Westinghouse Non-Proprietary Class 3

WCAP-14798-NP
Revision 2

March 2003

Generic W* Tube Plugging Criteria for 51 Series Steam Generator Tubesheet Region WEXTEX Expansions

Westinghouse

WCAP-14798-NP, Revision 2

Generic W* Tube Plugging Criteria for 51 Series Steam Generator Tubesheet Region WEXTEX Expansions

March 2003

Westinghouse Electric Company LLC
P.O. Box 355
Pittsburgh, PA 15230-0355

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

ABSTRACT

Alternate steam generator tube plugging criteria were developed to reduce the need to repair or plug 51 Series steam generator tubes having indications in the WEXTEX explosive expansion region. The criteria address indications located below the top of the tubesheet and below the bottom of the WEXTEX transition. Indications which meet the W* criteria also meet RG 1.121 criteria for tube integrity, and indications left in service would have an aggregate leakage below allowable limits based on radiation exposure during a postulated SLB accident. The alternate tube plugging criteria, or W* criteria, are based on maintaining structural and leakage integrity of tubes returned to service with indications in the WEXTEX region. The W* criteria analysis are based on bounding conditions which were developed from a review of the operating conditions of the WEXTEX plants participating in the study. W* plugging criteria related to the structural integrity of the tube have been defined for two zones of the tubesheet. A methodology is provided to determine the faulted condition leak rate contribution of cracks for five different radial zones of the tubesheet and on both hot and cold leg sides, as a function of the distance between the upper tip of an axial indication and the bottom of the WEXTEX expansion transition.

GENERIC W* TUBE PLUGGING CRITERIA FOR
51 SERIES STEAM GENERATOR
TUBESHEET REGION WEXTEX EXPANSIONS

1.0 BACKGROUND

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 will constrain the tube and complement tube integrity in that region by essentially precluding tube deformation beyond the expanded outside diameter. The resistance to both tube rupture and tube collapse is significantly 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 plugging criteria applicable to the portion of tubing expanded by the Westinghouse explosive tube expansion (WEXTEX) process is supported by the test and analysis results of this report.

For 51 Series steam generators with WEXTEX expansions, the full depth expansion can be generally defined as follows. From the tube lower end and extending upward for a length of approximately 2.75 inches is a region expanded by the roll expansion process. From the top of the roll expansion to the vicinity of the top of the tubesheet, the tube-to-tubesheet expansion is accomplished by the WEXTEX explosive expansion process. The resulting full depth tube-to-tubesheet expansion can be considered as four distinct regions. These are described below, starting from the bottom of the tubesheet, and are illustrated in Figure 1.0-1.

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

2. *Roll Transition (RT)* - 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. *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. *WEXTEX Transition* - The portion of the tube which acts as a juncture between the WEXTEX region and the unexpanded region of the tube. This region starts at the top of the explosively expanded region and extends for approximately 0.25 inches.

This report documents the basis for criteria which were developed to reduce the need to repair or plug steam generator tubes having eddy current indications in the explosively expanded region below the expansion transition. This report summarizes the generic 51 Series SG WEXTEX plant W* tube integrity evaluation with respect to:

1. Maintenance of tube integrity for all power loadings associated with normal plant conditions, including startup, operation in power range, hot standby and cooldown, and anticipated transients.

2. Maintenance of tube integrity under postulated limiting conditions of primary-to-secondary and secondary-to-primary differential pressure.

3. Limitation of primary-to-secondary and secondary-to-primary leakage consistent with allowable leakage limits and the desire to minimize leakage.

This report is a generic evaluation for 51 Series SGs with WEXTEX expansions. Site-specific operating parameters must be reviewed against the bounding analysis conditions described in this report, and any leak rates determined for the W* region must be combined with leak rates of other applicable criteria and compared to plant specific allowable leak rates. In addition, crack growth rate data and operating periods are used in determining the potential end-of-cycle length of cracks as input to leakage evaluations.

a,c,e

Figure 1.0-1 Regions in the WEXTEX Full Depth Tube-to-Tubesheet Expansion

2.0 SUMMARY AND CONCLUSIONS

2.1 OVERALL SUMMARY

WEXTEX-expanded region alternate tube plugging criteria, or W* criteria, were developed for the tubesheet region of 51 Series steam generators considering the most stringent loads associated with plant operation, including transients, and postulated accident conditions. The W* criteria are developed to prevent tube burst and axial separation due to axial pullout forces acting on the tube, and to demonstrate that steam line break (SLB) leakage limits are not exceeded. The W* criteria developed in this report permit tubes with indications in the tubesheet region to be returned to service.

The approach taken to develop the W* criteria is to utilize the general methodology of the L* criteria (Reference 9.1) for hardroll expansions and adapt the methods for WEXTEX expansions. The hardroll L* criteria utilize an L* length of undegraded tubing to limit leakage and permit a flexible length (F*) to resist pullout forces which may be increased if degradation is present within the minimum F* length. Since WEXTEX expansions have lower tube-to-tubesheet contact forces than hardroll expansions, limited leakage is possible under SLB conditions and the L* length is replaced in W* by the requirement to calculate SLB leakage for indications left in service. SLB leakage is dependent upon the location of the top of the crack below the bottom of the WEXTEX transition (BWT). A flexible W* length patterned after the flexible F* length of the L* criteria is applied in W*. Because of the limited number of circumferential and volumetric indications found within the W* length, circumferential and volumetric indications within the W* region are not specifically addressed by the W* criteria and these indications would be repaired if found in an inspection. Below the W* length, any type of tube degradation is acceptable as tube integrity is not required to accommodate axial loads on the tube or to limit tube leakage.

2.2 SUMMARY AND CONCLUSIONS

The development of the generic W* criteria included testing of samples representative of the WEXTEX expanded tube-to-tubesheet joints, analysis of contact pressures between the tube and tubesheet at relevant operating conditions, and analysis of axial loads acting on the tube. Testing included pull force tests to determine the coefficient of friction between the tube and the tubesheet and the force required to cause movement of the tube within the tubesheet.

Leak rate tests were performed to develop a WEXTEX leak rate model relating leak rate to location of the crack within the tubesheet and with operating conditions. The model is used to estimate potential leakage from tubes with indications left in service under SLB accident conditions.

The generic W* alternate plugging criteria can be summarized as follows:

W* Length

The W* length in the hot leg shall be 7.0 inches in W* Zone B and 5.2 inches in W* Zone A. The W* length is the length of tubing below the bottom of the WEXTEX transition (BWT) which must be demonstrated to be undegraded in accordance with the following criteria. If cracks are found within the W* region, the flexible W* length must be applied to account for the assumed lack of axial restraint over the length of the crack (Section 5.4). The flexible W* length is the total RPC-inspected length as measured downward from the BWT, and includes NDE uncertainties and crack lengths within W* as adjusted for growth. For most inspections, it is expected that the RPC inspection length will be measured from the top of tubesheet (TTS). In this case, the distance of the BWT below the TTS must be subtracted from the inspected length for comparisons with the flexible W* length. Below the flexible W* length any type or combination of tube degradation is acceptable.

The following are the length requirements to be applied in the two zones across the tubesheet with and without degradation within the flexible W* distance:

- Without degradation

  W* Length below BWT = 7.0" (5.2" for Zone A) + ΔNDE_{W*}

- With degradation in W* length

  Flexible W* Length below BWT = 7.0" (5.2" for Zone A) + $\Delta NDE_{W*} + \Sigma CL_i + N_{CL} \bullet \Delta NDE_{CL} + N_{CL} \bullet \Delta CG$

where ΔNDE_{W*}, CL_i, N_{CL}, ΔNDE_{CL}, and ΔCG are, respectively, the NDE uncertainty for the measurement of the W* length, the overall crack length for the i^{th} group of parallel cracks, the number of crack groups, the NDE uncertainty for the measurement of crack lengths and the crack growth in length per operating cycle. The uncertainty, ΔNDE_{W}, for measurement of the W* length relative to the BWT includes the uncertainty for locating the BWT relative to the TTS since all measurements are made relative to the TTS.

Allowable Tube Degradation Within W* Length

Tube degradation within the W* length shall be limited as follows:

- Axial indications left in service shall have the upper crack tip below the BWT by at least the NDE uncertainty, ΔNDE_{CT}, on locating the crack tip relative to the BWT.

- Resolvable, single axial indications (multiple indications must return to the null point between individual cracks) within the flexible W* distance can be left in service. RPC or equivalent coils or a UT inspection can be used to demonstrate return to null between multiple axial indications or the absence of circumferential involvement between the axial indications.

- Tubes with inclined axial indications less than 2.0 inches long (including the crack growth allowance) having inclination angles relative to the tube axis of $\leq 45°$ minus the NDE uncertainty, ΔNDE_{CA}, on the measurement of the crack angle can be left in service. That is, the measured crack angle must be less than ($45° - \Delta NDE_{CA}$). Tubes with two or more parallel (overlapping elevation), inclined axial cracks must be repaired. The limit of 2.0 inches for inclined axial indications is conservatively applied to limit the circumferential involvement of the indication. For application of the 2.0 inch limit, an inclined indication is an axial crack that is visually inclined on the RPC C-scan, such that an angular measurement is required and the measured angle exceeds the measurement uncertainty of ΔNDE_{CA}. There is no length limit on axial indications that are not inclined by this definition.

- All circumferential or volumetric indications within the flexible W* distance and axial indications with inclination angles greater than ($45° - \Delta NDE_{CA}$) are to be repaired.

- Any type or combination of tube degradation below the W* length is acceptable.

<u>SLB Leakage Evaluation</u>

The SLB leakage evaluation shall be based upon:

- Deterministic leakage analyses (Section 6.4) utilizing leak rates for Zones A and B1 through B4 as a function of the distance of the upper crack tip below the BWT. The total leak rate is obtained as a sum of the leak rates from individual indications in the SG. As an option, Monte Carlo SLB leak rate analyses may be performed to reduce conservatism in the deterministic analysis method.

- For a condition monitoring assessment (analysis of as-found inspection results), the RPC measured distance of the crack tip below the BWT shall be reduced by the measurement uncertainty (ΔNDE_{CT}).

- For an operational assessment (analysis of projected EOC conditions), the RPC measured distance of the crack tip below the BWT shall be reduced by the measurement uncertainty (ΔNDE_{CT}) and the crack growth allowance (ΔCG).

- The total leak rate from RPC-inspected tubes in the W* region will be divided by the percent of tubes inspected by RPC or equivalent probes to obtain the total leak rate from all indications.

- The combined predicted leakage from all tubes with indications, including those which have been returned to service previously, must be compared to the plant specific allowable SLB leakage limits. The leakage from W* indications shall be added to the predicted leakage for indications left in service based on other implemented alternate repair criteria (ARC). If the predicted leakage is less than the allowable limit, the tubes with indications may be returned to service provided that all other W* criteria are met. If the allowable leakage limit is exceeded, tubes shall be repaired until the allowable leakage limit is met.

Inspection Requirements

The inspection requirements for implementing the W* repair criteria, given in more detail in Section 8.6, can be summarized as follows.

- The W* criteria provide for disposition of indications found by bobbin or RPC inspections and do not mandate a specific inspection sample size.

- Indications within the flexible W* length found by bobbin coil inspection must also be inspected by RPC (or equivalent coil such as + Point) to characterize crack lengths and elevations.

- All indications left in service within the flexible W* length must be RPC inspected at each subsequent planned inspection.

- *When RPC inspections are performed of the WEXTEX transition region, the inspection shall* include the full length of the flexible W* region.

- Bobbin coil inspection results shall include, as a minimum: the tube location, the elevation of each indication relative to the top of the tubesheet, the peak-to-peak voltage of each indication and the phase angle and/or depth of the indication. The recorded results shall include all indications in the tubesheet region and are provided for information only since the bobbin data are not used in W* applications, except to identify indications for RPC inspection.

- Recording of results from the RPC inspection shall include: tube location; length of RPC inspection relative to the TTS (or BWT) on either an inspection basis if constant for all tubes inspected or on a tube basis if not uniform for all inspected tubes; location of the BWT relative to the TTS; elevation below the TTS (or BWT) to the uppermost crack tip of each indication; crack length of each axial or inclined indication; the inclination angle of the crack relative to the tube axis for axially oriented cracks clearly inclined relative to the tube axis; the inspection record shall distinguish between multiple axial indications which can be individually resolved and those which cannot be individually resolved (RPC amplitude does not return to null level between indications); the elevation of circumferential and volumetric indications relative to the TTS or BWT and the circumferential arc length or angular extent; maximum RPC voltage (peak-to-peak) of each indication; and RPC phase angle and/or depth of each indication.

3.0 TECHNICAL APPROACH

3.1 REQUIREMENTS FOR W* CRITERIA

3.1.1 Regulatory Requirements

Regulatory Guide (RG) 1.121, "Bases for Plugging Degraded PWR Steam Generator Tubes", issued for comment in August of 1976, describes a method acceptable to the NRC staff for meeting General Design Criteria (GDC) numbers 14, 15, 31 and 32 by reducing the probability and consequences of steam generator tube rupture through determining the limiting safe conditions of degradation of steam generator tubing, beyond which tubes with unacceptable cracking, as established by inservice inspection, should be removed from service by plugging. The recommended W* plugging criteria for the tubesheet region of WEXTEX expansions may result in tubes with partial throughwall and/or throughwall (non-leaking) cracks being returned to service. In the limiting case, the presence of a throughwall crack alone is not reason enough to remove a tube from service. The regulatory basis for leaving throughwall cracks in service in the tubesheet region of WEXTEX expansions is provided below.

Steam generator "tube failure" is defined by the NRC within RG 1.83 as the full penetration of the primary pressure boundary <u>with subsequent leakage</u>. <u>Consistent with this definition, upon the implementation of the tube plugging criteria of this report, known leaking tubes will be removed from service.</u> <u>The tube plugging criteria of this report are established such that operational leakage is not anticipated.</u>

The NRC defines steam generator tube rupture within RG 1.121 as any perforation of the tube pressure boundary accompanied by a flow of fluid either from the primary to secondary side of the steam generator or vice versa, depending on the differential pressure condition. As stated within the regulatory guide, the rupture of a number of single tube wall barriers between primary and secondary fluid has safety consequences only if the resulting fluid flow exceeds an acceptable amount and rate. This rate has been defined in NUREG-0844 as exceeding the make-up capacity of the plant. Loss of steam generator tube integrity means loss of "leakage integrity". Loss of "leakage integrity" is defined as the degree of degradation by a throughwall crack penetration of a tube wall membrane that can adversely affect the margin of safety leading to "tube failure", burst, or collapse during both normal operation and postulated accident conditions. Acceptable service, in terms of tube integrity, limits the allowable primary to secondary leakage rate during normal operating conditions and provides that the consequences of postulated accidents would be within the guidelines of 10 CFR 100. In order to determine that steam generator tube integrity is not reduced below a level acceptable for adequate margins of safety, the NRC staff position focused on specific criteria for limiting conditions of operation. These include:

1. Secondary Water Monitoring
2. Primary-to-Secondary Tube Leakage
3. Steam Generator Tube Surveillance
4. Steam Generator Tube Plugging Criteria

Tubes with throughwall cracks will maintain "leakage integrity" and are acceptable for continued operation if the extent of cracking can be shown to meet the following RG 1.121 criteria:

1. Tubes are demonstrated to maintain a factor of safety of three against failure for bursting under normal operating pressure differential.

2. Tubes are demonstrated to maintain adequate margin against tube failure under postulated accident condition loadings (combined with the effects of SSE loadings) and the loadings required to initiate propagation of the largest longitudinal crack resulting in tube rupture. All hydrodynamic and flow induced forces are to be considered in the analysis to determine acceptable tube wall penetration of cracking.

3. A primary-to-secondary leakage limit under normal operating conditions is set in the plant technical specifications which is less than the leakage rate determined theoretically or experimentally from the largest single permissible longitudinal crack. This action would ensure orderly plant shutdown and allow sufficient time for remedial action(s) if the crack size increases beyond the permissible limit during service.

In addition to the RG 1.121 criteria, it is necessary to satisfy FSAR accident condition limits for primary-to-secondary leak rates. Leak rate limits must be satisfied on a plant specific basis to the guidelines of 10 CFR 100. For Westinghouse plants, a steamline break event (SLB) is generally the limiting event for radiological consequences and the SLB is applied in this report as the reference event for limiting accident condition leakage.

3.1.2 Requirements for W* Tube Plugging Criteria

Tube Burst Considerations

Tube burst is precluded for cracks within the tubesheet by the constraint provided by the tubesheet. Thus the RG 1.121 criteria are satisfied by the tubesheet constraint. Crack lengths do not need to be limited by burst considerations, and operating leakage limits are not required since, without the potential for tube burst, there is no need for leak-before-burst leakage limit.

Conceivably, however, a 360° throughwall circumferential crack or many axially oriented cracks could permit severing of the tube and tube pullout from the tubesheet under the axial forces on the tube from primary to secondary pressure differentials. The W* criteria are required to prevent tube pullout from the tubesheet under axial loading conditions. A W* length is required such that the tube to tubesheet contact pressures integrated over the W* length are sufficient to compensate for the axial forces on the tube and thus prevent tube pullout. Within the W* length, tube degradation must be limited to permit the axial loads to be transmitted over the entire W* length without severing of the tube. The W* criteria limit the number, angle of inclination, and length of axial cracks to sustain acceptable axial load capability. Because of the limited number of circumferential and volumetric indications in the W* length and consequently a limited growth history, circumferential and volumetric indications within the W* region are not specifically addressed by W* criteria; these indications would be repaired. Below the W* length, any type of tube degradation is acceptable as tube integrity is not required to accommodate axial loads on the tube or to limit tube leakage.

Operating Leakage Considerations

WEXTEX region cracks could potentially occur as the result of primary water stress corrosion cracking (PWSCC). Extensive European operating experience has been obtained with axial PWSCC cracks left in service as summarized in Reference 9.2. This operating experience has demonstrated negligible normal operating leakage from PWSCC cracks even under free span conditions in roll transitions. PWSCC cracks (if they were to occur) in WEXTEX expansions in the tubesheet region would be even further leakage limited by the tight tube-to-tubesheet crevice and the limited crack opening permitted by the tubesheet constraint.

Consequently, negligible operating leakage is expected from cracks in the tubesheet region of WEXTEX expansions and no requirements must be applied to limit operating leakage.

Accident Condition Leakage

As noted in Section 3.1.1, the accident condition leakage must be limited to acceptable limits established by plant specific FSAR evaluations. The SLB event is limiting for the Series 51 steam generator leakage evaluation and is applied in this report. Since the pressure differentials associated with a SLB event can open cracks that had negligible operating leakage, the W* criteria must provide a method to calculate SLB leakage to demonstrate compliance with FSAR requirements. Leakage is limited for cracks in the tubesheet by crack size and the small crevice opening within the tube to tubesheet crevice. Based on Westinghouse models for leakage through cracks, and leak rate tests of WEXTEX expansions, a SLB leakage analysis model is developed in this report to calculate SLB leak rates for cracks left in service.

Application of the W* tube plugging criteria requires the use of plant specific leak rate limits. SLB leak rate analyses for cracks left in service must be performed using the methods of this report to demonstrate leak rates less than the acceptable limits. The leak rates calculated from other alternate plugging criteria must also be included in the totals for comparison to the plant specific leak rate limit. If tubesheet region cracks, as accounted for in the SLB leak rate analysis are the only deep (>40% depth) cracks left in service, it is expected that SLB leakage will not exceed allowable limits.

Operating Conditions for the Generic W* Criteria

The normal operating conditions and design parameters utilized in this analysis are summarized in Table 3.1-1. The values were developed from a review of the licensed and current operating conditions of WEXTEX units participating in this study. They are intended to be conservative estimates of potential operating conditions. They do not represent currently allowable operating conditions, but were developed to encompass most potential future operating conditions in units employing the W* criteria.

Sensitivity analysis was performed to determine the effect of variations in steam pressure and hot leg temperature at 100% of rated power on tube radial contact pressures at the top of the tubesheet. Secondary side pressure was assumed to act on the tube OD over the full depth of the tube/tubesheet crevice. [

]a,c A full load steam pressure of [ ]a,c higher than the steam pressure in any of the Series 51 WEXTEX units reviewed, was selected for the tubesheet structural analysis. Since the thermal coefficient of expansion of the Alloy 600 tubing is higher than that of the SA-508 tubesheet, lower primary pressures produce lower radial interference pressures; a limiting, lower bound primary temperature of [ ]a,c was selected for analysis purposes.

