates using the regression analysis predictions presented in Section 9.0 for constrained cracks.

7) The concern regarding the contact pressure difference between the leak rate test specimens and the finite element model results has been addressed and the expected differences are in the range of 470 minimum to 760 psi maximum (at the inboard location of Zone A) depending on the location of the tube in the tubesheet.

8) There are a number of conservative elements in the methodology discussed herein, the inclusion of any of which would result in a reduction in the predicted leak rate. For example, increasing the complexity of crevice model to include both depth and contact pressure results in a large reduction in predicted leak rate. Further reduction would be effected by considering the resistance of the crevice in series with that of the crack. The aggregate effect is that the leak rate is being significantly over predicted.

The bounding approach to estimating the leak rate from indications within the tubesheet has been demonstrated to be conservative and is appropriate for use at Salem Unit 2.

14.0 References

1. WCAP-14797, Revision 2, "Generic W* Tube Plugging Criteria for 51 Series Steam Generator Tubesheet Region WEXTEX Expansions," Westinghouse Electric Company LLC, Pittsburgh, PA, March 2003.

2. NEI 97-06, Revision 1, "Steam Generator Program Guidelines," Nuclear Energy Institute, Washington, DC, January 2001.

3. 10CFR50 (Title 10, Part 50 of the Code of Federal Regulations, "Energy, Containing a Codification of Documents of General Applicability and Future Effect," Office of the Federal Register, National Archives and Records Administration, Washington, DC 20408, January 2004.

4. 10CFR100 (Title 10, Part 100 of the Code of Federal Regulations, "Reactor Site Criteria," Office of the Federal Register, National Archives and Records Administration, Washington, DC 20408, January 2004.

5. E-EP-05-006, "Salem Unit 2 Tubesheet Degradation History and Operating Parameters," P. Fabian, Public Service Electric & Gas, Salem, NJ, June 2005.

6. "Safety Evaluation by the Office of Nuclear Reactor Regulation Related to Amendment No. 129 to Facility Operating License No. DPR-80 and Amendment No. 127 to Facility Operating License No. DPR-82 Pacific Gas and Electric Company Diablo Canyon Nuclear Power Plant, Units 1 and 2 Docket Nos. 50-275 and 50-323," United States Nuclear Regulatory Commission, Washington, DC, 1999.

7. L-04-089, "Beaver Valley Power Station, Unit No. 1 Docket No. 50-334, License No. DPR-66 License Amendment Request No. 328 Revised Steam Generator Inspection Scope for One Cycle of Operation," FirstEnergy Nuclear Operating Company, Beaver Valley Power Station, Shippingport, PA, June 28, 2004.

8. NRC Letter, "Beaver Valley Power Station, Unit No. 1 (BVPS-1) – Issuance of Amendment Re: Revised Steam Generator Inspection Scope for One Cycle of Operation (TAC No. MC3671," United States Nuclear Regulatory Commission, Washington, DC, October 15, 2004.

9. TVA-SQN-TS-03-06, "Sequoyah Nuclear Plant (SQN) – Unit 2 – Technical Specifications (TS) Change 03-06 Change Inspection Scope for Steam Generator Tubes," Docket No. 50-328, Tennessee Valley Authority, Soddy-Daisy, TN, December 2, 2004.

10. LTR-CDME-04-147 (Proprietary) & LTR-CDME-04-148 (non-Proprietary), "Application of W* to the Sequoyah Unit 2 Steam Generator Tubes," Westinghouse Electric Company LLC, Pittsburgh, PA, October 29, 2004.

11. NRC Letter, "Request for Additional Information Related to Tennessee Valley Authority Sequoyah Nuclear Plant, Unit 2 (TAC MC5212) Docket No. 50-328," United States Nuclear Regulatory Commission, Washington, DC, January 2005.

12. "Sequoyah Nuclear Plant, Unit 2 – Issuance of Amendment Regarding Changes to the Inspection Scope for the Steam Generator Tubes (TAC No. MC5212) (TS-03-06)," United States Nuclear Regulatory Commission, Washington, DC, May 3, 2005.

13. "Sequoyah Nuclear Plant, Unit 2 – Issuance of Technical Specification Amendment Regarding Steam Generator Tube Inspection Scope (TAC No. MB4994)(TS 02-05)," United States Nuclear Regulatory Commission, Washington, DC, May 10, 2002.