3.2 LOADING CONDITIONS

The loading conditions for which tube integrity must be maintained include all power loadings associated with normal operation, including startup, operation in power range, and hot standby as well as anticipated transients and postulated accident conditions. Specific conditions evaluated were normal operation, steamline break (SLB) + SSE, feedline break (FLB) + SSE, and LOCA + SSE.

The applied loads acting on the tube which could result in tube pullout from the tubesheet during normal and postulated accident conditions are predominantly axial and due to the internal-to-external pressure differentials. For a tube that has not been degraded, the axial load is given by the product of the differential pressure and the internal cross-sectional area of the tube. However, for a tube with degradation, e.g., cracks oriented at an angle to the axis of the tube, the internal pressure may also act on the flanks of the degradation. Therefore, for a tube which is conservatively postulated to be severed at some location within the tubesheet, the total force acting to remove the tube from the tubesheet is given by the product of the pressure and the cross-sectional area of the tube outside diameter, i.e., the inside diameter of the tubesheet hole for an expanded tube.

The loads from normal and faulted conditions act from the inside of the tube and are tensile in nature, tending to pull the tube from the tubesheet. The LOCA loadings are due to pressure acting on the OD of the tube and are compressive and tend to push the tube into the tubesheet. The magnitude of these loads is addressed below.

3.2.1 Normal Operating Loads

For analysis of the axial force loadings from normal operating conditions it is assumed that the tube has degradation and that the pressure acts on the combined internal and wall cross-sectional area of the expanded diameter of the tube. This approach develops higher loads than those exhibited from end cap loads, in which the pressure load is applied only on the tube ID.

The pullout loads are developed from the primary-to-secondary pressure differential, so the limiting loads are developed by low steam pressure conditions. A review of plant operating data was performed of the units participating in this effort to determine a near term lower bound estimate of normal operating steam pressure. The value found in the evaluation is [ ]^{a,c} psia. This value does not take credit for the pressure drop between the steam nozzle exit and the SG lower bundle, which would give a reduced normal operating condition differential pressure at the tubesheet secondary face.

The primary operating pressure for the Series 51 units is 2250 psia. The normal operating condition pullout load requirement per RG 1.121 is the normal operating primary-to-secondary pressure differential, or $3\Delta P_{n.o.}$, with a factor of safety of three.

The force acting on the tube under the bounding normal operating pressure shown in Table 3.1-1 can be expressed as:

[

]^{a,c,e}

With a safety factor of three, the normal operation axial load bearing requirement for Series 51 WEXTEX plant tubes is thus [ ]^{a,c,e} lbs. Other forces such as fluid drag forces in the U-bends and vertical seismic forces are negligible by comparison.

3.2.2 Faulted Condition Loads

The RG 1.121 faulted condition load requirements are that the pullout load be reacted with a factor of safety of 1.0/0.7, or 1.43, in the faulted SG during any portion of the transient. The maximum faulted condition load occurs at the maximum primary-to-secondary pressure differential. Including the adjustment for safety valve setpoint error, the feedline break transient provides a more limiting primary-to-secondary pressure differential (2650 psi) than a steam line break (2560 psi), and is therefore used in the pullout load analyses. Pressure loadings are conservatively applied to the entire cross-sectional area of the expanded tube (i.e., pressure was applied to the cross-sectional area of the tube), nominally [ ]^{a,c} diameter. The faulted condition load is then calculated as follows:

[

]^{a,c,e}

The above "Case (1)" faulted analysis condition assumes that the full 2650 psi pressure differential occurs instantaneously after the break, at the minimum operating hot leg temperature of [ ]^{a,c}. The secondary temperature for the "Case (1)" faulted condition is the associated steam temperature of [ ]^{a,c}.

A review was performed of the conditions later in the SLB and FLB transients. The limiting W* faulted condition for pullout loads, "Case (2)", was found for the 412 plant (4-Loop) at [

]a,c The faulted conditions analysis cases are summarized in Table 3.2-1.

As discussed in Reference 9.3, these loads need not be further augmented for dynamic loading effects because of the sequence of events during the transient.

As previously noted, the SLB condition is limiting for the leakage analysis. Consistent with established alternate repair criteria analyses, W* leakages are determined for the SLB ΔP of 2560 psi with a hot leg temperature of 600°F, as shown in Table 3.2-2. Both the leak rate calculation and the leakage structural model are evaluated for the Table 3.2-2 conditions.

3.2.3 Other Transient Conditions

An evaluation was performed to consider operating transients which could result in the condition where the tube would be at a temperature lower than the tubesheet. In this situation some of the engagement preload would be lost as the tube would shrink relative to the tubesheet. The worst case occurs for a Loss of Flow transient where the tube temperature becomes about 10 degrees lower than the tubesheet temperature. However, during this transient the decrease in primary side pressure offsets the effects of the decrease in primary side temperature and the temperature difference between the tube and the tubesheet, such that a net increase occurs in the contact pressure between the tube and tubesheet hole.

3.2.4 LOCA

The axial load acting on the tube under LOCA conditions is approximately [ ]a,c,e lbs. and is compressive from the tube OD. Therefore, it tends to force the tube into the tubesheet rather than to pull it out, and is not a factor in W* analyses.

3.2.5 Other Faulted Load Considerations

Seismic analysis of the Series 51 steam generators, Reference 9.4, has shown that axial loading of the tubes is negligible during a safe shutdown earthquake (SSE).

a,c,e

Table 3.1-1 W* Normal Condition Analysis and Design Parameters

Table 3.2-1
W* Structural Analysis Conditions (W* Length and Pullout)

Structural Analysis Case	Primary Pressure (psia)	Secondary Pressure (psia)	Pullout Load (lbs.)	Hot Leg Temp., (°F)	Cold Leg Temp., (°F)	Secondary Temp., (°F)

a,c

Table 3.2-2
W* Leakage Analysis Condition

Leakage Analysis Case	Primary Pressure (psia)	Secondary Pressure (psia)	Hot Leg Temp., (°F)	Secondary Temp. (°F)

a,c

4.0 PULLOUT LOAD REACTION LENGTH

4.1 EVALUATION METHODS AND LOADS

In the unlikely event that a steam generator tube is circumferentially degraded within the tubesheet to the extent that tube separation could occur, significant tube axial movement would likely be prevented by the tube support plates (with or without denting), adjacent tubes in the U-bend, and/or the AVB retaining rings. Nevertheless, if a tube separation within the tubesheet occurs, that portion of the tube from the separation to the top of the tubesheet must react the applied loads to meet RG 1.121 requirements. The largest normal and largest faulted operation axial load requirements are [ ]^{a,c,e} pounds, respectively, as developed in Section 3.2. These loads must be reacted by the axial restraint afforded by the contact pressure between the tube and tubesheet times the friction coefficient of the tube-to-tubesheet interface acting over some interface length. For the purposes of this evaluation, the length of engagement of a tube in the tubesheet necessary to meet the pullout load requirements is defined as the pullout load reaction length, or PLRL.

To determine the PLRL it is necessary to know the magnitude of the contact pressure between the tube and tubesheet, which is the contact pressure during operation and postulated accidents, plus that from the WEXTEX expansion process, and the value for the static coefficient of friction for the tube/tubesheet material couple. Contact pressures occurring during normal or faulted conditions have been calculated through finite element analysis as described in Section 4.3. The contact pressure from the WEXTEX process was determined through testing of WEXTEX fabricated samples representative of the WEXTEX tube-to-tubesheet expansions described in section 4.2. The friction coefficient for the tube-to-tubesheet interface was also determined from these tests, in section 4.2.2.

The engagement length, i.e., PLRL, is the length of tube, measured from the bottom of the WEXTEX transition, where the integrated resistance load is equal to the applied load, and is provided in section 4.4.

4.2 TESTING

4.2.1 Approach

A review was made of the field-implemented WEXTEX process to identify process parameters and controls affecting pullout load resistance, so that a conservative test technique could be employed. Two of the more significant factors are:

<u>WEXTEX Charge Variability</u>: The explosive expansion process has been the subject of extensive research in the nuclear and other industries. The WEXTEX process employed in the Series 51 SGs systematically controlled by design and procurement procedures, and was reviewed with regard to structural, materials, manufacturing, safety, process and other features. The WEXTEX charge density was statistically controlled, and sampling of each lot of detonating charge was performed to confirm that these values were maintained.

Tube Yield and Ultimate Strength Variability: WEXTEX expansion of Series 51 SGs was performed in the field, after SG shipment. A range of tube yield strengths exists in these units. The WEXTEX charge imparts an energy which is sufficient to produce the strain deformation necessary to cause the tube to come into contact the tubesheet hole. The confirmation of a complete expansion can be determined from bobbin and RPC inspections, including observation of the WEXTEX transitions at the proper location. Since WEXTEX expansions in [

]^{a,c}

Reviews of WEXTEX expansions by profilometry analyses have shown full expansions below the BWT for lengths considerably larger than the required W* distances of about 6 inches. Thus, identification of the BWT is sufficient to confirm expansion over the W* length and further confirmation of the expanded length is not required. The elevation of the BWT below the TTS is typically variable within a few tenths of an inch. Lack of an expansion near the TTS would be identified by the inability to locate the BWT, and exclusion of the tube under W* criteria.

4.2.2 Pullout Load Test Specimen Descriptions

4.2.2.1 W* Pullout Test Specimens

The W* pullout test samples were selected from a number of specimens prepared in the W* program to provide a bounding case condition with regard to pullout resistance. These samples were similar in configuration to those used in the L* program. The W* pullout test samples consisted of carbon steel collars approximately [

]^{b,c,e}

Since the WEXTEX expansion is a high energy process which causes the tube OD to impact and to be formed into even small variations in the tubesheet hole bore surface, the feature which is of most significance to pullout load resistance is the surface finish of the tubesheet hole. The Series 51 SG tubesheet hole bore finish requirement was [ ]^{a,c} microinch rms maximum. The samples in the test program were procured to a [ ]^{a,c} rms requirement. For the W* pullout tests, two tubesheet collar specimens were selected: specimen W4-006, which appeared to have a bore surface roughness at the upper end of the bore finish requirement, and specimen W8-007A, which was smooth throughout. Specimen W8-007A was cut from a longer length specimen, and surface roughness measurements on the cutoff end were found to vary from only [ ]^{a,c} microinch rms. Both of the tubesheet collar samples had uniform diameter profiles.

The tube specimens were fabricated from Quality Assurance (QA) controlled stock and fabrication of the collars was done under QA surveillance. The WEXTEX expansions were fabricated per approved procedures and detonation cord analysis was within the range of the WEXTEX explosive charge procurement specification.

The collars used to simulate the tubesheet were [

]b,c,e

The WEXTEX samples fabricated for pull force testing were of a [

]b,c,e

The samples were also noted to have [

]b,c,e

A number of preliminary specimens, identified by an "NLS-" prefix, were prepared prior to the above test program. These specimens were 0.875 inch nominal tube size, and had the same tube material, collar material, and collar sizes as the above samples, but were not fabricated with full QA certification. These specimens were exposed a 750°F doped steam environment in a corrosion test, and results are provided for information purposes.

4.2.2.2 W* NDE Specimens Modified for Pullout Test

To ascertain the degree of conservatism in the above W* pullout load test specimens, additional pullout testing was performed to provide more typical, clean condition (conservative) WEXTEX radial contact pressure and friction coefficient results using the W* NDE test specimens described in section 7.3.2 after NDE testing was completed. The WEXTEX-expanded NDE specimens were prepared in [

]b,c,e The NDE specimens were modified for pullout testing by [

]b,c,e Surface roughness measurements made prior to tube installation on the hole bore surface were as follows:

[

]b,c,e

4.2.3 Pullout Test Description and Results

4.2.3.1 W* Pullout Test Specimens

The W* pullout samples were tested at various temperature and internal pressure conditions to assess the pull forces associated with the WEXTEX joint. The test samples used for the pressurized and unpressurized tests were slight modifications of the as-expanded double ended sample described in 4.2.2.1. The test sample configurations are illustrated in Figure 4.2-2. As noted in the figure, the samples were tested by applying an axial tensile load to the tube while restraining the collar.

The testing was performed on a SATEC testing machine and a load/crosshead displacement curve was recorded as the test progressed. The pull force of the sample was taken to be the load where "first slip" of the tube in the collar occurred as reflected by a drop in the test load. In those tests at room temperature where there was no noticeable drop in the load, the pull force was taken as the load that is present when the tube was at [ ]b,c,e inch crosshead movement.

The samples were tested at differing steady state temperature and pressure conditions to obtain pull forces at [ ]b,c,e different tube-to-collar interface contact pressures. The nominal test conditions included [

]b,c,e

The curves of pullout load versus crosshead displacement (deflection) exhibited [

]a,c. Figure 4.2-3 illustrates the pullout load/deflection curve for specimen W8-007A at [

]a,c,e

The length of the constant diameter section (length of engagement) of the specimens and the pullout load results for the pull test samples are given in Table 4.2-1. The test specimens include a typical "taper region" as discussed previously, and thus the effective contact length of 2.0" from room temperature measurements is taken as the constant diameter region of the test specimen. As discussed in the analysis of the test data (Section 4.4.2), a review was made of the effect of varying the effective interface length of 2.0", to adjust it for changes in the contact pressure between the tube and collar. The review concluded that [

][a,c]

Table 4.2-1 shows that the preliminary "NLS-" specimens, which were exposed to doped steam, had pullout loads per unit length about a [ ][a,c] than those of the non-exposed specimens. This is generally consistent with observations from L* test programs.

4.2.3.2 W* NDE Specimens Modified for Pullout Test

Pullout testing of the modified W* NDE specimens was performed according to a revision of the W* pullout test procedure described above. Table 4.2-2 illustrates the specimen condition and test conditions for the pullout tests.

Since it was pressurized internally during testing and had the highest radial contact pressures, the specimen [ ][b,c,e] The first data point for this specimen was at [

][b,c,e] Table 4.2-3 lists the pull test results for all of the W* NDE specimen test conditions. Analysis of the W* pullout test and W* NDE specimen pullout test data is provided in section 4.4.2.

Specimens [

][b,c,e]

Specimen NDE 02-2 was stress relieved [

][b,c,e]

test conditions, and is believed to be the reason for a decrease in slip load. Section 4.4.2 provides analysis of the data.

4.3 ANALYSIS OF TUBESHEET

The analysis of 51 Series SG tube/tubesheet contact pressures involves a 2-D axisymmetric finite element analysis model to determine the contraction and dilation of the tubesheet holes as a function of operating temperatures and pressures and tubesheet location. These are used with calculations of contact pressure from thick cylinder equations to develop the tube-to-tubesheet interface contact pressure. The finite element model was developed of the 51 Series SG tubesheet, channel head, and lower shell in Reference 9.6. This model is shown in Figure 4.3-1.

4.3.1 Material Properties and Tubesheet Equivalent Properties

The tubesheet, shell and channel head are fabricated of SA-508 Class 2, SA-533 Grade A Class 1, and SA-216 Gr. WCC materials, respectively. Tables 4.3-1 to 4.3-3 list the applicable mechanical, thermal, and strength properties for the tubesheet, shell and channel head materials, taken from Reference 9.7. The perforated tubesheet in the Series 51 channel head complex is treated as an equivalent solid plate in the finite element analysis. It is assumed that the tubesheet is a thick plate and that the loading results in a generalized plane strain condition. The finite element model conservatively neglects the stiffening effect from the tubes in calculating the tubesheet displacements. The perforated pattern is square with a pitch of 1.281 inch and maximum hole diameter of [ ]^{a,c}. To account for the perforations in the plate, the modulus of elasticity, E, and the Poisson's ratio, ν, for the plate material are modified. The ligament efficiency is used in the determination of these values, and is defined as:

$$\text{Ligament Efficiency, } \eta = \frac{h_{nominal}}{P_{nominal}}$$

where
$h_{nominal} = P_{nominal} - d_{maximum}$
$P_{nominal} = 1.281$, Pitch of the square pattern
$d_{maximum} = [\quad]^{a,c}$, tube hole diameter

Therefore,
$h_{nominal} = 1.281 - [$
$]^{a,c}$

The resulting E* and ν* from Slot (Reference 9.8) are input as tubesheet material properties in the analytical model:

a,c

[ ]

Table 4.3-1 gives the modulus of elasticity, E, of the tubesheet material at various temperatures. Using the ratio E*/E calculated above gives the modulus of elasticity for the equivalent solid plate in the perforated region of the tubesheet for the finite element model. The material properties of the tubes are not utilized in the finite element model, but are listed in Table 4.3-4 for use in calculations of the tube/tubesheet contact pressures.

4.3.2 Analysis of Tubesheet Rotation Effects

Using the finite element model of Figure 4.3-1, displacements throughout the tubesheet were obtained for the unit loads listed below:

Unit Load	Magnitude
Primary Side Pressure	1000 psi
Secondary Side Pressure	1000 psi
Tubesheet Thermal Expansion	500°F ΔT
Shell Thermal Expansion	500°F ΔT
Channel Head Thermal Expansion	500°F ΔT

The three temperature loadings consist of applying a uniform thermal expansion to each of the three component members, one at a time, while the other two remain at ambient conditions. The boundary conditions imposed for all five cases are UX = 0 at all nodes on the center line, and UY = 0 at one node on the outer surface of the tubesheet. In addition, an end cap axial stress (psi) is applied to the top of the secondary side shell elements (based on the shell R_i and R_o) for the 1000 psi secondary side pressure unit load, equal to:

a,c

[ ]

This yielded displacements throughout the tubesheet for the unit loads.

The axisymmetric analysis does not include the effect of the divider plate in restraining the tubesheet displacements. Calculations performed with a 3-D finite element model of a Model D4 steam generator (Reference 9.9) showed that the displacements at the center of the tubesheet when the divider plate is included are [ ][a,c,e] of the displacements without the effect of the divider plate. Since the 51 Series SG channel head/tubesheet/divider plate geometry is effectively identical to that of the Model D4, the same factor of [ ][a,c,e] was applied to the 51 Series tubesheet displacements. This [ ][a,c,e] factor is applied to the tubesheet displacements (y-axis) produced by the pressure unit loads; as seen below, this limits the changes in tubesheet hole dilation on the secondary face of the tubesheet. The radial displacements produced by the thermal unit loads are unaffected by the divider plate.

The radial deflection at any point within the tubesheet is found by scaling and combining the unit load radial deflections at that location according to:

[

]a,c

The above expression provides the radial deflections along a line of nodes at a constant axial elevation (e.g., top of the tubesheet) within the perforated area of the tubesheet.

The expansion of a hole of diameter D in the tubesheet at a radius R is given by:

[ ]a,c

U_R is available directly from the finite element results. dU_R/dR may be obtained by numerical differentiation. Using central differences,

[ ]a,c

for all nodes except those at the inside and outside boundaries of the perforated region of the tubesheet. At these locations, second order forward or backward differences are used.

[ ]a,c

[ ]a,c

This numerical differentiation has been shown to be sufficiently accurate for calculating dU/dR (Reference 9.3).

The maximum expansion of a hole in the tubesheet is in either the radial or circumferential direction. Typically, these two values are within 5% of each other. Since the analysis for calculating contact pressures is based on the assumption of axisymmetric deformations with respect to the centerline of the hole, a representative value for the hole expansion must be used that is consistent with the assumption of axisymmetric behavior. A study was performed in Reference 9.10 to determine the effect of hole out-of-roundness on the contact pressures between the tube and tubesheet.

The equation used for the hole ΔD is:

[ ]a,c

where SF is a scale factor between zero and one. For the eccentricities typically encountered during tubesheet rotations, SF is usually between [ ]a,c. These are listed in the table below:

[ ]a,c

These data were fit to the polynomial below:

[ ]a,c

This hole expansion includes the effects of tubesheet rotations and deformations caused by the system pressures and temperatures. It does not include local effects produced by interactions between the tube and tubesheet hole. Thick shell equations from Reference 9.11 in combination with the hole expansions from above are used to calculate the contact pressures between the tube and tubesheet.

The unrestrained radial expansion of the tube, ΔR_t, is given by:

$$\textit{Thermal:} \qquad \Delta R_t^{th} = c\,\alpha_t\,(T_t - 70)$$

[ ]a,c

where P_i = Internal pressure, psi
P_o = External pressure, psi
b = Inside radius of tube, in.
c = Outside radius of tube, in.
α_t = Coefficient of thermal expansion of tube, in./in./°F
E_t = Modulus of elasticity of tube, psi.
T_t = Temperature of tube, °F
ν = Poisson's ratio

The radial expansion of the hole, ΔR_{TS}, is given by:

Thermal: $\Delta R_{TS}^{th} = c\ \alpha_{TS}\ (T_{TS} - 70)$

a,c

[ ]

where the additional terms are,

E_{TS} = Elastic modulus of the tubesheet, psi

α_{TS} = Coefficient of thermal expansion of tubesheet, in./in./°F

d = Outside radius of cylinder which provides same radial stiffness as the tubesheet, in.