14. NRC GL 2004-1, "Requirements for SG Tube Inspections," United States Nuclear Regulatory Commission, Washington, DC, August 30, 2004.

15. RG 1.121 (Draft for Comment), "Bases for Plugging Degraded PWR Steam Generator Tubes," United States Nuclear Regulatory Commission, Washington, DC, August 1976.

Table 1: Comparison of W* for Salem SG Tubes Relative to Generic Information				
Item	Analysis Term & Description	Salem Unit 2	Generic W*	Application of the Result
1	ΔP, Applied Pressure (End cap load)	$P_S \approx 793$ psia ($P_S > 760$ psia)	$P_G = 760$ psia	Salem W* < Generic W*
2	P_T, Thermal Tightening	$T_{hot} = 602°F$ (minimum)	$T_{hot} = 590°F$	Salem W* < Generic W*
3	P_P, Pressure Tightening	$P_S \approx 793$ psia ($P_S < 900$ psi)	$P_G = 900$ psia	Salem W* < Generic W*
4	P_D, Dilation Loosening	$\Delta P = 1457$ psi	$\Delta P = 1490$ psi	Salem W* < Generic W*
5	F, Three times normal end cap load	$F_S = 2719$ lb_f ($F_S < F_G$)	$F_G = 2781$ lb_f	Salem W* < Generic W*

Table 2: Salem 2 W* Leak Rate Calculation		
Depth in Tubesheet	Axial Cracking	Circumferential Cracking and Volumetric Degradation
Inspect from Zero to 8 Inches	Plug on detection. CM SLB leakage per the constrained crack model for the tube specific zone from the finite element analysis of the tubesheet.	Plug on Detection Calculate the leak rate using the constrained crack relations developed for axial cracks.
Do not inspect 8 to 12 inches	Determine the number of undetected flaws, axial, circumferential and volumetric, between 8 and 12 inches and assign a bounding leak rate on 0.0028 gpm to each undetected indication.	
Do not inspect > 12 Inches	Bounded by the leak rate assigned for circumferential cracking.	A bounding leak rate of 0.00009 gpm SLB leakage will be assigned to all tubes not inspected below a depth of 12 inches into the tubesheet.

Table 3: SLB Leak Rate as a Function of Crevice Length Regression Analysis

$$\log(Q) = a_0 + a_1 L$$

(Leak in GPM and Length in Inches)

a,c,e

Table 4: SLB Leak Rate as a Function of Crevice Length & Contact Pressure Regression Analysis

$$\log(Q) = b_0 + b_1 L + b_2 P_c$$

(Leak in GPM, Length in Inches, Pressure in psi)

a,c,e

Table 5: Contact Pressure as a Function of Depth Relations (Pressure in psi and Depth in Inches)					

a,c,e

Table 6: Contact Pressure Polynomial Function Coefficients for Linear Relation Coefficients (See Figure 7.)		

a,c,e

Table 7: Summary of Salem 2 Tube Indications as a Function of Inspection Depth

Refuel Outage	Inspection Depths by SG (inches)				Indications Reported						
					Axial		Circum-ferential		Joint		Deepest Location (inches)
	SG21	SG22	SG23	SG24	PDF	CDF	PDF	CDF	PDF	CDF	
2R06	3	3	3	3	1	1	0	0	1	1	-0.17
2R07	3	3	3	3	26	27	0	0	26	27	-3.7
2R08	3	3	3	3	5	32	0	0	5	32	-1.96
2R09	3	3	3	3	168	200	5	5	173	205	-5.48
2R10	3	3	3	5.5	39	239	4	9	43	248	-6.11
2R11[1.]	5	7	5	5	71	310	0	9	71	319	-6.65
2R12[2.]	8	8	8	8	25	335	2	11	27	346	-11.05
2R13[3.]	8	8	8	8	15	350	0	11	15	361	-8.3
2R14[4.]	8	8	8	8	41	391	0	11	41	402	-9.38

Notes:
1. A total of 58 indications were found in the 0 to 3 inch depth range.
2. Of the 27 total indications, 20 were in the range of 0 to 5 inches below the TTS.
3. There were 13 of the 15 total indications in the range of 0 to 3 inches.

a,c,e

[ ]

Figure 1: Regression of Leak Rate on Contact Length for $\Delta P = 2650$ psi at 600°F

a,c,e

[ ]