T_{TS} = Temperature of tubesheet,°F

If the unrestrained expansion of the tube O.D. is greater than the expansion of the ID of the tubesheet hole, then the tube and the tubesheet are in contact. The inward radial displacement of the outside surface of the tube produced by the contact pressure between the tubesheet and tube, δ_t, is given by:

a,c

[ ]

where

P_2 = Contact pressure between tube and tubesheet, psi

The equation for the contact pressure P_2 is obtained from:

a,c

[ ]

where

ΔR_{TS}= Hole expansion produced by tubesheet rotations obtained from finite element results.

The resulting equation is:

a,c

[

]

For a given set of primary and secondary side pressures and temperatures, the above equations are solved for selected elevations in the tubesheet to obtain the contact pressures between the tube and tubesheet as a function of tubesheet radius. Negative "contact pressures" indicate a gap condition.

4.3.3 Results for Normal and Faulted Conditions

The unit load displacements were taken from Reference 9.6 along lines of constant axial elevation in the perforated part of the tubesheet. These displacements are used to calculate tube/tubesheet contact pressures using the equations defined above. Contact pressures for the unit load conditions are scaled to correspond to the appropriate pressure and temperature conditions for normal operation and faulted conditions. Scale factors are also applied to adjust the contact pressures to the actual material properties at normal operating cold leg and hot leg temperatures.

The loadings considered in this analysis were selected to provide the limiting conditions for the 51 Series SG WEXTEX plants in this study. The conditions for pullout load evaluations were summarized in Table 3.2-1, and the conditions for SLB leakage are shown in Table 3.2-2. Primary pressure is assumed to act on the inside of the tube and the secondary pressure is assumed to act on the outside of the tube and the inside of the tubesheet hole.

Tube/Tubesheet Dimensions and Material Properties

From Reference 9.6, the dimensions of the WEXTEX section of the tube and the tubesheet unit cell are:

[

]a,c,e

Material properties at the limiting temperatures are:

[

]a,c,e

For these sets of primary and secondary side pressures, temperatures and material properties, the equations derived in Section 4.3.2 are solved for selected elevations in the tubesheet to obtain the contact pressures between the tube and the tubesheet as a function of tubesheet radius for both the hot leg and cold leg.

Contact pressures from the combined effects of differential thermal expansion between the tube and tubesheet, pressure, and tubesheet bending for the pullout load evaluations are provided in Tables 4.3-5 to 4.3-10. Contact pressures for the leakage analysis conditions are provided in Table 4.3-11. The results in these tables do not include the contact pressure component due to the WEXTEX expansion. Negative contact pressures near the top of the tubesheet do not represent a tensile condition, nor do they constitute a loading condition which non-conservatively reduces tubesheet rotation at the top of the tubesheet; instead, they are the result of the equations used to combine the tube and tubesheet interaction results with the results of the tubesheet finite element model. Negative contact pressures represent gap conditions, and therefore do not contribute to pullout load resistance.

4.4 CALCULATION OF PULLOUT LENGTH

The pullout load resistance length (PLRL) has been defined as the length of sound tube engagement in the tubesheet necessary to resist the analysis axial loads resulting from the pressure differentials. The axial resistance to pullout is due to the force resulting from the radial contact pressure between the tube and the tubesheet and the friction coefficient between these two components.

The radial contact pressure between the expanded tube and the tubesheet during steam generator operation includes radial contact pressures related to the thermal expansion mismatch (0.40 E-6 in/in/°F) between the alloy steel tubesheet and the Alloy 600 tube at approximately 600°F, and to the differential pressure across the tube wall. Any radial interference contact pressure resulting from the WEXTEX expansion process also contributes to the total radial contact pressure.

To determine the engagement length necessary to react the axial loads, it is necessary to define the operating radial contact pressure and the expansion process radial contact pressure. The steam generator operating radial contact pressures were calculated from a structural model and the results were provided in Section 4.3. The WEXTEX fabrication contact pressure, S_{rW}, and friction coefficient, μ, are developed in this section using the pull test results from Section 4.2. From analysis of the combined WEXTEX and operating radial contact pressures, this section also develops the pullout load lengths required to meet the structural criteria. Since radial contact pressure varies with increasing tubesheet radius, the analysis is performed for two tubesheet zones, defined as Zone A (near periphery) and Zone B (centrally located). Although W* degradation has only been observed on the hot leg to date, pullout lengths are also calculated for the cold leg.

4.4.1 Normal Operation Contact Pressures

Radial contact pressures for normal operating conditions were determined in Section 4.3, and the loads and related temperatures were provided in Section 3.2.

The pullout load model assumes that the bottom of the WEXTEX transition (BWT) coincides with the top of the tubesheet. This approach is employed since BWTs are not higher than the top of the tubesheet, and since tubesheet contact pressures are conservatively lower near the top of the tubesheet. Figure 4.4-1 illustrates the model used for W* length calculations.

4.4.2 WEXTEX Radial Contact Pressure and Friction Coefficient from Tests

The radial contact pressure between the tube and collar is composed of residual contact pressure from WEXTEX expansion, contact pressure due to the differential thermal expansion of the tube (higher coefficient of thermal expansion) into the tube (lower), and pressure expansion of the tube into the collar. The product of the integrated contact pressure, the surface area in contact between the tube and tubesheet, and the friction coefficient provides is equal to the pull force. For a discrete length with a uniform contact pressure, this is expressed as:

[ ]^{a,c} (4.4-1)

where,

PF = Pull Force measured during test, lbs.
D = tube OD and collar ID, inch
μ = friction coefficient
S_{rW} = radial contact pressure from WEXTEX expansion, psi
S_{rT} = radial contact pressure from thermal expansion mismatch between the tube and collar, psi
S_{rP} = radial contact pressure from internal pressure, psi
L_e = effective engagement length, inch

The determination of the radial contact pressure from WEXTEX expansion, S_{rW}, and the friction coefficient, μ, from the pullout test results required a calculation of the applied contact pressures for each test condition. Applied contact pressures are those due to pressure and thermal expansion (at room temperature and pressure the applied contact pressure is zero.) A calculation similar to that employed for the tubesheet contact pressure was developed, as described below.

At the tube OD surface, outward movement of the tube due to internal pressurization and thermal expansion is opposed by the radial contact pressure from interaction with the tubesheet collar. The collar ID surface moves outwardly, δ_{TS}, a distance equal to the tube outward movement, δ_{tube}, in response to contact pressure at the collar ID and thermal expansion. These are shown as:

$$\delta_{tube} = \delta_{tube,\ thermal} + \delta_{tube,pressure} \quad (4.4\text{-}2)$$

$$\delta_{TS} = \delta_{TS,\ thermal} + \delta_{TS,\ pressure} \quad (4.4\text{-}3)$$

The formulas of Reference 9.11 provide:

a,c

[ ] (4.4-4)

where,

[

]^{a,c}

The thermal expansion of the tube and collar are:

$$\delta_{tube,\ thermal} = b\ \alpha_{tube} * (T - 70) \qquad (4.4\text{-}5a)$$

$$\delta_{TS,\ thermal} = b\ \alpha_{TS} * (T - 70) \qquad (4.4\text{-}5b)$$

where,

α_{tube} = Coefficient of thermal expansion of the tube, in./in./°F
α_{TS} = Coefficient of thermal expansion of the tubesheet, in./in./°F
T = Temperature of the tube and collar, °F

The "70" value is room temperature, in degrees Fahrenheit.

The formulas of Reference 9.11 also provide:

a,c

[ ] (4.4-6)

where,

P = Radial contact pressure, psi
E_{TS} = Young's modulus for the tubesheet collar, psi
c = Outside radius of tubesheet collar, in.

There is no external pressure differential across the tubesheet collars.

Solving equations (4.4-2) through (4.4-6) for P results in:

a,c

[ ] (4.4-7)

The material properties for the 1018 carbon steel collars and the I-600 tubing were obtained from Reference 9.7.

Pullout Load Test Material Properties vs. Temperature			
Temperature, °F	70	400	600
Tube Elastic Modulus, E_t, psi	31.0E+06	29.5E+06	28.7E+06
Collar Elastic Modulus, E_{TS}, psi	29.5E+06	27.7E+06	26.7E+06
Tube Coeff. of Thermal Expansion, α_{tube}, in/in./°F	6.90E-06	7.57E-06	7.82E-06
Collar Coeff. of Therm. Expansion, α_{TS}, in./in./°F	6.50E-06	7.07E-06	7.42E-06

Dimensional values for the test are:

[

]^{a,c}

The W* pullout load test contact pressure results are shown in Tables 4.4-1 and 4.4-2 for [ ]^{a,c} the unrestrained differential thermal expansions between the tube and collar for each are [

]^{a,c}.

Test Specimen Effective Engagement Length: The effective engagement length, L_e, is the length of tube which provides pullout resistance in the test specimen. The "constant diameter" fully expanded zone, L_o, of these samples is [ ]^{a,c}. At each end of the "constant diameter zone", there is a slight taper over a [

]^{a,c}

Since increases in the applied contact pressure (due to pressure and thermal expansion) will cause a greater length of the tube to come in contact with the collar, and hence a greater radial load, an evaluation was performed of potential adjustments to the contact length as a function of the changes in contact pressure due to internal pressurization and heatup. On the "low end" of the analysis cases, [

]a,c

"End effect" corrections are employed as a conservatism in pullout load resistance length criteria since a degraded portion of tube adjacent to the sound tube portion could induce an edge rotation at the end of the sound tube section, thereby reducing the contact pressure in the sound tube portion. The end effect correction was not used for the W* pullout test specimens, since the reduction in effective length that occurs with such an assumption produces a larger, less conservative friction coefficient.

Applied Radial Contact Load: Equation (4.4-1) was modified to develop the total radial contact load at each test condition. The total applied radial contact load, $P_{applied}$, is portion of the radial contact load which varies with changes in the test temperature and tube internal pressure, and is the product of the applied radial contact pressure and the area of the contact pressure:

[ ]a,c (4.4-8)

where,

D = Tube diameter at contact, inch

and the other parameters are the same as defined for Equation 4.4-1.

The temperature and pressure [

]a,c This is represented as following:

[ ]a,c (4.4-9)

where,

SL = Slip load from the applied load vs. reacted load curve, lbs.
P_0 = The slip load corresponding to zero applied load, lbs.

Figure 4.4-2 illustrates the above method.

From equation 4.4-1, S_{rW} is found when $(S_{rT} + S_{rP}) = 0$, and PF = P_0:

[ ]a,c (4.4-10)

Figure 4.4-3 illustrates the regression fits of applied versus slip loads for all of specimens tested. The results for each specimen are generally quite linear, indicating that [

]^{b,c} Referring to Table 4.2-3, it is also noted that the initial slip load for specimens [

]^{a,c,e} and illustrates the margin inherent in the approach. The above test results also do not take credit for any potential decrease in pullout load due to the EDM notches.

From equation 4.4-10, the WEXTEX contact pressure, S_{tW}, is [

]^{a,c}

4.4.3 W* Pullout Length

Since the contact pressure between the tube and tubesheet varies across and through the tubesheet as a result of primary and secondary temperature and pressure differentials, the engagement length was determined by dividing the load for a given criterion by the axial resistance load (Equation 4.4-1) at incremental, increasing depths in the tubesheet.

Table 4.4-3 provides the W* length calculation summary for the hot leg normal operating conditions. The column at left is the distance below the top of tubesheet at which the radial contact pressures are calculated. The radial contact pressures shown in the next two columns, "Total Contact Pressure" are the calculated contact pressures from the structural model for the normal operating conditions [ ]^{a,c} as described in Section 3.2 and include the WEXTEX contact pressure of [ ]^{a,c}. The contact pressures are the minimum contact pressures for each W* zone, with the 2.28" radius being the limiting position for Zone B, and 37.7" the limiting radius for Zone A. The "Incremental Load at Depth" provides the pullout resistance load developed over the given depth increment, e.g., for this case [ ]^{a,c} lbs. of load is developed by the length of undegraded tubing between [ ]^{a,c} inch below the top of the tubesheet. No pullout load resistance is attributed to [

]^{a,c}. The final columns sum the incremental loads at each depth. At bottom, the W* length is shown by interpolating the incremental load and adding to the largest cumulative load which is less than the criterion load of [ ]^{a,c}.

End effects, which are typically small (on the order of 0.1"), are not included in the WEXTEX W* length calculation since the WEXTEX expansion process is performed in one continuous step. Unlike the stepwise roll expansions, WEXTEX expansions have negligible residual internal moments, and a complete severance of the tube at any given position in the WEXTEX-expanded length has a negligible effect on the pullout resistance of a neighboring tube section. This is evidenced by the tight contact and negligible ID changes found when sectioning collars with WEXTEX expansions.

Tables 4.4-5, -6, -7, and -8 provide the contact pressures and W* length determinations for faulted conditions. Case (2) is the limiting faulted condition.

Cracking in WEXTEX tube-to-tubesheet joints has been observed only in the hot leg to date, however, cold leg W* lengths were calculated in the event that cold leg W* region indications are observed. Cold leg W* lengths are provided in Tables 4.4-4 and 4.4-6 for the normal condition and faulted Case (1), respectively. Cold leg W* lengths are not calculated for faulted condition Cases (2) and (3) since the cold leg W* lengths are essentially the same as the hot leg lengths.

Table 4.4-9 provides a summary of the W* lengths for each analyzed case. Due primarily to a lower thermal contact pressure component, the cold leg W* lengths are slightly increased in comparison to the hot leg lengths. The limiting hot leg W* lengths occur for normal operating conditions, and are 7.0 inches for W* Zone B, and 5.2 inches for W* Zone A.

4.5 ZONES FOR W* LENGTH AND LEAKAGE

In a given tube, a length of sound expansion equal to the W* length provides that the structural criteria for pullout are met. Two W* length zones have been defined. These correspond to the zones currently used at WEXTEX plants for inspection of the expansion transitions. W* Zone A includes the same tubes as expansion transition inspection Zones 1, 2, and 3. W* Zone B corresponds to expansion transition inspection Zone 4. Inspection can be limited to the maximum W* length calculated within these two zones. This reduces inspection time as compared to a single W* length criterion. Figure 4.5-1 shows W* Zones A and B on a tubesheet map.

For the leakage calculation described in Section 6.0, Zone B has been subdivided into four zones designated Zones B1 through B4. Refer to Figure 8.2-1 for a tubesheet map of these zones.

TABLE 4.2-1

WEXTEX EXPANSION JOINT PULL FORCE TEST RESULTS

a,c

[ ]

Table 4.2-2

Specimen Conditions and Test Conditions
for Pullout Tests of W* NDE Samples

Specimen Number	Stress Relief (time at temp.)	Temperatures Tested (°F)	Internal Pressures Tested (psig)	Collar Lengths Tested (inch)

a,c

Table 4.2-3

Pull Test Results for W* NDE Specimens

Sample Number	Slip Load at Indicated Temperature, Pressure (lbs.)				Tube Internal Pressure (psi)	Collar Length (inches)	Engagement Length (inches)(1)
	70 (°F)	200 (°F)	400 (°F)	600 (°F)			

a,c,e

* First slip load.
(1) Measured from centerline of WEXTEX transition.
(2) Test suspended to avoid tube yield (no slippage).
(3) Tube yielding observed.

Table 4.3-1
Summary of Material Properties
Tubesheet Material
SA-508 Class 2

PROPERTY	TEMPERATURE (°F)						
	70	200	300	400	500	600	700
Young's Modulus psi x 1.0E+06	29.20	28.50	28.00	27.40	27.00	26.40	25.30
Coefficient of Thermal Expansion in/in/°F x 1.0E-06	6.50	6.67	6.87	7.07	7.25	7.42	7.59
Density lb-sec²/in⁴ x 1.0E-04	7.32	7.3	7.29	7.27	7.26	7.24	7.22

Table 4.3-2
Summary of Material Properties
Shell Material
SA-533 Grade A Class 1

PROPERTY	TEMPERATURE (°F)						
	70	200	300	400	500	600	700
Young's Modulus psi x 1.0E+06	29.20	28.50	28.00	27.40	27.00	26.40	25.30
Coefficient of Thermal Expansion in/in/°F x 1.0E-06	7.06	7.25	7.43	7.58	7.70	7.83	7.94
Density lb-sec²/in⁴ x 1.0E-04	7.32	7.30	7.283	7.265	7.248	7.23	7.211

Table 4.3-3
Summary of Material Properties
Channel Head Material
SA-216 WCC

PROPERTY	TEMPERATURE (°F)						
	70	200	300	400	500	600	700
Young's Modulus psi x 1.0E+06	29.50	28.80	28.30	27.70	27.30	26.70	25.50
Coefficient of Thermal Expansion in/in/°F x 1.0E-06	5.53	5.89	6.26	6.61	6.91	7.17	7.41
Density lb-sec²/in⁴ x 1.0E-04	7.32	7.30	7.29	7.27	7.26	7.24	7.22

Table 4.3-4
Summary of Material Properties
Alloy 600 Tube Material

PROPERTY	TEMPERATURE (°F)						
	70	200	300	400	500	600	700
Young's Modulus psi x 1.0E+06	31.00	30.20	29.90	29.50	29.00	28.70	28.20
Coefficient of Thermal Expansion in/in/°F x 1.0E-06	6.90	7.20	7.40	7.57	7.70	7.82	7.94
Density lb-sec²/in⁴ x 1.0E-04	7.94	7.92	7.90	7.89	7.87	7.85	7.83
Thermal Conductivity Btu/sec-in-°F x 1.0E-04	2.01	2.11	2.22	2.34	2.45	2.57	2.68
Specific Heat Btu-in/lb-sec²-°F	41.2	42.6	43.9	44.9	45.6	47.0	47.9

Table 4.3-5
Normal Operating Conditions
Hot Leg Contact Pressures Through the Tubesheet Thickness

a,c

Table 4.3-6
Normal Operating Conditions
Cold Leg Contact Pressures Through the Tubesheet Thickness

a,c

Table 4.3-7
Faulted Case 1
Hot Leg Contact Pressures Through the Tubesheet Thickness

a,c

Table 4.3-8
Faulted Case 1
Cold Leg Contact Pressures Through the Tubesheet Thickness

a,c

Table 4.3-9
Faulted Case 2
Hot and Cold Leg Contact Pressures Through the Tubesheet Thickness

a,c

Table 4.3-10
Faulted Case 3
Hot and Cold Leg Contact Pressures Through the Tubesheet Thickness

a,c

Table 4.3-11
SLB Leakage Analysis Conditions
Hot Leg Contact Pressures Through the Tubesheet Thickness

a,c

Table 4.4-1
Pullout Load Test - Specimen W8-007A
Determination of WEXTEX Radial Contact Pressure, S_{rW}, and Friction Coefficient, μ

Design Values:
Tube Inside Radius
Tube Outside Radius
Tubesheet Collar Equiv. Radius
Ambient Temperature

[ ] a,c

Test Conditions

[ ] a,b,c

Contact Length Employed	Friction Coefficient, μ	WEXTEX Contact Pressure, SrW, (psi)	Hot Leg Zone B W* Length, Normal Op.	Hot Leg Zone B W* Length, Faulted Case (2)

[ ] a,b,c

c:\wsta\w_length\PULLOUTS.XLS W8-007A d.3

Table 4.4-2
Pullout Load Test - Specimen W4-006
Determination of WEXTEX Radial Contact Pressure, S_{rw}, and Friction Coefficient, μ

Design Values:
Tube Inside Radius
Tube Outside Radius
Tubesheet Collar Equiv. Radius
Ambient Temperature

[ ] a,c

Test Conditions

[ ] a,b,c

Contact Length Employed	Friction Coefficient, μ	WEXTEX Contact Pressure, SrW, (psi)

[ ] a,b,c

Table 4.4-3
Incremental and Cumulative Pullout Resistance Load vs. Distance from TTS
Normal Operating Conditions - Hot Leg

Distance from TTS (in.)	Total Contact Pressure (psi)		Incremental Load at Depth (lbs.)		Cumulative Load at Depth (lbs.)	
	Zone B	Zone A	Zone B	Zone A	Zone B	Zone A

a,b,c

Zone B	Load (lbs.)	Zone A	Load (lbs.)

a,b,c

Table 4.4-4
Incremental and Cumulative Pullout Resistance Load vs. Distance from TTS
Normal Operating Conditions - Cold Leg

Distance from TTS (in.)	Total Contact Pressure (psi)		Incremental Load at Depth (lbs.)		Cumulative Load at Depth (lbs.)	
	Zone B	Zone A	Zone B	Zone A	Zone B	Zone A

a,b,c

Zone B	Load (lbs.)	Zone A	Load (lbs.)

a,b,c

Table 4.4-5
Incremental and Cumulative Pullout Resistance Load vs. Distance from TTS
Faulted Conditions Case (1) - Hot Leg

Distance from TTS (in.)	Total Contact Pressure (psi)		Incremental Load at Depth (lbs.)		Cumulative Load at Depth (lbs.)	
	Zone B	Zone A	Zone B	Zone A	Zone B	Zone A

a,b,c

Zone B	Load (lbs.)	Zone A	Load (lbs.)

a,b,c

Table 4.4-6
Incremental and Cumulative Pullout Resistance Load vs. Distance from TTS
Faulted Conditions Case (1) - Cold Leg

Distance from TTS (in.)	Total Contact Pressure (psi)		Incremental Load at Depth (lbs.)		Cumulative Load at Depth (lbs.)	
	Zone B	Zone A	Zone B	Zone A	Zone B	Zone A

a,b,c

[ ]

Zone B	Load (lbs.)	Zone A	Load (lbs.)

a,b,c

[ ]

Table 4.4-7

Incremental and Cumulative Pullout Resistance Load vs. Distance from TTS

Faulted Conditions Case (2) - Hot Leg and Cold Leg

Distance from TTS (in.)	Total Contact Pressure (psi)		Incremental Load at Depth (lbs.)		Cumulative Load at Depth (lbs.)	
	Zone B	Zone A	Zone B	Zone A	Zone B	Zone A

a,b,c

Zone B	Load (lbs.)	Zone A	Load (lbs.)

a,b,c

Table 4.4-8
Incremental and Cumulative Pullout Resistance Load vs. Distance from TTS
Faulted Conditions Case (3) - Hot Leg and Cold Leg

Distance from TTS (in.)	Total Contact Pressure (psi)		Incremental Load at Depth (lbs.)		Cumulative Load at Depth (lbs.)	
	Zone B	Zone A	Zone B	Zone A	Zone B	Zone A

a,b,c

Zone B	Load (lbs.)	Zone A	Load (lbs.)

a,b,c

Table 4.4-9
W* Length Summary

	W* Length (inches)			
	Hot Leg		Cold Leg	
Conditions	Zone B	Zone A	Zone B	Zone A
Normal	7.0	5.2	7.5	5.5
Faulted Case (1)	5.5	3.4	5.8	3.4
Faulted Case (2)	6.7	4.3	6.7	4.3
Faulted Case (3)	6.6	4.2	6.6	4.2

a,c,e

Figure 4.2-1 As-Fabricated WEXTEX Sample for Pull Tests

a,c,e

Figure 4.2-2 Pull Force Sample Configurations Tested

a,c,e

Figure 4.2-3 Load/Deflection Curve for Specimen W8-007A at 600°F, and 1620 psid

a,c,e

Figure 4.3-1 Tubesheet/Channel Head/Lower Shell Finite Element Model

a,c,e

Figure 4.4-1 Structural Model for W* Length Calculation

Figure 4.4-2
Determination of Friction Coefficient from Test Data

a,c

Figure 4.4-3
Applied Load vs. Reacted Slip/Pull Load
W* Pullout Specimens

a,c,e

Applied Radial Load (lbs.)

a,c

Figure 4.5-1 W* Length Zones A and B and Expansion Transition Zones 1 Through 4

5.0 DEGRADED TUBE STRENGTH

5.1 EVALUATION METHODS

Earlier F* and L* (Reference 9.1) work for roll expanded tubesheet joints focused on the presence of degradation below the bottom of the roll expansion transition of the single band degradation (SBD) and multiple band degradation (MBD) types. These forms of degradation, which are an annular group or groups of multiple cracks, have not been observed in WEXTEX expansions. The absence of band-type degradation in WEXTEX expansions is consistent with the expansion process; roll expansion occurs in discrete steps, whereas WEXTEX expansion essentially occurs in one step.

WEXTEX region degradation has occurred primarily as single circumferential and single axial or near-axial cracks. Nearly all of the circumferential indications are located at the expansion transition, and the axial indications include those in and above the expansion transition plus those located below the transition. The largest reported W* region SAI from the inspection database presented in section 7.0 was 0.68 inch long. Although data on MAIs is more limited, the longest reported W* region MAI is 0.24 inch, and the MAIs reviewed usually were comprised of only two axial or near axial cracks. No SAIs nor MAIs with crack angles in excess of 30° from vertical were observed.

The W* criteria address only those indications located below the bottom of the WEXTEX transition. There were some circumferential and volumetric indications and a few multiple axial indications reported at distances well below the WEXTEX transition, however, secondary review of these indications has shown them to be very small and volumetric in appearance. Circumferential and volumetric indications are not permitted under W* criteria, and unless other alternate plugging criteria are applied, circumferential indications would be repaired. Volumetric indications would also be plugged since they represent a different degradation mode than PWSCC. Undegraded sections of tubing within the tubesheet region are referred to as sound WEXTEX expansions.

This section addresses the structural acceptance basis for single axial or near-axial, and multiple axial or near-axial cracks in the W* criteria. For vertically-oriented cracks located in the W* region, there is no effect on the axial pull strength of the tube. However, should slanted single or slanted multiple axial cracks occur within the W* region, there can be a reduction in axial pull strength. The degraded region must therefore have sufficient strength to transmit loads to sound regions of the tube within the W* length to meet pullout load criteria. A conservative approach used in analyzing slanted crack effects on axial pull strength is to take no credit for the reduction in the axial load on successive degradation bands because of axial resistance afforded by the prior (nearer to the top of the tubesheet) sound expansion regions. Thus, all degraded regions in this evaluation are assumed to experience the total axial load. In the most conservative case, i.e., no axial restraint attributed to the degraded expansion, the applied axial loads are considered to be reacted by the aggregate length of sound tube portions above and below any bands of axial or near-axial indications.

The evaluation of degraded tube strength considers the most stringent axial load on the tube for the normal, FLB and LOCA conditions. These are summarized below:

5.1.1 Normal Operation Loads

As developed in Section 3.2, the axial load to be borne by the tube under normal operation conditions is [ ]^{a,c,e}. A safety factor of three is applied to this load so the tube axial load requirement for normal operation is [ ]^{a,c,e} pounds. This represents the most stringent axial load on the tube for all conditions considered.

5.1.2 Feed Line Break

Also as developed in Section 3.2, the axial load to be borne under feed line break (FLB) conditions is [ ]^{a,c,e}. A safety factor of 1.43, corresponding to an ASME Code factor of 1.0/0.7 for allowable stress for faulted conditions, is applied to this load. Therefore the axial loadbearing requirement for FLB is [ ]^{a,c,e} pounds.

5.1.3 Loss of Coolant Accident

An axial load from a LOCA event acts to move a tube downward. Therefore this condition does not apply a tensile load to the tube and is not considered further.

5.2 ANALYSIS OF DEGRADED TUBE STRENGTH

The strength of a degraded tube is dependent on the crack geometry as well as the number of cracks and the angle of the cracks relative to the tube axis. Figure 5.2-1 illustrates the case of multiple, slanted axial cracks. The transmission of axial force across the crack array creates a bending moment in the ligaments of material between cracks and lowers the load required for plastic collapse. This crack case was previously presented in Reference 9.1 for L* criteria. The load required to yield the slanted crack array is given by Equation 5-1. The variables for the equation are shown in Figure 5.2-1. The axial plastic displacement, δ_p, resulting from yielding and then rotation of the crack array is given by Equation 5-2.

a,c

[ ] (5-1)

a,c

[ ] (5-2)

If the crack array plastic displacement computed from the above equations, as a function of axial load, is added to the baseline load-displacement record of an otherwise identical tube without a crack array, the computed load-displacement record closely approximates actual measurements of an array with straight, slanted cracks as illustrated in Figure 5.2-2.

The evaluation of degraded tube strength for the WEXTEX tubes included analysis of the response of degraded regions of tubing to axial loads based on data from previous tests performed to determine the axial load bearing capability of degraded tube-to-tubesheet rolled joints (Reference 9.1). The referenced tests were performed to determine the tensile strength of non-degraded and degraded 0.75" OD x 0.043" wall Alloy 600 MA tubes rolled into AISI 1018 carbon steel collars. Some additional degraded samples were tested in the unexpanded condition and others were tested in the decollared condition. Throughwall degradation was simulated by electric discharge machined (EDM) slots in the tube specimens. The slots were [ ][a,c,e] inches long and were machined at an angle of [ ][a,c,e] degrees from the axial centerline of the tube. The number of slots in the tubes was either [ ][a,c,e].

Laboratory measurements of the axial pull strength of rolled 0.75 inch OD tubes showed that the maximum pull strength is far above the yield load when substantial numbers of slanted cracks are present (Reference 9.1). The presence of the slanted cracks leads to early yielding as the ligaments between cracks deform in bending. As plastic deformation proceeds, rotation of the slanted crack network occurs, and the tube rotates while becoming longer. As rotation occurs the effective moment arm for bending of the ligament between cracks decreases and plastic deformation becomes more difficult. This is an example of geometric hardening. Maximum strength is reached when tearing at the crack tips occurs. The onset of crack tearing depends on the cracked body toughness of the material. In tests of roll expanded tubes with slanted slots, the maximum pull strength correlated reasonably well with a J integral value of [ ][a,c,e] in-lb/in. Applied J values can be obtained from computed load versus plastic displacement definition of J. The high toughness and small scale geometry of cracked Alloy 600 tubes makes neglecting the elastic loading a reasonable approach in the estimation of maximum pull strength.

A very conservative approach to axial pull strength is to accept crack geometries on yielding criteria since, as noted above, the yield loads of slanted crack arrays are substantially below measured maximum loads. Figure 5.2-3 is a plot of yield load versus the crack length of slanted cracks for 0.875 OD by 0.050 inch wall tubing with [ ][a,c,e] crack angles developed from Equation 5-1. Figure 5.2-4 is a similar plot for [ ][a,c,e] crack angles. The results are applicable to the tubesheet expansion zone of WEXTEX tubes. In both Figure 5.2-3 and 5.2-4, all geometries above the [ ][a,c,e] pound level (See Section 5.1.1) are acceptable.

5.3 LIMITATIONS ON ALLOWABLE DEGRADATION

Figure 5.2-3 indicates that an array of up to [ ][a,c,e] or less from vertical will meet the $3\Delta P$ axial load requirement of [ ][a,c,e] pounds. Figure 5.2-4 shows that an array of up to [ ][a,c,e] or less from vertical will meet the $3\Delta P$ axial load requirement.

The basis for acceptability of W* region degradation was determined from the above results, and is described in Sections 8.4 and 8.6. The W* requirements include additional limitations on crack number and orientation, to provide additional margin above that included in this evaluation, and to simplify the implementation of W*.

Note that all circumferential and volumetric indications within the flexible W* distance and axial indications with inclination angles > 45° are repaired to exclude circumferential involvement within the W* length.

5.4 W* ADJUSTMENTS FOR TUBE DEGRADATION

The effect of axial cracking on tube pullout loads has not been fully quantified. In the limiting case, long, closely spaced, uniform axial cracks in which the axial ligaments do not interact with each other could result in a reduction in pullout resistance load. Therefore, if a crack occurs in the W* length, it is assumed that the axial resistance to applied loads is effectively reduced. While the effect of the crack on axial resistance may be localized, it is conservatively assumed that the full axial extent of the tube having an axial crack provides no pullout restraint. As discussed above, the region will, however, transmit the axial loads to the sound portion of the tube below the crack. The total length necessary to react the postulated axial load then becomes the length of the undegraded region of the tube above the crack plus the appropriate length of sound, undegraded tube below the crack.

The method of accounting for the non-active region of the tube (in terms of providing axial restraint) is to delete the length of the crack. Since the continuous W* expansion process differs from the stepwise roll expansion process, no added length is required to account for end effects. This method is summarized in Section 8.0.

a,c,e

Figure 5.2-1 Model for Plastic Collapse of Slanted Straight Crack Array

a,c,e

Figure 5.2-2 Comparison of Load-Displacement Records, Computed Versus Measured for 30 Slots at $\phi = 45°$

Figure 5.2-3
Array Yield Load for Arrays of Differing Numbers (N) of Cracks Slanted at 45 Degrees vs. Crack Length

a,c,e

Figure 5.2-4
Array Yield Load for Arrays of Differing Numbers (N) of Cracks Slanted at 30 Degrees vs. Crack Length

a,c,e

[ ]

6.0 LEAK RATE EVALUATION

The leak rate evaluation for the W* alternate plugging criteria is based on a combination of empirical and analytical methods. Section 6.1 describes the operating and faulted pressure conditions analyzed. Section 6.2 reviews the testing of prototypic WEXTEX tubesheet expansions used to develop the crevice leak rate model. Section 6.3 describes two test sequences with constrained crevices used to develop an effective crack length leak rate model. Section 6.4 describes the leak rate analysis model, and includes a calculation of leak rate for a sample set of W* region indications. Section 6.5 provides the statistical confirmation of the deterministic leak rate calculation methodology.

6.1 EVALUATION METHODS AND CONDITIONS

At normal operating pressures, leakage from PWSCC cracks in WEXTEX expansions in the W* zone is limited by both the tube-to-tubesheet crevice and the restrictions on crack opening provided by the tubesheet constraint. Consequently, negligible normal operating leakage is expected from cracks within the tubesheet region of WEXTEX expansions. This has been evidenced by extensive European operating experience with axial PWSCC cracks left in service, summarized in Reference 9.2, which showed negligible normal operating leakage from PWSCC cracks even under free span conditions in the roll transitions.

The steamline break (SLB) conditions provide the most stringent radiological hazards for postulated accidents involving a loss of pressure or fluid in the secondary system, and W* leak rates are calculated with the steam line break primary-to-secondary pressure differential. The evaluation of SLB leakage includes calculation of leak rate for all cracks left in service. The total leakage, i.e., the combined leakage for all such tubes, plus the combined leakage developed by any other alternate repair criteria, must be below the plant Technical Specification leak rate limit.

The method for assessing leakage from cracks in the W* region considers the leak rate across the tube-to-tubesheet interface to be a function of the differential pressure across the tube wall, the radial contact pressure between the tube and the tubesheet, and crevice length. The crevice length is taken as the distance from the BWT to the upper tip of the crack, reduced by the NDE uncertainty and crack growth. The radial contact pressure between the tube and tubesheet hole was provided for applicable operating conditions in Section 4.3. Leak rates for WEXTEX joints were determined through testing of prototypic WEXTEX tube-to-tubesheet joints. The test data were used to generate a leak rate model that permits the calculation of leak rate for a given crack depth within the tubesheet. From this model leak rates can be determined for cracks within the W* region. Furthermore, the model shows that below the W* region the leakage will be negligible, such that leakage from cracks below the W* length does not need to be considered in the SLB leakage limits.

The loads considered in the analysis are those resulting from normal operation, faulted and LOCA as described in Section 3.0 and summarized below.

6.1.1 Normal Operation

The differential pressure between the primary side and secondary side during normal operation is [ ]^{a,c} Negligible leakage is expected from cracks under normal operating conditions and no W* requirements are applied to limit operating leakage.

6.1.2 Faulted Condition - Steam Line Break

The primary-to-secondary differential for the SLB condition is [ ]^{a,c} and is the basis for W* leakage calculations.

6.1.3 LOCA

The ~1000 psi secondary-to-primary pressure differential during LOCA will tend to close cracks and restrict leakage, and is not used for W* leakage calculation.

6.2 WEXTEX EXPANSION LEAK RATE TESTS

6.2.1 Sample and Test Description

The samples for the leak rate tests were designed to simulate the WEXTEX tube-to-tubesheet interface characteristics. The samples consisted of carbon steel collars each approximately [

]^{b,c,e} The tube specimens were fabricated from Quality Assurance (QA) controlled stock and fabrication of the collars was done under QA surveillance. WEXTEX expansions were fabricated per approved procedures.

The collars used to simulate the tubesheet were [

]^{b,c,e}

The configuration of the WEXTEX leak rate test samples is shown in Figure 6.2-1. The sample was rolled and welded at one end prior to WEXTEX expansion to create a seal at one end of the tube-to-collar crevice. As was the case with the pull force test samples described in Section 4.2, the as-fabricated leak rate test samples had smaller diameters between the BWT and the fully expanded region, which starts about [

]^{b,c,e} locations are given in Table 6.2-1 along with the average diameter over the fully expanded region. These data are used in the determination of the average contact pressure along the tube-to-collar crevice leak path.

6.2.2 Test Description

Samples were tested at various temperatures and pressures to assess WEXTEX joint leakage at normal and faulted conditions, which are more stringent than the LOCA condition, to develop a leak rate model. The tests were performed in accordance with an approved, referenceable test specification.

After expansion, each sample was drilled with a series of [

]^{b,c,e}

The room temperature leak tests were performed in [

]^{b,c,e}

The elevated temperature tests were also performed in [

]^{b,c,e}

6.2.3 Test Results

The results of the tests are summarized in Table 6.2-2. The nominal crevice length shown is the distance from the top of the collar to [

]^{b,c,e}

The staking operation noted above deformed the tube in the vicinity of the through-wall hole and effectively shortened the crevice length. As shown in the Figure 6.2-3 example of test sample

W4-018, the staking, combined with the radius of the drilled hole, decreased the crevice length by [

]b,c,e For the RT-1620 psi test condition with a nominal crevice length of 2 inches, this sample would be estimated to have zero contact pressure at approximately [

]b,c,e

The average contact pressure for the test is the integrated contact pressure over the effective crevice length after accounting for the reduced contact pressure resulting from the smaller tube diameter. End effects, which were discussed in Section 4.4.2, were also included in the determination of integrated contact pressure.

The reduced data from the WEXTEX joint leak tests are summarized in Table 6.2-3 and include the leak rate, the effective crevice length, and the average contact pressure over this length for each test. The average contact pressure includes that due to differential thermal expansion and primary-to-secondary differential pressure. Contact pressure due to the WEXTEX expansion is inherent in both the test samples and SG tubes and is not included in the average contact pressure. These data are used in the development of the leak rate model for the WEXTEX tube-to-tubesheet joints (Section 6.4).

6.3 CONSTRAINED CRACK LEAK RATE TESTS

6.3.1 Test Design and Description

Additional testing was performed to provide an enhanced basis for the prediction of leak rates from WEXTEX-expanded tubes. Previous leak rate models utilized the crack opening area of free-span lengths of tubes, and did not simulate the reinforcing effect which the tubesheet has in limiting crack opening and leakage. The test program described in this section was performed to provide an empirical basis for [

]b,c

[

]b,c

Figure 6.3-1 illustrates the overall test arrangement. The correlation between crevice depth (or length) and loss coefficient are known from the testing reported in Section 6.2, [

]b,c

6.3.2 Sample Preparation and Test Assembly

[

]b,c It is noted that the actual crack lengths are not an input to the leak rate calculation since, as described later, the leak rates were found to be essentially independent of crack length and to correlate strongly with contact pressure. The room temperature and elevated temperature free span leak rates for the specimens confirm the significant leakage potential of these cracks when crevice constraint is not present.

The [

]b,c,e

6.3.3 Test Conditions

Leak rate data were first obtained for [

]b,c,e pressure differentials, respectively.

Leak rate data were then obtained [

]b,c The test matrix for the leak rate tests is presented in Table 6.3-2.

6.3.4 Leak Rate Test Results and Conclusions

Leak rate test results are presented in Table 6.3-3. The leak rate for each sample and operating condition is presented. In addition, calculated gaps and contact pressures are listed.

Analysis of the leak rates was performed in two steps. First, [

]^{a,c} This relationship permits application of the leak rate test results to field cracks in WEXTEX crevices.

Figure 6.3-5 displays all the free span test data, plotted against the predictions of CRACKFLO. The figure demonstrates that [

]^{a,c}

In order to integrate the constrained crack test results into the leak rate calculation model, a link is needed between the test crack physical environment in the collars and an actual crack physical environment in a WEXTEX crevice. A primary characteristic of crack constraint in a crevice is the radial contact pressure which the wall of the collar or tubesheet exerts on the tube OD surface. This contact pressure provides the link between the test and cracks in the field.