Figure 2: Regression of Leak Rate on Contact Length at 600°F

a,c,e

Figure 3: FEA Contact Pressure for Zones B and A for Pullout Analysis

a,c,e

Figure 4: Results of Regression of Ln(Leak Rate) on Length & Contact Pressure

a,c,e

Figure 5: SLB Leak Rate from Constrained Crack Specimens.

a,c,e

Figure 6: Total Contact Pressure for Various W* Leak Rate Zones

a,c,e

Figure 7: Contact Pressure for Coefficients

a,c,e

Figure 8: SLB Leak Rate from Constrained Crack Specimens, Zone B1 Example.

a,c,e

Figure 9: SLB Leak Analysis Contact Pressures

a,c,e

Figure 10: SLB Leak Rate for Axial & Circumferential Cracks

a,c,e

Figure 11: SLB Leak Rate for 360° Circumferential Cracks from the Crevice Tests

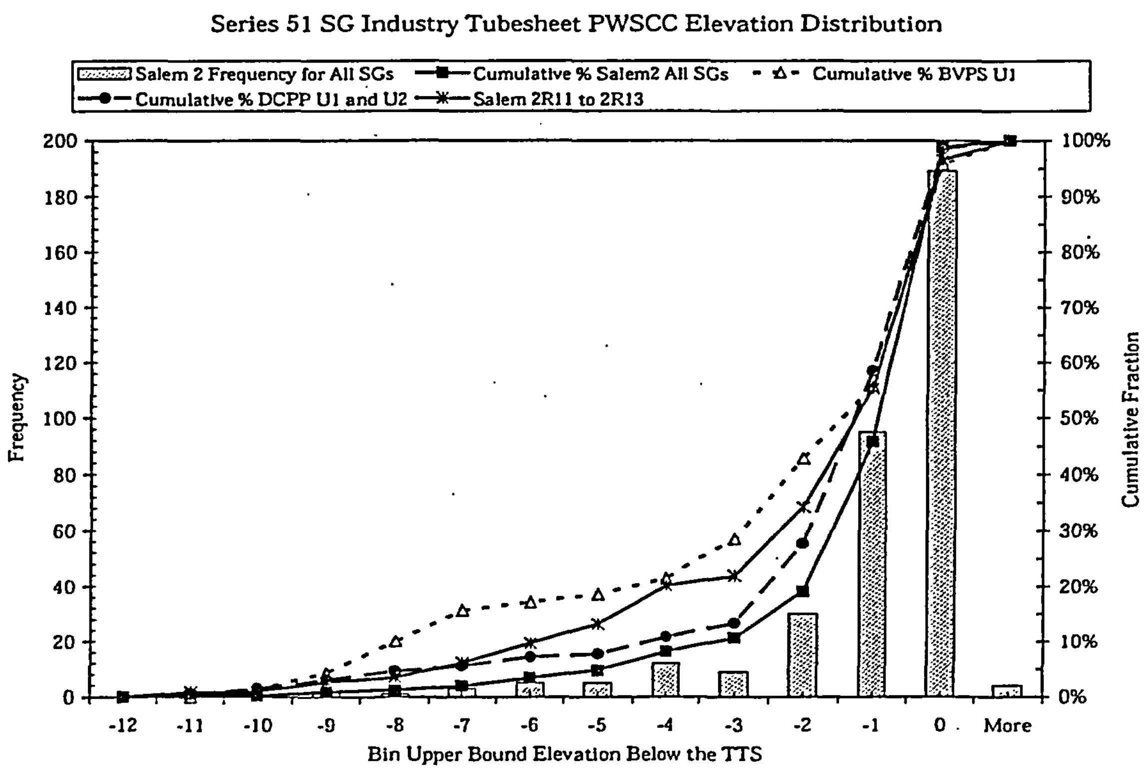

Figure 12: Industry Distribution of PWSCC Indications

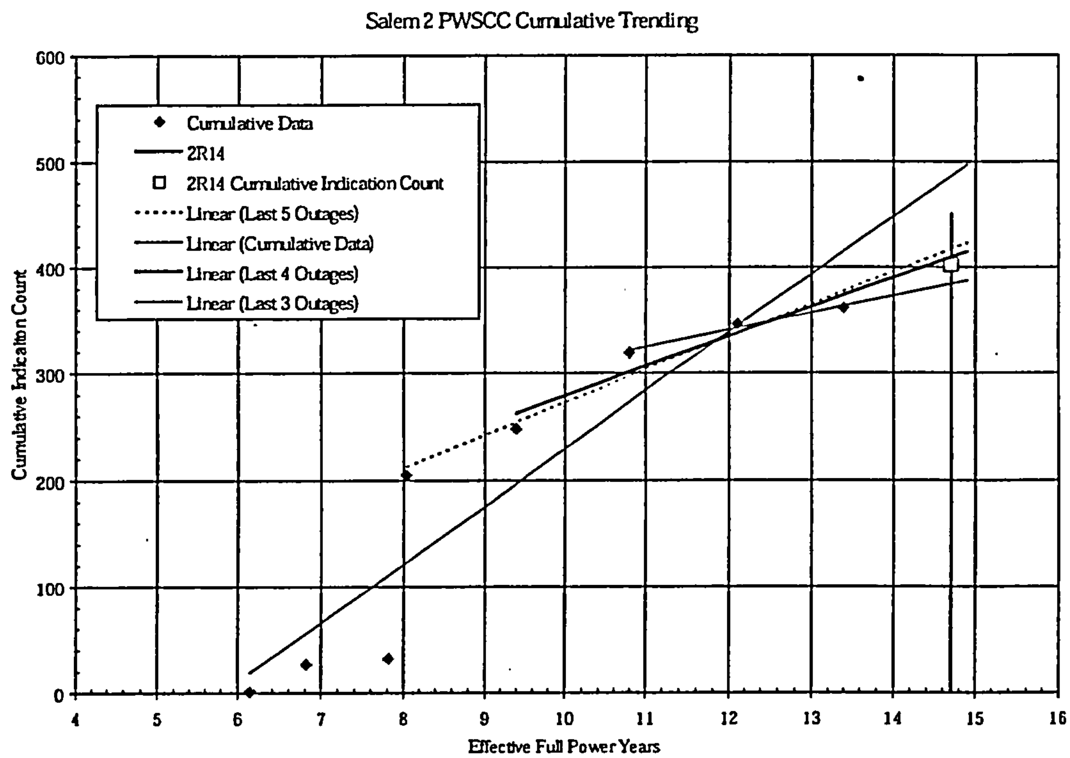

Figure 13: Trend Analysis of PWSCC Indications for Salem 2