For the data in Table 6.3-3, which was at operating temperature and [

]^{a,c} Figure 6.3-8 shows the [

]^{a,c}

6.4 LEAK RATE ANALYSIS MODEL

Calculation of leakage from an axial crack within the tubesheet and below the WEXTEX transition uses the CRACKFLO code for crack leakage in series with a crevice, represented by laminar flow through a porus medium. The combined calculation is performed by the DENTFLO Code. This code calculates the primary to secondary leakage rate through an axial crack with a flow resistance between the exit of the crack and the secondary side pressure. In the case of the WEXTEX joint, the flow resistance is the crevice between the tube OD and the tubesheet hole surface.

Application of the DENTFLO Code requires the input of a [

]a,c

Earlier applications of this analysis model calculated the crack opening as if it were a free span crack. The test results presented in section 6.3.3 show [

]a,c

In this section, a deterministic leak rate model is developed and used to calculate leak rates as a function of crack depth and tubesheet radial position. The following section statistically assesses the leak rate model by conducting a Monte Carlo simulation. This evaluation demonstrates the margin inherent in the deterministic leak rate model.

6.4.1 DENTFLO Model Description

The DENTFLO Code was developed to assess leakage through tube cracks within the tubesheet. Leakage is determined by crack leakage characteristics as well as the flow resistance of the crevice. The code [

]a,c

In DENTFLO, the model for crack leakage is the same as the one used in the CRACKFLO Code. This code uses [

]a,c One such comparison is reported section 6.3.4 of the present report.

6.4.2 DENTFLO Inputs for Leak Rate Calculation

As noted, principal inputs to DENTFLO are [
]a,c Values for both these parameters are developed from correlations with contact pressure between the tubesheet hole surface and the OD of the tube. Contact pressure is a function of depth below the tubesheet surface and radial position on the tubesheet; these relations

are developed in Section 4. In addition to its dependence on effective crack length and crevice flow resistance, crack leakage is a function of tube properties and operating conditions.

Crack Effective Length
The DENTFLO Code assumes [

]a,c

Based on the results of Section 6.3, [

]a,c DENTFLO will calculate the leakage for the constrained crack as a function of the primary pressure and temperature and the back pressure between the tube and the tubesheet, resulting from the crevice pressure drop.

Crevice Flow Resistance
Similar to the crack leakage model, the crevice leakage model relates leakage flow through the crevice to the pressure drop between the crack outlet and the secondary side pressure. The governing equation is provided by Darcy's Law for laminar flow in porous media for tight crevices. The law is adapted to two phase flow by incorporating a two phase multiplier.

Solution of the Darcy equation requires knowledge of the WEXTEX crevice flow resistance. The loss coefficient needed to characterize the crevice flow resistance was developed from the results of the tests of simulated WEXTEX tube-to-tubesheet joints reported in Section 6.2. The results were summarized in Tables 6.2-2 and 6.2-3. The leakage model was used in conjunction with the test data for leakage rate and test conditions to determine the loss coefficient. Figure 6.4-2 shows [

]a,c

To apply the DENTFLO Code to the WEXTEX field analysis requires input of the [

]a,c

Calculation for WEXTEX Tubes

With crack effective length and crevice average loss coefficient known as a function of crack depth at different tubesheet radial positions, crack leakage can be calculated. DENTFLO was used in a parametric study to calculate leakage under faulted conditions as a function of crack distance below the bottom of the WEXTEX transition for five tubesheet radial zones, as defined in Table 6.4-1. For each region, the minimum contact pressure at each depth (Table 4.3-11) was used and, therefore, the calculation yields maximum leakage for the tubes in each zone. The results of this parametric study are given in Figure 6.4-3. W* leakage zones are shown in Figure 8.2-1.

6.4.3 Sample Leak Rate Calculation

To demonstrate the application of the leak rate model, total leak rate was calculated for a set of 75 cracks. These cracks are typical of a set which might be found in a steam generator, based on the database described in Section 7. The 75 cracks assumed are listed in Table 6.4-2 with their assumed indicated depths and tubesheet radial zones. It can be seen from this table that two thirds of the cracks are within one inch of the BWT.

The leak rate model was used to calculate the leak rate from each of the 75 cracks for two cases. For each case, a total leak rate was obtained. The first case calculated represents the leakage assessment at the end of a completed cycle and is defined as "condition monitoring." Before this calculation, the indicated depth of each crack tip, which appears in Table 6.4-2, is reduced by the NDE uncertainty of [ ]a,c, developed in Section 7. Figure 6.4-4 shows the cumulative leak rate, starting from the deepest cracks. The bulk of the [

]a,c

The second case of total leak rate calculated is described as an "operational assessment." This case projects the leakage to the end of the upcoming cycle and, in addition to accounting for NDE uncertainty, accounts for crack growth. Crack growth (Section 7) is calculated to be [ ]a,c in per EFPY. An 18 month fuel cycle is assumed and the crack tip depths from table 6.4-2 are reduced by a total of [

]a,c. Also for this case, tubes which either have or are projected to have, at the end of the cycle, a crack tip above the BWT, are assumed to be plugged. Applying the above depth adjustments to Table 6.4-2, about one half of the tubes are required to be plugged. Since these are the tubes closest to the BWT they have the largest leak rates. Deleting these tubes, even with the growth of the remaining tubes to shallower depths during the cycle, causes the total leak rate to be reduced to [ ]a,c

6.4.4 SLB Leakage below W*

It is desirable to limit the inspection and characterization of cracks to the region between the top of the tubesheet and the W* distance. Inspection for cracks below the W* region is not necessary if it can be shown that any leakage from cracks left in service is negligible, or if a reasonable accounting for potential leakage from this region is made.

The SLB leak rate for cracks at the W* depth is reduced by factors of [ ]^{a,c} depending on the tubesheet zone. Further, based on the database described in section 7, the number of cracks in evidence decreases at 2-3 inches below the BWT (Figure 7.1-3b). The combination of these factors provides that [

]^{a,c}

6.5 LEAK RATE MODEL STATISTICAL EVALUATION

In order to assess the conservatism of the deterministic model in estimating the total leak rate from the W* tube indications, a computer code was written to calculate a 95% confidence bound on the total leak rate based on Monte Carlo simulations of the leak rate from the individual indications. The simulation methodology is in accord with the USNRC's Generic Letter 95-05, Reference 9.12, and, in general, conforms to the methods presented in Reference 9.13.

6.5.1 Overview of the Calculation of the Leak Rate

The calculation of the total leak rate from indications in tubes in the W* region is performed similar to that from ODSCC indications at the elevations of the TSPs. For W*, there are [

]^{a,c} Additional input data are unchanged for the Monte Carlo simulations. The main program in DENTFLO was converted to a subroutine of the code WEXTLEAK for the Monte Carlo analyses. Otherwise it is unchanged from the version used for the deterministic calculations.

An overview of the simulation steps is provided in the following list:

1) *The contact stress, σ_i, as a function of elevation into the tubesheet, x, with the origin* at the top of the tubesheet (TTS) with downward reckoned as positive, is given by,

$$\sigma_c = a_0 + a_1 x, \tag{6.5-1}$$

where the a's are a function of tubesheet radius. For the leak rate evaluations, a discrete number of radii are considered to approximate the parameters instead of determining them as continuous functions. Because the coefficients, a's, are obtained from a structural analysis, they are not stochastic variables and Monte Carlo variation of these coefficients is not to be performed. Typical values of the contact pressure as a function of the depth below the BWT/TTS are illustrated on Figure 6.5-1. Also illustrated are regression curves from a linear regression analysis of the calculated contact pressure values on the depths for contact pressures greater than or equal to zero. [

]a,c

2) The local fluid loss coefficient, K, as a function of contact pressure or stress, σ_c, is given by,

$$K = 10^{b_1 + b_2 \sigma_c}, \tag{6.5-2}$$

where the b's are stochastic variables obtained from the regression analysis of the logarithm of K on the contact stress. The results of the regression analysis are summarized in Table 6.5-1. The p-value for the slope coefficient is [ ]a,c which is well below the value of 0.05 required by Generic Letter 95-05. The data values of the local loss coefficient as a function of contact pressure are illustrated on Figure 6.5-2. Also illustrated is the regression curve for the common logarithm of the loss coefficient and a lower 95% confidence bound for the median (the average of the logarithm of the loss coefficient) and average local loss coefficients as a function of the contact pressure. A scatter plot of the residuals versus the predicted values of the logarithm of the loss coefficient is illustrated on Figure 6.5-3. Inspection of the figure indicates that the residuals are not correlated to the predicted values. In addition, the intercept, slope and index of determination from a linear regression of the residuals on the predicted values were all found to be zero. A plot of standardized normal deviates against the ordered residuals is illustrated on Figure 6.5-4. The plotted data do not contradict the assumption of normality of the residuals. The extreme values of the residuals are less than expected, indicating a lack of outliers in the data. The examination of the residuals confirms the assumptions inherent in performing the regression analysis, which, when coupled with the small p-value obtained for the slope coefficient, justifies the use of the correlation in predicting loss coefficients from contact pressures.

3) The average or effective loss coefficient, K_i, for an indication is found by integrating the local loss coefficient over L_i, the distance from the BWT/TTS to the elevation of the top of the indication, i.e.,

$$K_i = \frac{1}{L_i} \int_0^{L_i} K(\sigma_c, R_i)\,dx. \tag{6.5-3}$$

where R_i is the radial location of the tube in the tubesheet. Since the contact pressure is zero over some length from the BWT/TTS, the loss coefficient is a constant over that length corresponding to the flow through a crevice with a zero contact pressure. The local loss coefficient as a function of distance below the top of the tubesheet is illustrated on Figure 6.5-5. The average loss coefficient corresponding directly to the regression curve is also shown. The loss coefficient has a constant value of [

]^{a,c} Below the elevation of zero contact pressure the loss coefficient is governed by Equation (6.5-2). These regions are illustrated on Figure 6.5-5 for tubes at a radius of 2.3" from the center of the SG.

4) The effective free span length of each indication, L_i, is calculated as,

$$L_i = b_4 + b_5 \sigma_c, \tag{6.5-4}$$

where the b coefficients are obtained from a regression analysis. Hence, the b's are also stochastic variables and must be simulated. The results from the regression analysis are summarized in Table 6.5-2. The p-value for the slope coefficient is [ ]^{a,c} which is significantly less than the value of 0.05 required by Generic Letter 95-05. The database and the regression curve for the [

]^{a,c}

A scatter plot of the residuals versus the predicted values of the logarithm of the loss coefficient is illustrated on Figure 6.5-7. Inspection of the data illustrated indicates that the residuals are not correlated to the predicted values, although the presence of some outlying data, the extreme upper and lower values of the effective length, is indicated. In addition, the intercept, slope and index of determination from a linear regression of the residuals on the predicted values were all found to be zero. A plot of standardized normal deviates against the ordered residuals is illustrated on Figure 6.5-8. The plotted data support the assumption that the residuals are normally distributed about the regression line. The extreme values of the residuals are significantly greater than expected, indicating the presence of outlying data values. An investigation of the test program performance and specimens did not reveal any information indicating abnormal testing conditions associated with the potential outliers, hence, the data were retained in the database. The evaluation of the residuals confirms the assumptions inherent in performing the regression analysis, which, when coupled with the small p-value obtained for the slope coefficient, justifies the use of the correlation in predicting effective free-span crack lengths from the contact pressures corresponding to the elevations of the tops of the WEXTEX indications.

5) The average loss coefficient and the effective length are both input variables to the leak rate calculation computer code DENTFLO, and the leak rate calculated, i.e.,

$$Q_i = \text{DENTFLO}(K_i, L_i, \ldots). \qquad (6.5\text{-}5)$$

Here, DENTFLO is actually a subroutine to the computer code WEXTLEAK.

6.5.2 Monte Carlo Simulation Methods

The simulation of the regression equations was performed using methods essentially identical to those described in Reference 9.13. One simulation of all of the W* indications in a SG was performed to estimate the total W* leak rate for the SG. For each simulation of the SG, random values of the parameters of the correlating equations were calculated and used for the W* indications in the SG for that simulation. Thus, the first step was to [

]a,c

6.5.2.1 Simulation of the Loss Coefficient

From the BWT/TTS to a depth of 0.7", designated x_0, the local loss coefficient is a constant value of [

]a,c with the value at the zero contact elevation calculated as,

a,c

[ ] (6.5-6)

The logarithm of the local value thus found is considered to vary with the same standard deviation as the local values governed by the regression equation.

Below the elevation of zero contact pressure, a local value of the loss coefficient as a function of depth in the tubesheet is found as, a,c

[ ] (6.5-7)

where Z is a random deviate from the standardized normal distribution and β_3 is the simulated standard deviation of the population of residuals about the regression curve. For elevations within Regions 2 and 3 of Figure 6.5-5, the minimum loss coefficient is restricted to being greater than or equal to [

]^{a,c} Thus, no significant error is introduced by the numerical integration procedure. Furthermore, the estimated loss coefficient is lower than the actual loss coefficient, so the error is in the direction of additional margin relative to the leak rate calculation.

The numerical integration to obtain the effective loss coefficient, K_e, for a specific elevation of an indication, x, is based on discretizing the $K(x)$ relationship as,

$$K_e = \frac{K_{L0}\,x_0 + \sum K_{Lj}\,\Delta x_j}{x}, \tag{6.5-8}$$

where Δx_j is a uniform fraction of the distance from x_0 to x, and each K_{Lj} is calculated per Equation (6.5-7). Note that because of the stochastic behavior of each individual K_{Lj}, the numerical integration of the function is significantly easier than attempting an algebraic integration to quantify the distribution of the sum, especially since the loss coefficients are assumed to be lognormally distributed about the regression curve.

6.5.2.2 Simulation of the Effective Length

The effective length simulated for input to DENTFLO is a single value as opposed to the integrated value of the loss coefficient. Therefore, a random value of the effective length for one indication in the SG, L_i, was found from the estimated coefficients of equation (6.5-4) as,

$$L_i = \beta_4 + \beta_5\,\sigma_c + Z\,\beta_6, \tag{6.5-9}$$

where the β's are calculated for the SG, σ_c is found from equation (6.5-1), Z is a random variable from the standardized normal distribution, i.e., ~N(0,1), and β_6 is the simulated standard deviation of the population of the residuals about the regression curve.

6.5.3 Monte Carlo Simulation Results

For comparison with the deterministic estimation results, a distribution of seventy-five (75) indications was created with elevation distances below the BWT/TTS ranging from 0.01 to 3.5". A 95% confidence bound for the 95th percentile of the distribution of total leak rates from the test distribution was calculated to be [

]a,c The trend of estimated value decreasing with increasing number of simulations is similar to historical results from simulations of the total leak rate from ODSCC indications at TSPs.

The deterministic estimate of the total leak rate from the same indications was [

]a,c

a,c,e

[ ]

TABLE 6.2-2
WEXTEX EXPANSION JOINT LEAK RATE TEST RESULTS

SAMPLE NUMBER	TEMP., °F	DIFFERENTIAL PRESSURE, PSI	CREVICE LENGTH, IN.	TEST TIME MINUTES[3]	LEAK RATE, DROPS/MIN.

a,c

TABLE 6.2-2 (Cont'd)
WEXTEX EXPANSION JOINT LEAK RATE TEST RESULTS

SAMPLE NUMBER	TEMP., °F	DIFFERENTIAL PRESSURE, PSI	CREVICE LENGTH, IN.	TEST TIME MINUTES	LEAK RATE, DROPS/MIN.

a,c

TABLE 6.2-3
WEXTEX EXPANSION LEAK RATES, CREVICE LENGTHS AND AVERAGE CONTACT PRESSURE

Test Conditions

Sample Number	Temp. (°F)	Differential Pressure (psi)	Crevice Length (inch)	Average Contact Pressure (psi)	Leak Rate (Drops per min.)	Loss Coefficient In^{-4}

a,c

TABLE 6.2-3 (cont'd)
WEXTEX EXPANSION LEAK RATES, CREVICE LENGTHS AND AVERAGE CONTACT PRESSURE

Test Conditions

Sample Number	Temp. (°F)	Differential Pressure (psi)	Crevice Length (inch)	Average Contact Pressure (psi)	Leak Rate (Drops per min.)	Loss Coefficient In^{-4}

a,c

Table 6.3-2
Constrained Crack Leak Rate Test Series

Test Type	Temperature °F	Pressure Difference psi

a,c

[ ]

Table 6.3-3
Leak Rate Test Data - Constrained Crack Opening

Tube #	Free Span Leak Rate @ RT (gpm)	Collar A Leak Rate @ RT (gpm)	Collar A Diam'l Gap (mils)	Collar A Contact Pressure (psia)	Collar B Leak Rate @ RT (gpm)	Collar B Diam'l Gap (mils)	Collar B Contact Pressure (psi)

a,c

Table 6.3-3 (cont.)
Leak Rate Test Data - Constrained Crack Opening

Tube #	Free Span	------- Collar A	--------		------ Collar B	--------	
	Leak Rate @ RT (gpm)	Leak Rate @ RT (gpm)	Diam'l Gap (mils)	Contact Pressure (psia)	Leak Rate @ RT (gpm)	Diam'l Gap (mils)	Contact Pressure (psi)

a,c

Table 6.4-1

Tube Sheet Zones for Leak Rate Analysis

W* Leakage Zone (Note 2)	Radial Distance to Centerline of Innermost Tube in Zone (in.)	Radial Distance to Centerline of Outermost Tube in Zone (in.)
B1	2.28	<19.97
B2	>19.97	<28.82
B3	>28.82	<33.50
B4	>33.50	(Note 1)
A	>37.70	(Note 1)

<u>Note 1:</u>
Zone B4 is based on the boundary between expansion transition Zone 3 and 4, i.e., between the boundary between W* Zone B and Zone A as shown in Figure 4.5-1. Figure 8.2-1 illustrates the W* leakage zones.

<u>Note 2:</u>
Tube radial distance (R) from the centerline of the SG may also be calculated for a given Row and Column number from the following formula:

$R = (X^2 + Y^2)^{0.5}$,
where,
$X = (47.5 - \text{Column}) * 1.28125$
$Y = 2.1875 + (\text{Row} - 1) * 1.28125$

Table 6.4-2

Sample Set of WEXTEX Tubesheet Indications

Tube Number	Depth below BWT-in.	W* Zone	Tube Number	Depth below BWT-in.	W* Zone	Tube Number	Depth below BWT-in.	W* Zone
1	-3.53	A	26	-0.89	B4	51	-0.41	A
2	-2.47	B3	27	-0.84	B3	52	-0.41	B4
3	-2.31	B3	28	-0.81	B2	53	-0.4	B1
4	-2.19	A	29	-0.79	B2	54	-0.38	B3
5	-1.97	A	30	-0.78	A	55	-0.38	B3
6	-1.9	B4	31	-0.75	B3	56	-0.36	B3
7	-1.76	B4	32	-0.75	B1	57	-0.35	B3
8	-1.71	B1	33	-0.75	B4	58	-0.34	B2
9	-1.67	B2	34	-0.74	A	59	-0.34	B4
10	-1.67	B4	35	-0.74	B3	60	-0.32	B2
11	-1.49	B2	36	-0.69	B2	61	-0.28	A
12	-1.47	B1	37	-0.69	B4	62	-0.28	B3
13	-1.45	B4	38	-0.64	B4	63	-0.26	B3
14	-1.4	B2	39	-0.61	B2	64	-0.25	B1
15	-1.39	B4	40	-0.58	B1	65	-0.24	B3
16	-1.27	B3	41	-0.56	A	66	-0.24	B3
17	-1.23	B2	42	-0.55	B3	67	-0.24	B3
18	-1.22	B3	43	-0.53	B4	68	-0.15	B3
19	-1.17	A	44	-0.5	B4	69	-0.14	B2
20	-1.14	B3	45	-0.47	B2	70	-0.13	B1
21	-1.12	B2	46	-0.47	B2	71	-0.11	A
22	-1.08	B4	47	-0.47	B2	72	-0.08	A
23	-0.99	A	48	-0.46	A	73	-0.02	B4
24	-0.99	A	49	-0.45	A	74	0	B1
25	-0.92	B2	50	-0.43	A	75	0	B1

Table 6.5-1: Regression Analysis Results, Log(Loss Coefficient) on Contact Pressure

$$K = 10^{b_1 + b_2 \sigma_c}$$

Parameter	Value

a,c

Table 6.5-2: Regression Analysis Results, Effective Length on Contact Pressure

$$L_t = b_4 + b_5 \sigma_c$$

Parameter	Value

a,c

a,c,e

Figure 6.2-1 As-Fabricated WEXTEX Sample for Leak Testing

a,c,e

Figure 6.2-2 Configuration of WEXTEX Leak Rate Samples

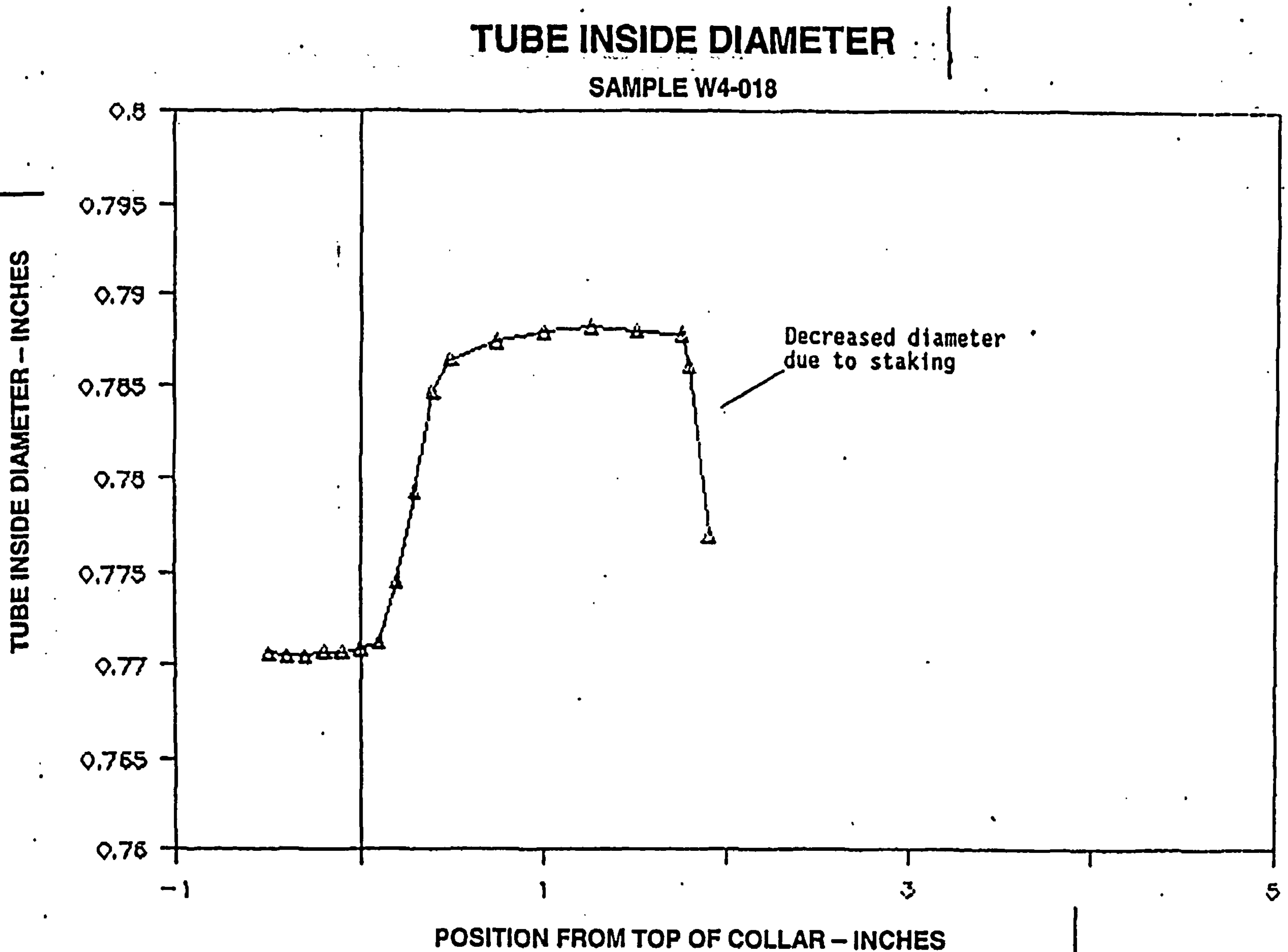


Figure 6.2-3. Inside Diameter of Leak Rate Sample W4-018

a,c

Figure 6.3-1 Constrained Crack Leak Rate Test Arrangement

a,c

Figure 6.3-2 Tube Specimens Utilized in Constrained Crack Leak Rate Tests

Figure 6.3-3
WEXTEX Leak Rate Test Crack Length Measurements

a,c

a,c

Figure 6.3-4 Type 410 Stainless Steel Collar Utilized in Constrained Crack Leak Rate Tests

a,c,e

[ ]

Figure 6.3-5 Measured Free Span Leak Rate vs. CRACKFLO Predictions

a,c,e

Figure 6.3-6 Measured Collar B ("Closed Gap") Leak Rate vs. CRACKFLO Predictions

a,c,e

Figure 6.3-7 Measured Collar A ("Tight Gap") Leak Rate vs. CRACKFLO Predictions

a,c,e

Figure 6.3-8 Effective Crack Length vs. Contact Pressure

a,c,e

Figure 6.4-1 Effective Crack Length Versus Tube-to-Tubesheet Contact Pressure

a,c,e

Figure 6.4-2 Crevice Local Loss Coefficient Versus Tube-to-Tubesheet Contact Pressure

a,c,e

[ ]

Figure 6.4-3 WEXTEX Crack - Crevice Leak Rates, Hot Leg, Faulted Conditions.

a,c,e

[ ]

Figure 6.4-4 Cumulative Leak Rate vs Depth below BWT for 75 Crack Set

Figure 6.5-1: Contact Pressure vs. Depth into Tubesheet

WEXTEX Expanded Tubes

a,c,e

Contact Pressure (psi)

Depth Below BWT/TTS

(Lr_monte.xls) CP.Plot

RF?: 1/25/97, 12:54 PM

Figure 6.5-2: Local Loss Coefficient vs. Contact Pressure

WEXTEX Expanded Tubes, Mean Correlations

a,c

Local Loss Coefficient (in-4)

Contact Pressure (psi)

d:\apc\wextex\KvsCP.xls [KvsCP.Plot]

RFK: 1/25/97, 12:31 PM

Figure 6.5-3: Residual vs. Predicted Log(Loss Coefficient)

Residuals Analysis Scatter Plot

a,c

Residual Logarithm of the Loss Coefficient

Predicted Logarithm of the Loss Coefficient, Log(K)

d:\apc\wextex\KvsCP.xls [Res.Scat]

RFK: 1/25/97, 12:31 PM

Figure 6.5-4: Normal Deviate vs. Residual Log(Loss Coefficient)

Residuals Analysis Normal Plot

a,c

Standardized Normal Distribution Deviate

Ordered Residual Log(Loss Coefficient)

[illegible] [Res Norm]

RFK: 1/25/97, 12:51 PM

Figure 6.5-5: Local Loss Coefficient vs. Depth Below BWT/TTS

WEXTEX Expanded Tubes, Mean Correlations

a,c

Local Loss Coefficient (in^{-4})

Distance Below BWT/TTS (in.)

Figure 6.5-6: Effective Crack Length vs. Contact Pressure

a,c

Effective Length (in)

Contact Pressure (psi)

d:\endwavtex\LvsCP via Leff.Plot

RFK: 1/25/97, 12:46 PM

Figure 6.5-7: Residual vs. Predicted Effective Crack Length

Residuals Analysis Scatter Plot

a,c

Residual Effective Crack Length (in.)

Predicted Effective Crack Length (in.)

Figure 6.5-8: Normal Deviate vs Residual Effective Crack Length

Residuals Analysis Normal Plot

a,c

Standardize Normal Distribution Deviate

Ordered Residual Effective Crack Length (in.)

7.0 WEXTEX PLANT INSPECTION RESULTS

Of the units with Series 51 steam generators and WEXTEX expansions in this study, the earliest began operation in 1976 and the latest began operation in 1985. The total operating periods (as of their most recent inspection), for these units range from 7.4 to 11.4 EFPY.

7.1 INDICATION DISTRIBUTION AND MORPHOLOGY

7.1.1 Indication Database and Summary

A database of WEXTEX tubesheet indications was assembled from Westinghouse and non-Westinghouse inspections of WEXTEX plants. The data were similar with respect to reporting of indication types, and included both RPC and PlusPoint examinations. The data were mostly from the two most recent inspections of the units in the study, but included some earlier results. The database totaled 511 hot leg tubesheet indications, including expansion transition indications plus those within the tubesheet. 382 of these indications were located below the top of the tubesheet. The data included some indication elevations reported with respect to the top of the tubesheet (TTS), and others reported with respect to the BWT.

Table 7.1-1 provides a summary of the 382 indications below the top of the tubesheet. The elevations of eighteen of these indications were located with respect to the BWT, and 364 were located with respect to the TTS. Of the 364 indications measured from the TTS, 227 (64%) were single axial, 4 (1%) were multiple axial, 2 (0.5%) were volumetric, and the remaining 131 (34%) were circumferential. Of the 18 indications measured from the BWT, all were single axial indications. The W* criteria address the portion of single and spaced multiple axial cracks which are positioned below the bottom of the WEXTEX transition (BWT), and exclude volumetric and circumferential indications. A further description of indication types and location follows.

7.1.2 WEXTEX Indication Tube Locations

Figure 7.1.2-1 shows the locations of single axial indications (SAIs) and multiple axial indications (MAIs) from the database that may be expected to be addressed by the W* criteria. Since the indication elevations were determined with respect to the top of the tubesheet rather than the BWT, it was decided to include only indications with the highest likelihood of applicability to W* criteria. Therefore, included in the figure, and referring to Table 7.1-1, are the 180 SAIs that are more than 0.40" below the top of the tubesheet, the 13 indications more than 0.40" below the BWT, plus two MAIs also located 0.40" or more from the top of the tubesheet. The tubesheet map shows that the indications are distributed relatively evenly, with a slight bias toward the center of the tubesheet. Of the 195 indications, 44 (23%) are in W* Zone A, and 151 (77%) are in W* Zone B.

Circumferential and volumetric indications in the expansion transition region are not addressed by the W* criteria, and unless other alternate repair criteria are applied, these would be required to be repaired. Circumferential and volumetric indications within the W* length are also not permitted under W* criteria, however, circumferential (or any) indications below the W* length are permitted per the W* criteria. Figure 7.1.2-2 shows the four circumferential (3 SCI and one MCI), one volumetric (SVI) and two closely spaced MAIs below the BWT reported in the WEXTEX expansion indication database. These indications were all within the expected W* length. Such indications are less frequent and less consistent with typical corrosion morphologies below the BWT, and are reviewed in sections 7.1.4 through 7.1.6.

7.1.3 Indication Elevation and Length Distributions

The indications elevations with respect to the top of tubesheet and BWT were developed for both circumferential and axial indications.

Figure 7.1.3-1a illustrates that most of the 131 circumferential indications are located within the first 0.2" from the top of the tubesheet. Because the WEXTEX process employs a single explosive expansion step (as compared to a step roller) the number of circumferential indications away from the expansion transition is expected to be small, as was generally observed.

Figure 7.1.3-1b shows the axial crack elevation distribution for indications below the TTS or BWT. A significant number of the indications are located near the expansion transition. The number of indications decreases significantly to about 0.8 inch depth, increases at 1.0 inch depth, and then falls to a plateau at about 2.4 inch depth.

7.1.4 Volumetric Indications

Of the 382 indications below the top of the tubesheet in Table 7.1-1, two were volumetric, including one at the transition and one within the tubesheet. Volumetric degradation in this region is generally considered to be inconsistent with PWSCC.

Figure 7.1.4-1 shows a volumetric indication at Plant Z2 R28C41 from a January 1996 inspection. The indication is located 2.1 inch below the top of the tubesheet, and was detected by both the PlusPoint axial and circumferentially-oriented probes. The graphics from PlusPoint examination appears to be exaggerated in the circumferential direction because of lead-in and lead-out effects. This indication is quite short in length, and includes only 5 to 6 axial scan lines. The indicated circumferential extent is 0.20 inch, or 27 degrees.

7.1.5 Circumferential Indications

Figure 7.1.5-1 shows a circumferential indication (SCI) reported at 1.47" below the top of the tubesheet at Plant Y1 tube R18C52. This scan was performed with the PlusPoint probe with the circumferentially-oriented coil (Channel 2). The circumferentially oriented coil provided a response as indicated in the Lissajous window in the upper left corner of the figure. The indication is small in extent, and is reported as 49.9° in circumference, and 2.19 volts peak.

Because of the circumferential content of this indication, W* criteria would not apply, and the tube would be plugged.

Figure 7.1.5-2 shows a circumferential indication (SCI) at Plant Y2 R30C56 from the 2R7 inspection in April 1996. This indication is located 0.69 inch below the top of the tubesheet. The indication is 34° in circumferential extent.

7.1.6 Multiple Axial Indications

A total of four multiple axial indications were found at depths greater than 0.39 inch below the top of the tubesheet. As shown in Table 7.1-1, for two of these indications, an RPC null point was found between the axial indications. These are illustrated in Figures 7.1.6-1 and 7.1.6-2, and the two indications which do not reach a null point are in Figures 7.1.6-3 and -4.

The Plant Z2 R5C51 MAI in Figure 7.1.6-1 is located 1.95" below the top of the tubesheet. This PlusPoint examination shows two clearly separated axial cracks, a larger one at about the 10° position, and a smaller one at about the 160° position. The circumferential aspect of the indication is exaggerated by PlusPoint.

Figure 7.1.6-2 is a Plant Z2 R12C69 indication from November 1994 inspection. This MAI, located 0.79 inch below the top of the tubesheet, includes two axial cracks which the RPC probe shows to be clearly separated; each scan line reaches a null position between the two axial indications.

Figure 7.1.6-3 is also a Plant Z2 tube, R20C43 from the March 1993 inspection. This RPC scan shows two closely spaced axial cracks, with an indefinite null condition between the indications. This indication would not be acceptable in the W* criteria.

Figure 7.1.6-4 shows Plant Z2 tube R20C58 from the March 1993 inspection. This MAI has appearances more consistent with a dent than a crack-like indication. The indication exhibits three closely spaced, parallel, axial ripples which occur over about an 80° circumferential extent.

7.1.7 Inclined Indications

The W* criteria limit the crack morphology to that of single and distinctly separate multiple axial cracks, as further defined in Section 5.0 and as defined in Section 8.7.

Approximately 319 C-scans of WEXTEX region indications from available data were reviewed to determine the orientation of the single axial and multiple axial cracks. Although a full determination of crack angles was not possible from the C-scans, nineteen of those reviewed were observed to be slanted from the vertical direction. The orientation of the cracks was most easily observed in contour plots developed from the C-scans.

Figures 7.1.7-1a and 7.1.7-1b present a slanted, slightly curved SAI in R4C18 from the March 1993 inspection at Plant Y2, SG-23. The relatively long, straight segment in the center of the indication is inclined at about a 28° angle from vertical. A small indication is noted near the tip of the larger section. The uppermost tip of the crack was reported as 2.08" below the top of the tubesheet, and the BWT was 0.14" below the TTS.

Figures 7.1.7-2a and 7.1.7-2b indicate a short SAI in R6C37 from also from the March 1993 inspection at Plant Y2, SG-24. The straight segment in the center of the indication is inclined at about a 22° angle from vertical. The tip of the crack was reported as 1.18" below the top of the tubesheet. The BWT was not determined.

7.1.8 Location of the Bottom of the WEXTEX Transition

Figure 7.1.8-1 illustrates the location of the bottom of the WEXTEX transition with respect to the top of the tubesheet for one unit. The median location of the BWT in this unit is between 0.2 and 0.3 inches below the top of the tubesheet.

7.2 DETECTION OF RPC-CONFIRMED INDICATIONS BY BOBBIN

Bobbin detection of RPC SAIs was analyzed for Plant W2 over a three-cycle time period. A total of 25 RPC indications detected were reviewed to determine if bobbin inspection also found an indication. Of the 25 indications, 8 (or 32 percent of the total) were found by bobbin inspection. Figure 7.2-1 illustrates that some relationship exists between peak RPC voltage and bobbin detection, with the largest of the RPC voltages detected by the bobbin coil. 41% of the RPC SAIs (17 of 41) at Plant Y2 during 2R6, 2R5, and 1R6 were also detected by bobbin.

Bobbin detection was also determined for 36 PlusPoint SAIs below the BWT at Plant Y1 and Y2 during 1R7 and 2R7. Table 7.2-1 shows these results. The PlusPoint voltages for these indications range from 0.31 to 3.80 volts. Two of largest indications, 3.80 and 2.16 volts, were found by bobbin. These results support bobbin detection of the largest voltage indications.

The bobbin coil appears capable of detecting potential leakers for indications below the BWT although detection is limited for smaller indications. The data of Figure 7.2-1 and Table 7.2-1 support adequate bobbin detectability for indications above about 3 volts by RPC. In situ testing of PWSCC axial indications in roll transitions for 29 indications up to 3.3 volts and 3 additional indications between 6.9 and 11 volts resulted in no leakage at SLB indications. Thus, it is expected that indications would have to exceed about 3.5 or larger volts to have a significant probability of leakage at SLB conditions and bobbin detectability should be adequate to detect significant leakers. The leakage calculations for W* are particularly conservative in assuming that all RPC indications are throughwall and contribute to SLB leakage.

Although bobbin detectability appears to be adequate for detection of indications that would leak at SLB conditions, the SLB leakage calculation is based on only the fraction of tubes inspected by an RPC or equivalent coil.

7.3 NDE UNCERTAINTIES

7.3.1 NDE Uncertainty Test Approach

Application of alternate repair criteria for axial cracks requires that provision be made in the engineering evaluations for uncertainties inherent in the measurement of NDE parameters. For W* these parameters include the elevation of the BWT (bottom of the WEXTEX transition), the distance between the BWT and the uppermost crack tip (CT), the crack(s) length, the W* length, the angle of inclination of axial cracks from the tube axis, and the resolving power of the eddy current coils used. A test program was performed to meet these requirements. A summary of the NDE uncertainties determined in the test program is provided in Table 7.3-1, and a description of the test program follows.

7.3.2 Sample Configuration

To provide the "ground truth" for the determination of the uncertainties relevant to W* measurements, [

]a,c As shown in Table 7.3-1, the measurement uncertainties needed to support W* were obtained with bobbin coil and 115 mil pancake for location of the BWT; the 115 mil pancake, a mid-range PlusPoint, and an 80 mil pancake were used for the length measurements related to the properties of the flaws.

Single-tube samples NDE-01-1, NDE-01-2, and NDE-02-1 were [

]a,c

The position of the WEXTEX expansion was determined for each sample. This was performed by [

]a,c

7.3.3 Data Acquisition and Analysis

A channel head mockup of a Model 51 Steam Generator was adapted so each test sample could be positioned at the elevation of the primary side face of the tubesheet. The eddy current probes were delivered through a standard end effector attached to the arm of a ROSA robot. The probe pusher was mounted below the channel head manway at the elevation of a platform. The eddy current data was recorded on an optical disk using a TECRAD TC6700 eddy current tester and a HP 650A data recorder. Both were set up to use the ANSER software.

The samples were tested with bobbin coils and rotating probes equipped with 3 coils, a 0.115" pancake, a PlusPoint configuration, and a 0.080" pancake. Testing was performed at [

]a,c

[

]a,c The actual values for each sample and the NDE measurements for each sample are given in Table 7.3-4 and 7.3-5 for the single tube and 21-tube samples, respectively.

7.3.4 BWT-to-Crack Tip Uncertainty

To promote uniformity in the analysis of the eddy current data, the position of the crack tip was measured in the same fashion as was the location of the BWT; i.e., both were located relative to the top of the tubesheet. To determine the uncertainty of measurement of the uppermost crack tip relative to the BWT, the standard error of the difference between the standard deviations of the individual measurements (TTS-BWT, TTS-Crack Tip) was calculated. The expected error and its standard deviation were calculated by:

[ ]a,c

where,

[

]a,c

Taking the relevant results from Table 7.3-1, the uncertainties in Table 7.3-6 are obtained for the rotating coils used in this study; in this case the mean error on the crack tip relative to the TTS is subtracted from the mean error on locating the BWT relative to the TTS.