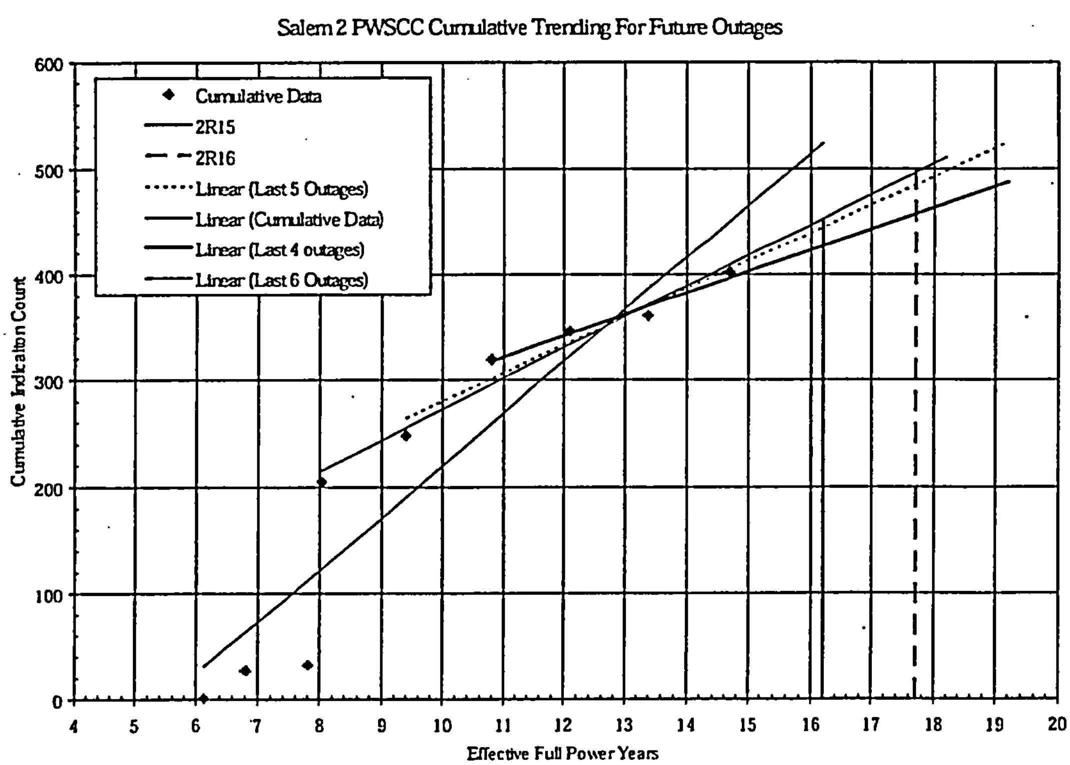

Figure 14: Trend Analysis for PWSCC for Future Outages

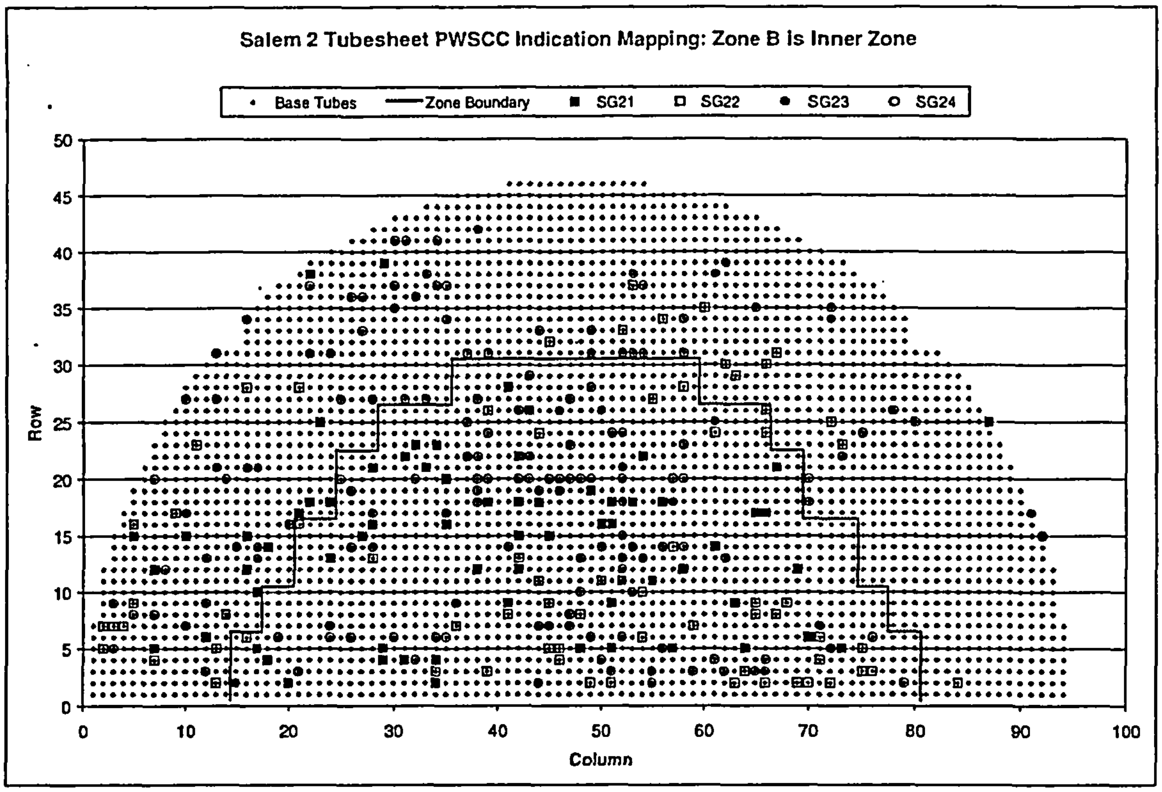

Figure 15: Planar Distribution of PWSCC Indications in the Tubesheet at Salem 2

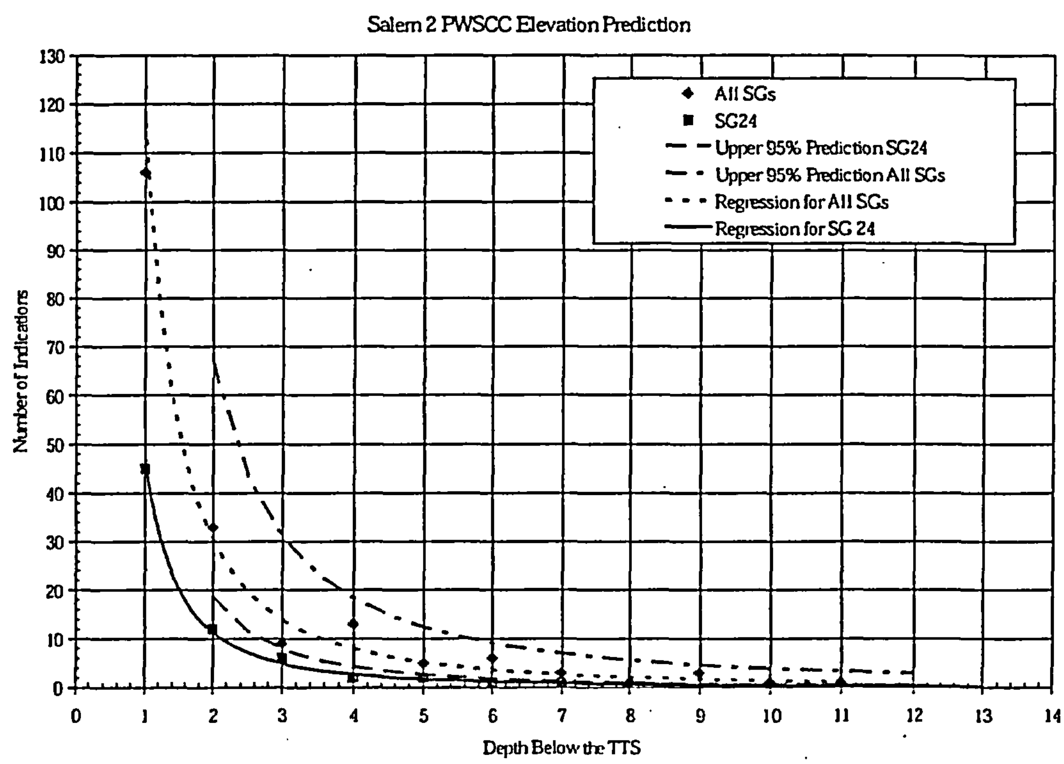

Figure 16: Regression of Number of Indications on Depth Below the TTS

TECHNICAL SPECIFICATION PAGES WITH PROPOSED CHANGES

The following Technical Specifications for Salem Unit 2 Facility Operating License DPR-75 are affected by this change request:

Technical Specification	Page
3/4.4.6, "Steam Generators"	3/4 4-10, 4-12 and 4-13

2. Tubes in those areas where experience has indicated potential problems.

3. A tube inspection (pursuant to Specification 4.4.6.4.a.8) shall be performed on each selected tube. If any selected tube does not permit the passage of the eddy current probe for a tube inspection, this shall be recorded and an adjacent tube shall be selected and subjected to a tube inspection.