As used in tube integrity calculations, the applied error values are used to decrease the distance from the BWT to the uppermost crack tip below the BWT. The applied error value assures a one-sided 95% upper bound on the actual distance; it is the net sum of the average error plus 1.65 times the standard deviation.

The performance of the bobbin probe in locating the BWT [

]^{a,c}

7.3.5 Crack Length Measurement Uncertainties

[

]^{a,c} of the measurements for these notches were noticeably longer than the lengths obtained for identical length notches whose examinations were not perturbed by the interference between the tube ends and the motor unit.

The values recorded in Table 7.3-1 represent the [

]^{a,c}

It was observed that [

]^{a,c} which require inclusion of the length between the null points at the ends of the flaw signal. The measurement uncertainties to be applied to crack lengths, based on this work, are summarized in Table 7.3-7.

The applied error given in Table 7.3-7 for flaw length measurement represents a value that is subtracted from the observed flaw length. The applied error value assures a one-sided 95% upper bound on the actual crack length; it is the net sum of the average error plus 1.65 times the standard deviation. Since NDE consistently overestimates the actual crack length and the mean error exceeds 1.65 σ, the net NDE uncertainty on crack length is a negative correction.

7.3.6 W* Length Uncertainty

Each of the samples designated "NDE-0x-x" was fitted with a [ ]^{a,c} these were located approximately [ ]^{a,c} measurements obtained were used to derive a measurement uncertainty for W* for each of the 3 rotating coils used in this study. The values derived from these measurements are given in Table 7.3-8 and summarized in Table 7.3-1.

The measurement uncertainties derived are comparable to those obtained for flaw length measurements. Observed values should be increased by the value of the appropriate applied error value.

7.3.7 Flaw Inclination Angles

A subset of the machined notches used in this study were set at inclined angles relative to the longitudinal axis of the tubing; these flaws were used to assess the effectiveness of the analysis guidelines to yield reliable measures of the angle of inclination. The guidelines require measurement of the circumferential arc length subtended by the signal peaks on the first and the last circumferential scan lines which reflect the presence of the flaw. This arc length is converted from degrees to inches by multiplying by the tube circumference divided by 360°. The angle of inclination is obtained using the arctangent function of arc length divided by the corresponding vertical component (axial) of the flaw length. (The tube circumference, ID or OD, should be chosen to best represent the degradation being evaluated.) The ID circumference was used in this report.

$$\theta = \arctan(\text{arc length}^\circ * \text{tube circumference}/ 360^\circ / \text{axial length})$$

where,

θ = angle of inclination

The inclination angles for the machined flaws ranged from [ ]^{a,c} and were associated with flaws whose vertical length components ranged from [ ]^{a,c} are affected by the interference noted above for the flaw length measurements. The effect of overstating the length of the notch is to decrease the tangent of the inclination angle, which in turn yields a lower inclination angle. Calculation of the error in measuring the angles using only the [ ]^{a,c} notches gives the measurement uncertainties for the three rotating coils which are given in Table 7.3-9, along with the applied error values for tube integrity calculation. There is approximately [ ]^{a,c} difference in the result obtained when all the inclined notches are included.

The measured angles underestimate the true angles in all cases. The smallest error is obtained with the 80 mil high frequency pancake. As applied the observed angles should be corrected by the value of the applied error for tube integrity calculations.

Measurements made with the PlusPoint coil for flaws with angles of inclination approaching [

]a,c For the EDM notches used in this study the results obtained with the PlusPoint were comparable to those obtained with the 115 mil coil.

7.3.8 Rotating Coil Resolution

Sample [

]a,c

The C-scan displays for the 115 mil pancake (300 kHz), PlusPoint (300 kHz), and 80 mil pancake (300 kHz and 600 kHz) rotating coils are provided as Figures 7.3-1, -2, -ad, and -3b respectively. By examining the C-scans in the "valleys" between the signal amplitude peaks, return to null can be determined between the signals. [

]a,c

7.4 AXIAL CRACK GROWTH RATES

Axial crack growth rates were determined for three of the plants based on consecutive examinations of axial indications within the tubesheet. This included 19 SAIs and 1 MAI from Plant W2, 11 SAIs from Plant W1, and 8 SAIs combined from Plants Y1 and Y2. The average growth rates of the indications were adjusted for cycle lengths, and found to be similar for these outages. The Plant W1 and W2 indications were all developed from RPC examination, had an average length increase of 0.06 and 0.12 inch per EFPY, respectively. The Plant Y data included axial crack length changes determined from comparison of 80-mil pancake to PlusPoint lengths, 3-coil circumferential element to PlusPoint lengths, and pancake to pancake lengths; these data averaged 0.10 inch length change. Figure 7.4-1 shows the axial crack length growth cumulative probability distribution. The distribution is reasonably linear in the range between minus 0.05 inch and 0.35 inch. The growth rate per EFPY at 95% cumulative probability is 0.25", based on the combined data.

Table 7.1-1
Summary of Database of WEXTEX Indications Below TTS

	SAI	MAI		SVI	Circ. (SCI or MCI)
	Single Axial Indication	RPC Null Point Reached Between Cracks	RPC Null Point Not Reached Between Cracks or Indeterminate*	Single Volumetric Indication*	Single or Multiple Circumferential Indication*
Elevation (Depth) Measured Relative to TTS					
<-0.4"	180	2	2	1	4
-0.4" to <-0.2"	24	0	0	0	23
-0.2" to <-0.1"	9	0	0	0	52
-0.1" to < 0.0"	14	0	0	1	52
Subtotals	227	2	2	2	131
		Total Indications Below TTS Measured Relative to TTS:			364
Elevation (Depth) Measured Relative to BWT**					
<-0.4"	13	0	0	0	0
-0.4" to <-0.2"	3	0	0	0	0
-0.2" to <-0.1"	1	0	0	0	0
-0.1" to < 0.0"	1	0	0	0	0
Totals	18	0	0	0	0
		Total Indications Below TTS Measured Relative to BWT:			18
		Total of All Indications below TTS:			382

* Criteria Not Applicable
** Circ. Cracks not included in BWT study

Table 7.2-1
Bobbin Detection of Plus Point SAIs

Plus Point Volts	Bobbin Detected?	Plus Point Volts	Bobbin Detected?	Plus Point Volts	Bobbin Detected?
0.31	No	0.64	No	2.16	Yes
0.36	No	0.71	No	3.80	Yes
0.36	No	0.81	No		
0.37	No	0.83	No		
0.40	No	1.06	No		
0.41	No	1.12	No		
0.42	No	1.24	No		
0.44	No	1.27	No		
0.44	No	1.35	No		
0.45	No	1.38	No		
0.47	No	1.46	No		
0.53	No	1.49	No		
0.54	No	1.74	No		
0.55	No	1.76	No		
0.57	No	1.98	No		
0.58	No	2.04	No		
0.61	No	2.61	No		

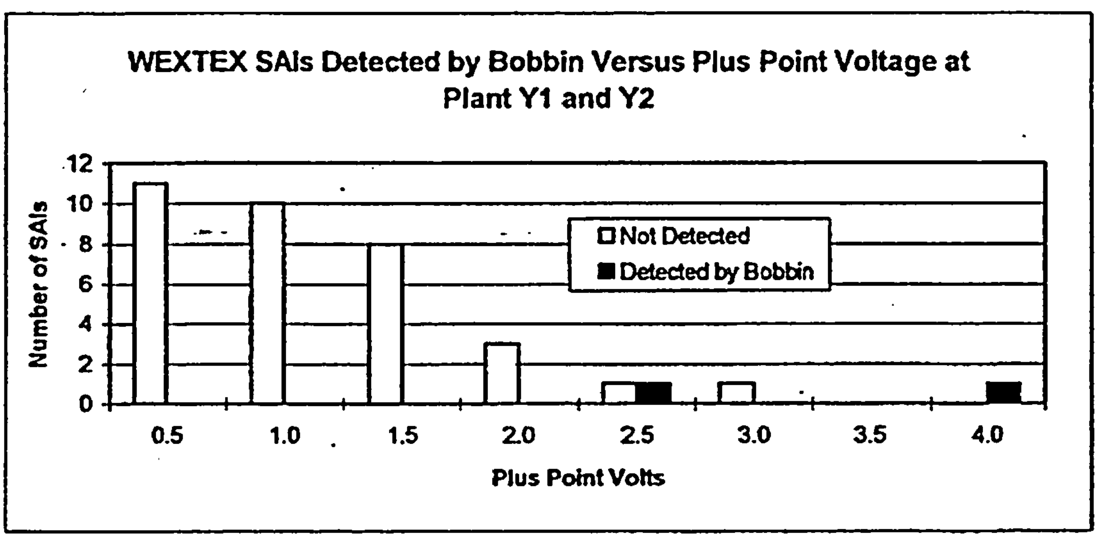


Table 7.3-1
W* Alternate Repair Criteria NDE Uncertainties
(Units in inches)

a,c

Measurement	Uncertainty (Actual - NDE)			
	0.115" Pancake	PlusPoint	0.080" Pancake	Bobbin

Table 7.3-2 Single Tube NDE Test Sample Identification							
			Flaw Description				
Single Tube Mockup Identification	Top of Tube to TTS (Inch)	Top of Tube to BWT (Inch)	Notch Identifier	Elevation (Inch)	Orientation (Degrees)	Length (inches)	Comment

a,c

Table 7.3-3 21-Tube Test Sample Identification							
21 Tube Mockup Identification	TTS (Elevation)	BWT (Elevation)	Flaw Description				
			Notch I.D.	Elevation*	Orientation (Degrees)	Length (inches)	Comment

a,c

Table 7.3-4 W* NDE Data for Single Tube Samples

a,c

Table 7.3-5 W* NDE Data for 21-Tube Mockup

a,c

Table 7.3-6
W* Measurement Uncertainties for Rotating Coils
for Distance from BWT to Uppermost Crack Tip
(All values in inches)

Rotating Coil	Measurement Error	Applied Error

a,c

Table 7.3-7
W* Flaw Length Measurement Uncertainties
(All Values in Inches)

Rotating Coil	Measurement Uncertainty	Applied Error

a,c

Table 7.3-8
W* Length Measurements
(Top of Tubesheet to Circumferential EDM Notch; All Values in Inches)

Rotating Coil	Measurement Uncertainty	Applied Error

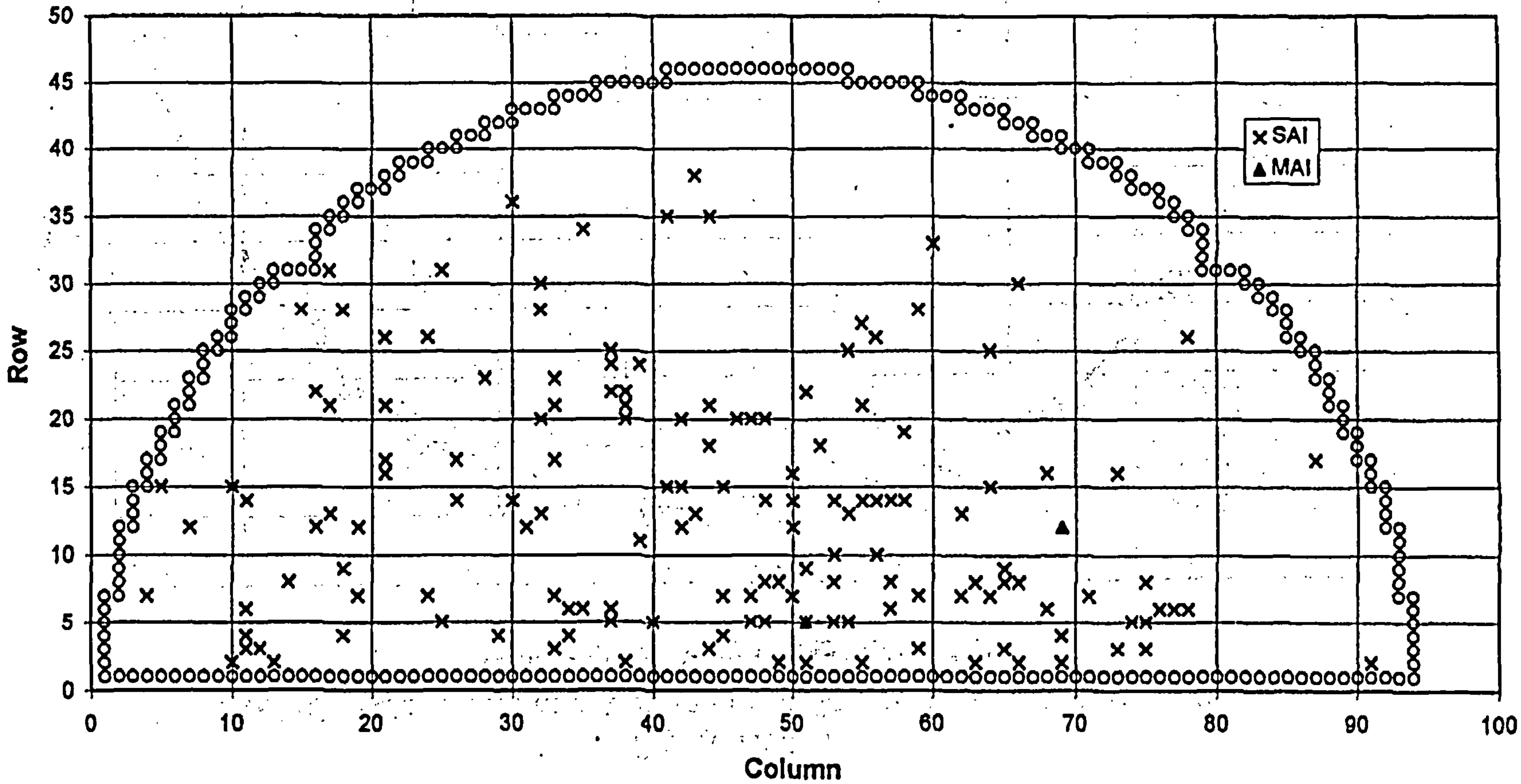
a,c

Table 7.3-9
W* Inclination Angle Measurement Uncertainties
(All Values in Degrees)

Rotating Coil	Uncertainty	Applied Error

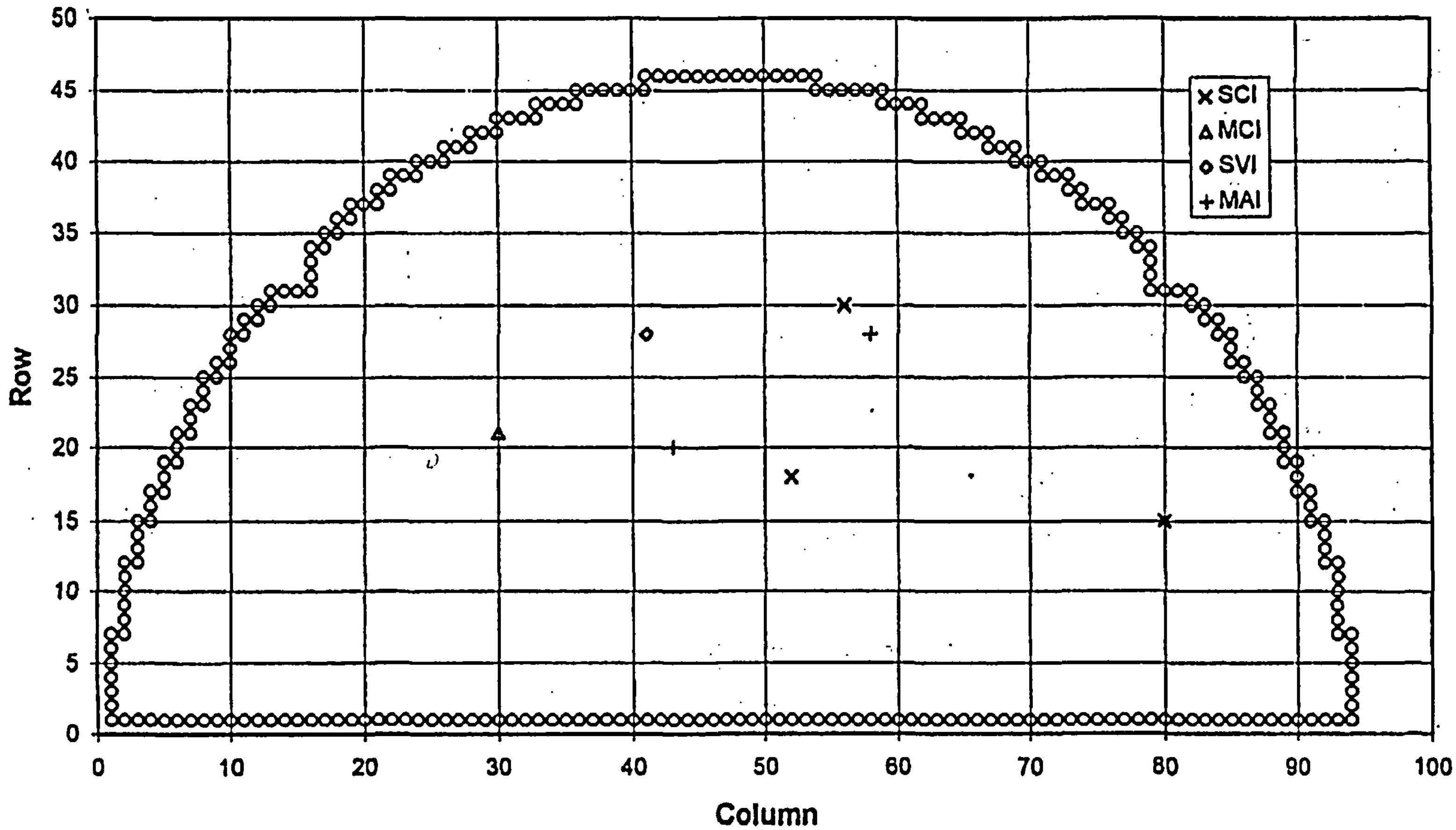
a,c

Figure 7.1.2-1
WEXTEX Single and Spaced Multiple Axial Indications Below TTS



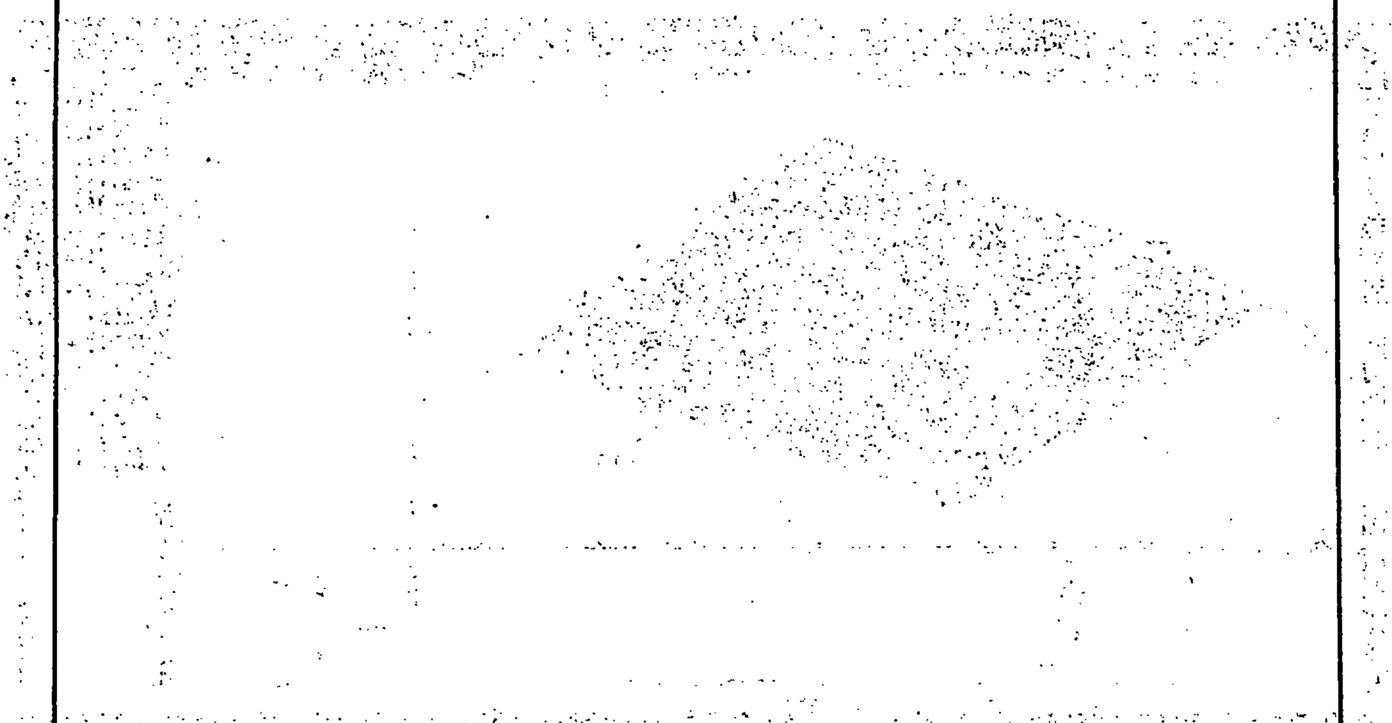
Q:\wextex\report\WEXTEX4.XLS:SAI_MAI Map (Outline)