c. The tubes selected as the second and third samples (if required by Table 4.4-2) during each inservice inspection may be subjected to a partial tube inspection provided:

1. The tubes selected for these samples include the tubes from those areas of the tube sheet array where tubes with imperfections were previously found.

2. The inspections include those portions of the tubes where imperfections were previously found.

ADD

d. Implementation of the steam generator WEXTEX expanded region inspection methodology (W*), requires a 100 percent inspection of the hot leg tubesheet W* distance.

The results of each sample inspection shall be classified into one of the following three categories:

Category	Inspection Results
C-1	Less than 5% of the total tubes inspected are degraded tubes and none of the inspected tubes are defective.
C-2	One or more tubes, but not more than 1% of the total tubes inspected are defective, or between 5% and 10% of the total tubes inspected are degraded tubes.
C-3	More than 10% of the total tubes inspected are degraded tubes or more than 1% of the inspected tubes are defective.

Note: In all inspections, previously degraded tubes must exhibit significant (greater than 10%) further wall penetrations to be included in the above percentage calculations.

REACTOR COOLANT SYSTEM

SURVEILLANCE REQUIREMENTS (Continued)

4.4.6.4 Acceptance Criteria

a. As used in this Specification:

1. Imperfection means an exception to the dimensions, finish or contour of a tube from that required by fabrication drawings or specifications. Eddy-current testing indications below 20% of the nominal tube wall thickness, if detectable, may be considered as imperfections.

2. Degradation means a service-induced cracking, wastage, wear or general corrosion occurring on either inside or outside of a tube.

3. Degraded Tube means a tube containing imperfections greater than or equal to 20% of the nominal wall thickness caused by degradation.

4. % Degradation means the percentage of the tube wall thickness affected or removed by degradation.

5. Defect means an imperfection of such severity that it exceeds the plugging limit. A tube containing a defect is defective.

6. Plugging Limit means the imperfection depth at or beyond which the tube shall be removed from service and is equal to 40% of the nominal tube wall thickness. This definition does not apply to service induced degradation identified in the W* distance. Tubes with service induced degradation identified in the W* distance shall be removed from service on detection by tube plugging. ADD

7. Unserviceable describes the condition of a tube if it leaks or contains a defect large enough to affect its structural integrity in the event of an Operating Basis Earthquake, a loss-of-coolant accident, or a steam line or feedwater line break as specified in 4.4.6.3.c, above.

8. Tube Inspection means an inspection of the steam generator tube from the point of entry (hot leg side) completely around the U-bend to the top support of the cold leg, excluding the portion of the tube within the tubesheet below the W* distance, the tube to tubesheet weld and the tube end extension. ADD

9. Preservice Inspection means an inspection of the full length of each tube in each steam generator performed by eddy current techniques prior to service establish a baseline condition of the tubing. This inspection shall be performed after the field hydrostatic test and prior to initial POWER OPERATION using the equipment and techniques expected to be used during subsequent inservice inspections.

INSERT 1

b. The steam generator shall be determined OPERABLE after completing the corresponding actions (plug all tubes exceeding the plugging limit and all tubes containing through-wall cracks) required by Table 4.4-2.

4.4.6.5 Reports

a. Following each inservice inspection of steam generator tubes, the number of tubes plugged in each steam generator shall be reported to the Commission within 15 days.

b. The complete results of the steam generator tube inservice inspection shall be included in the Annual Operating Report for the period in which the inspection was completed. This report shall include:

1. Number and extent of tubes inspected.

2. Location and percent of wall-thickness penetration for each indication of an imperfection.

3. Identification of tubes plugged.

ADD

4. Information regarding the application of W* inspection methodology; including calculated steam line break leakage, the number of indications, the location of indications (relative to the BWT and TTS), the orientation (axial, circumferential, volumetric), the severity of each indication (e.g., near through-wall or not through wall), the tube side where the indication initiated (inside or outside diameter), and an assessment of whether the results were consistent with expectations regarding the number of flaws and flaw severity (and if not consistent, a description of the proposed corrective action).

c. Results of steam generator tube inspections which fall into Category C-3 shall be evaluated for reportability pursuant to 10CFR50.72 and 10CFR50.73. The evaluation shall be documented, and shall provide a description of investigations conducted to determine cause of the tube degradation and corrective measures taken to prevent recurrence.

INSERT 1

10. Bottom of WEXTEX transition (BWT) is the highest point of contact between the tube and the tubesheet at, or below the top-of-tubesheet, as determined by eddy current testing.

11. W* Length is defined as the length of tubing below the bottom of the WEXTEX transition (BWT) that must be demonstrated to be non-degraded in order for the tube to maintain structural and leakage integrity. For the hot leg, the W* length is 7.0 inches, which represents the most conservative hot leg length defined in WCAP-14797, Revision 2.

12. W* Distance is defined in WCAP-14797, Revision 2, as the non-degraded distance from the top of the tubesheet to the bottom of the W* length, including the distance from the top-of-tubesheet to the bottom of the WEXTEX transition (BWT) and Non-Destructive Examination (NDE) measurement uncertainties (i.e., W* distance = W* length + distance to BWT + NDE uncertainties). The W* Distance shall be conservatively defined as a minimum of 8.0 inches below the TTS, or the W* distance as defined in WCAP-14797, Revision 2, whichever is greater.

PROPOSED CHANGES TO TS BASES PAGES

The following Technical Specifications Bases for Salem Unit 2, Facility Operating License No. DPR-75, are affected by this change request:

Salem Unit 2

Technical Specification	Page
Bases 3/4.4.6	B 3/4 4-3 through B 3/4 4-4

3/4.4.6 STEAM GENERATORS (continued)

Wastage-type defects are unlikely with proper chemistry treatment of the secondary coolant. However, even if a defect should develop in service, it will be found during scheduled inservice steam generator tube examinations. Plugging will be required for all tubes with imperfections exceeding the plugging limit of 40% of the tube nominal wall thickness. Steam generator tube inspections of operating plants have demonstrated the capability to reliably detect degradation that has penetrated 20% of the original tube wall thickness.

INSERT 2

INSERT 2

The W* criteria incorporate the guidance provided in WCAP-14797, Revision 2, "Generic W* Tube Plugging Criteria for 51 Series Steam Generator Tubesheet Region WEXTEX Expansions" and supporting information provided from Westinghouse Letter Report LTR-CDME-05-30, "W* Integrity Evaluation for Salem Unit 2 Limited SG Tube RPC Examination (Based on WCAP-14797, Revision 2). The W* length is the undegraded length of tubing into the tubesheet below the bottom of the WEXTEX transition (BWT) that precludes tube pullout in the event of a complete circumferential separation of the tube below the W* length. The W* distance is the undegraded distance from the top of the tubesheet to the bottom of the W* length including the distance from the top of the tubesheet to the BWT and measurement uncertainties. The maximum nondestructive examination (NDE) measurement uncertainty on the W* distance, provided from WCAP-14797 Revision 2, is 0.12 inch. Tubes with indications detected within the W* distance will be removed from service by tube plugging.

Tubes to which WCAP-14797 is applied can experience through-wall degradation up to the limits defined in Revision 2 without increasing the probability of a tube rupture or large leakage event. Tube degradation of any type or extent below the W* distance, including a complete circumferential separation of the tube, is acceptable and therefore may remain in service. As applied at Salem Unit 2, the W* methodology (WCAP-14797) is used to define the required tube inspection depth into the tubesheet, and is not used to permit degradation in the W* distance to remain in service. Furthermore, potential primary to secondary leakage in the W* distance, and below the W* distance, can be conservatively evaluated using WCAP-14797 Revision 2 and LTR-CDME-05-30. The leak rate potential for axial, circumferential, and volumetric indications within 12 inches from the top of the tubesheet can be conservatively calculated using the constrained crack model as delineated in WCAP-14797 Revision 2 and Westinghouse LTR-CDME-05-30.

The postulated leakage during a steam line break shall be equal to the following equation, as supported by WCAP-14797 Rev 2 and LTR-CDME-05-30:

Postulated SLB Leakage = Assumed Leakage $_{0''-8'' <TTS}$ + Assumed Leakage $_{8''-12'' <TTS}$ + Assumed Leakage $_{>12'' <TTS}$

Where: Assumed Leakage $_{0''-8'' <TTS}$ is the postulated leakage for indications that are deemed via flaw depth estimation techniques to be 100% throughwall, and therefore present a potential leak path. This term is applicable to detected indications during an in-service inspection and potentially undetected indications in the steam generator tubes left in service between 0 inches and 8 inches below the top of the

tubesheet (TTS). Since tubes with indications detected between 0 and 8 inches below the TTS are plugged upon detection, the calculation of this term for the assessment of SLB leakage for the subsequent operation cycle following an in-service inspection only requires consideration of potentially undetected indications. The calculation of this term for the assessment of SLB leakage for the previous operation cycle, following an in-service inspection, requires consideration of both detected and potentially undetected indications.

Assumed Leakage $_{8\text{-}12'' < TTS}$ is the conservatively assumed leakage from the total of identified and postulated unidentified indications in steam generator tubes left in service between 8 and 12 inches below the top of the tubesheet. The methodology for calculating potentially unidentified indications between 8 and 12 inches below the TTS is delineated in Westinghouse LTR-CDME-05-30. The conservative leakage assigned to each assumed unidentified indication between 8 and 12 inches below the TTS is 0.0028 gpm multiplied by the number of estimated indications. All postulated unidentified indications will be conservatively assumed to be in one steam generator. The highest number of identified indications left in service between 8 and 12 inches below TTS in any one steam generator will be included in this term.

Assumed Leakage $_{>12'' < TTS}$ is the conservatively assumed leakage from the bounding steam generator tubes left in service below 12 inches from the top of the tubesheet. This is 0.00009 gpm times number of tubes left in service in the least plugged steam generator.

The calculated SLB leakage provided above shall be reported to the NRC in accordance with applicable Technical Specifications, and must be less than the maximum allowable steam line break leak rate limit in any one steam generator in order to maintain doses within 10 CFR 100 guideline values and within GDC-19 values during a postulated steam line break event.