Figure 7.1.2-2
WEXTEX Circumferential, Volumetric Indications, and Closely Spaced Multiple Axial Indications Below TTS



Q:\wextex\report\WEXTEX4.XLS:COI_SCI_MCI_Map (Outline)

a,c



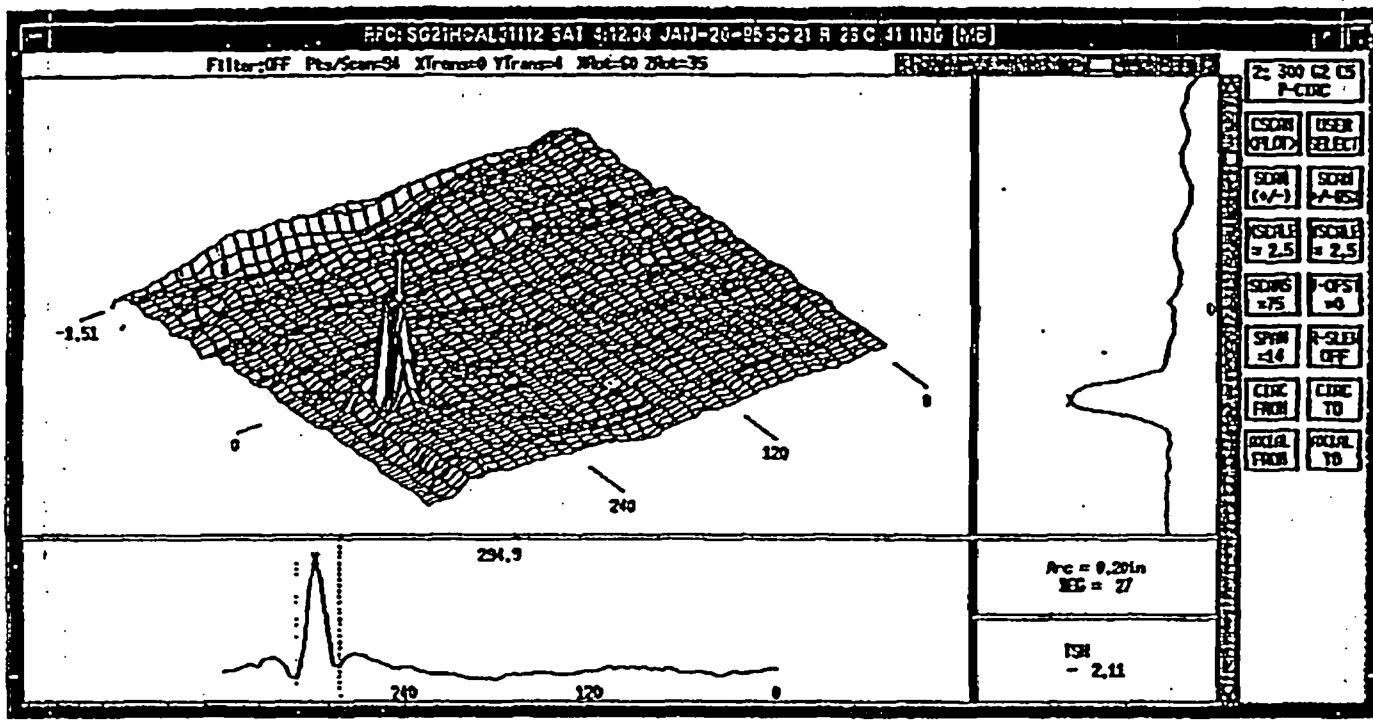


Figure 7.1.4-1
WEXTEX Volumetric Indication (SVI) from Plant Z2 R28C4

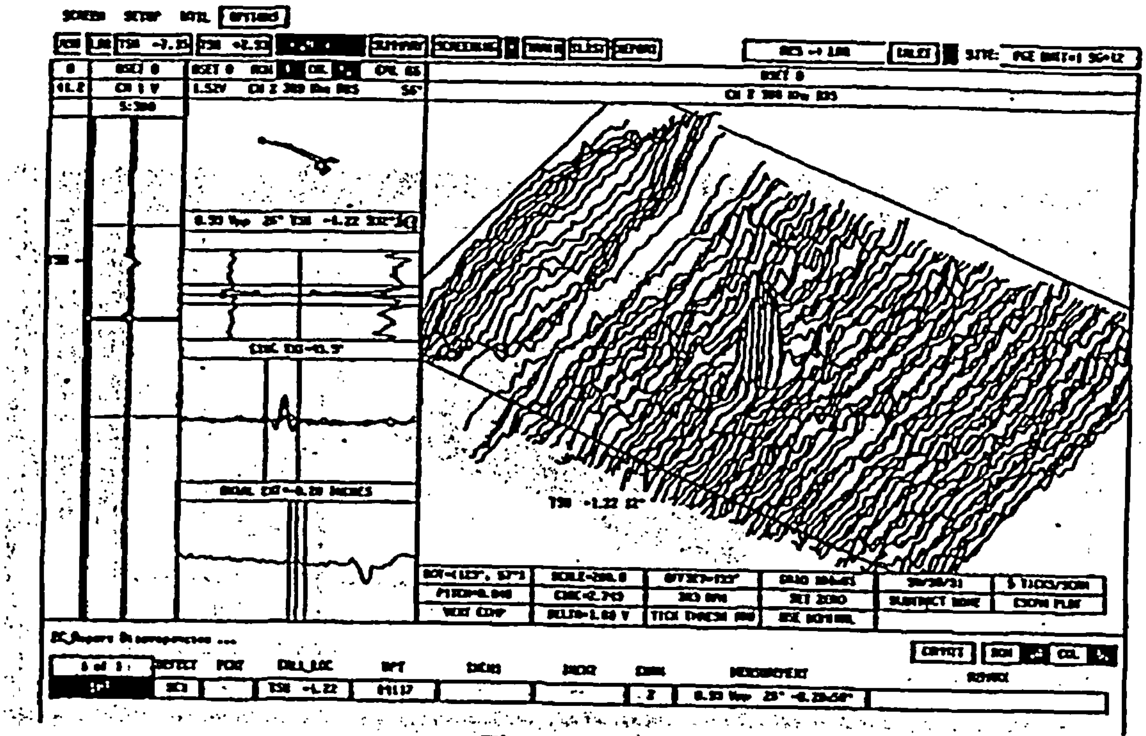


Figure 7.1.5-1
WEXTEX SCI at Plant Y1 Tube R18C52

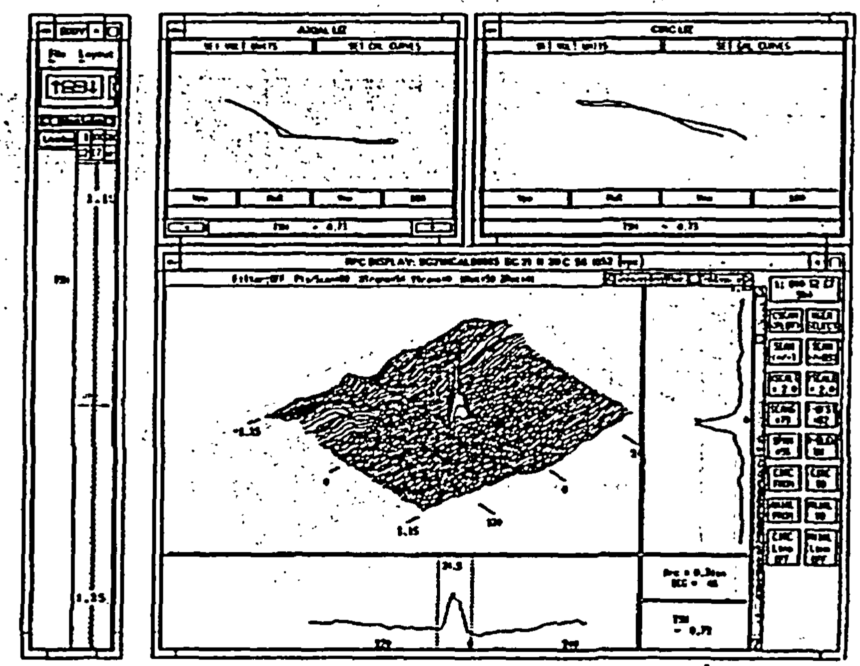


Figure 7.1.5-2
WEXTEX SCI at Plant Y2 R30C56

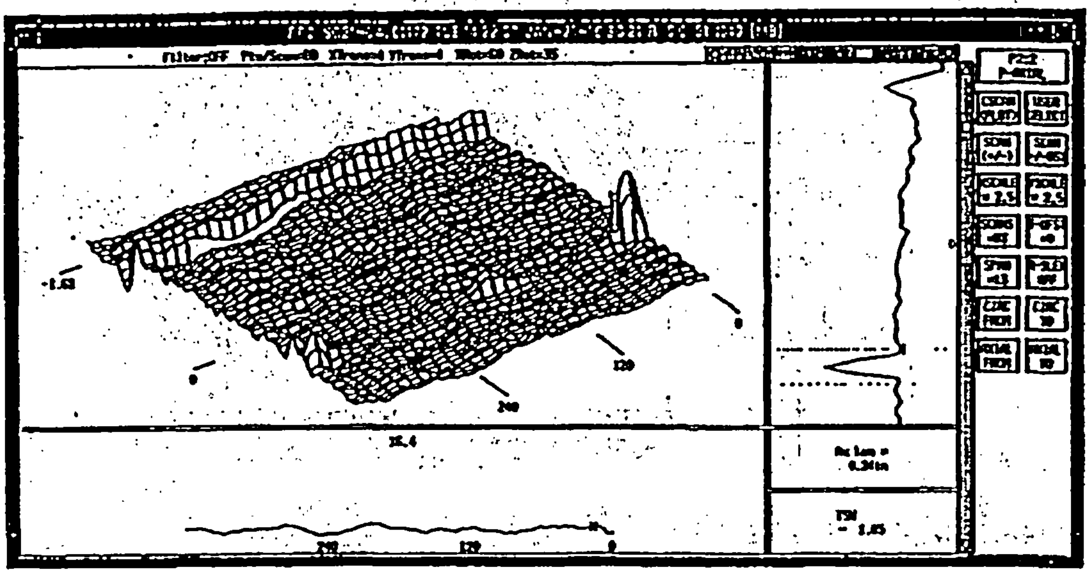


Figure 7.1.6-1
WEXTEX MAI at Plant Z2 R5C51

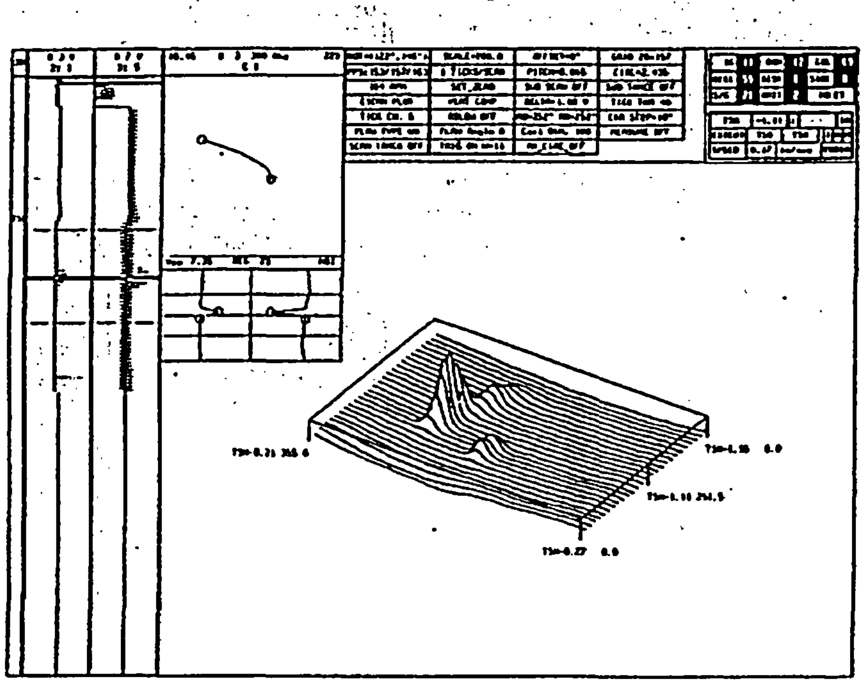


Figure 7.1.6-2
WEXTEX MAI at Plant Z2 R12C69

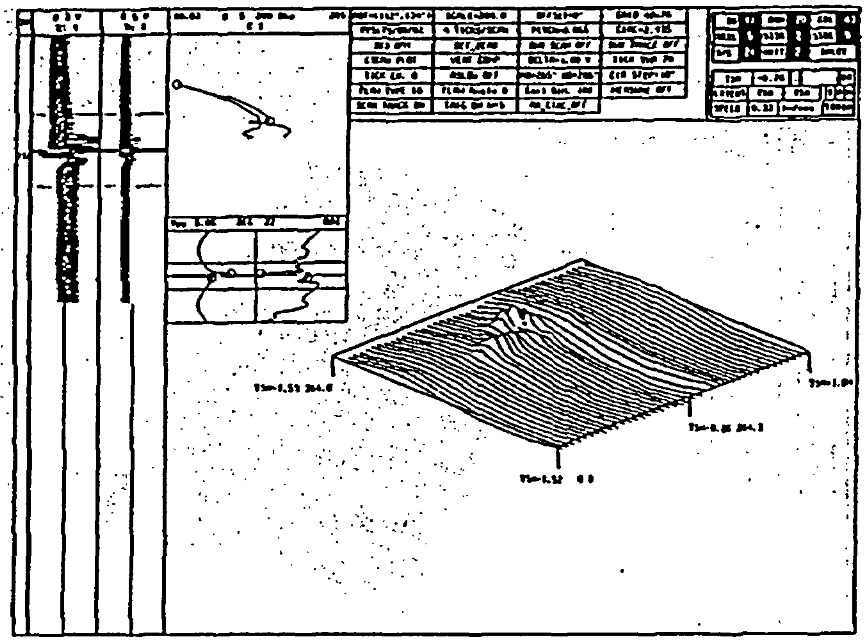


Figure 7.1.6-3
WEXTEX MAI at Plant Z2 R20C43

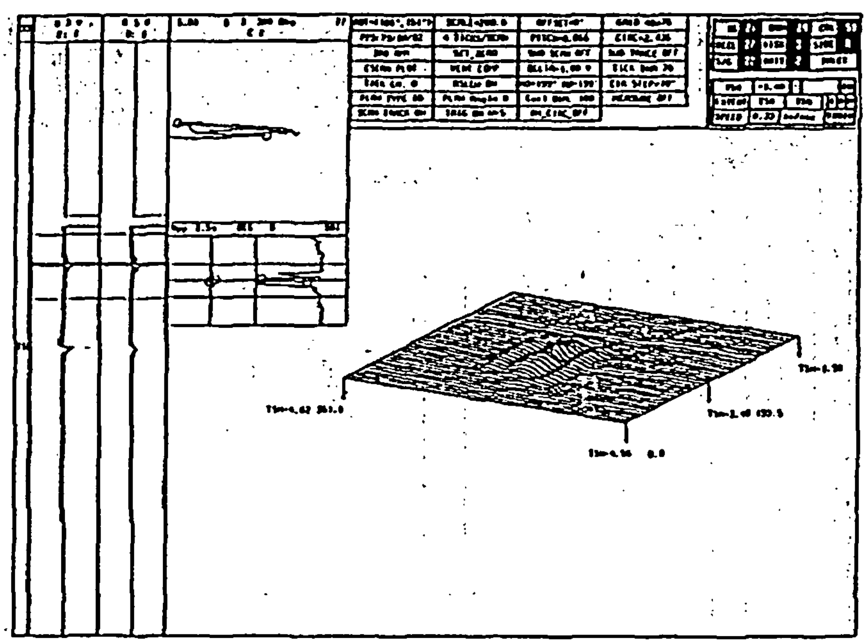


Figure 7.1.6-4
WEXTEX MAI at Plant Z2 R20C58

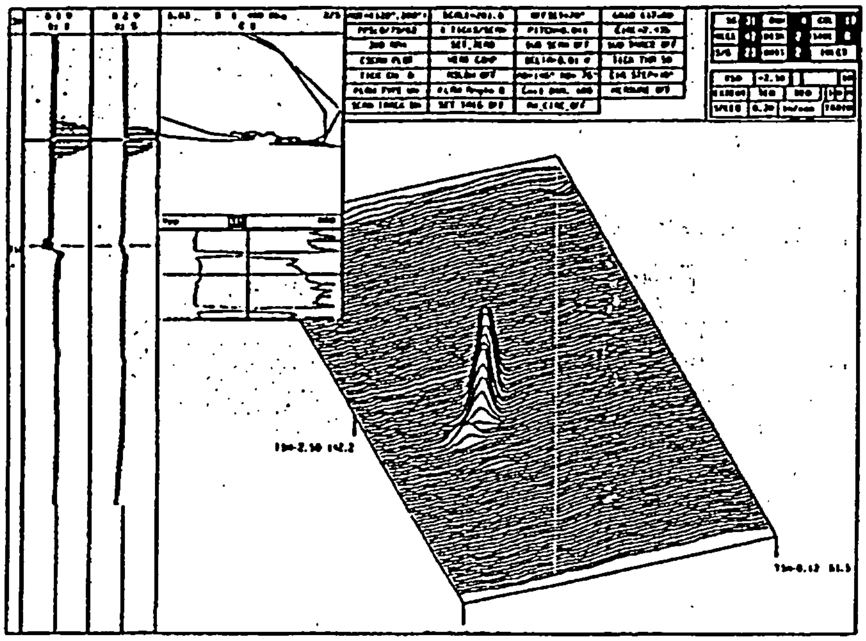


Figure 7.1.7-1a
Slanted SAI in Plant Y2 SG-23 R4C18 (Scan Line Plot)

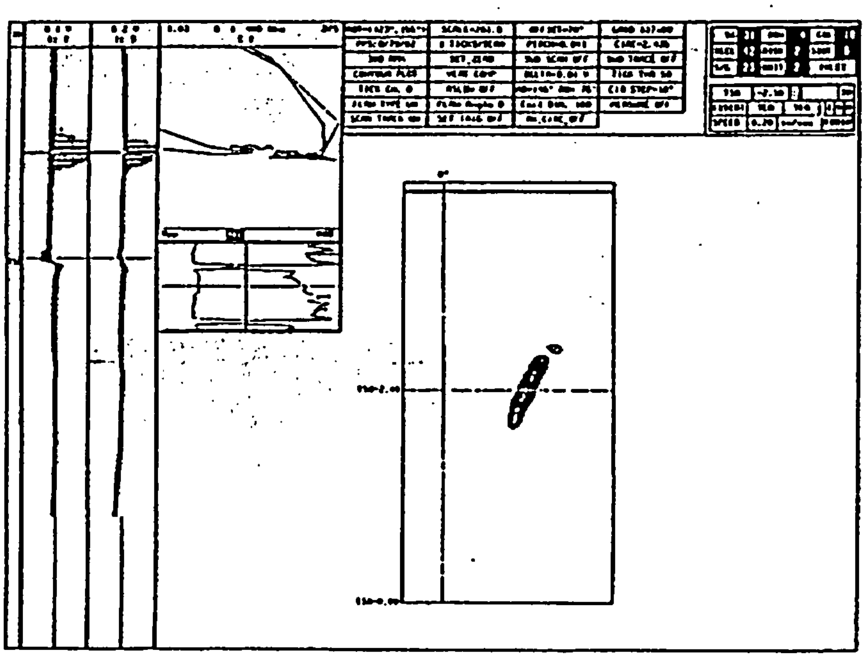


Figure 7.1.7-1b
Slanted SAI in Plant Y2 SG-23 R4C18 (Contour Plot)

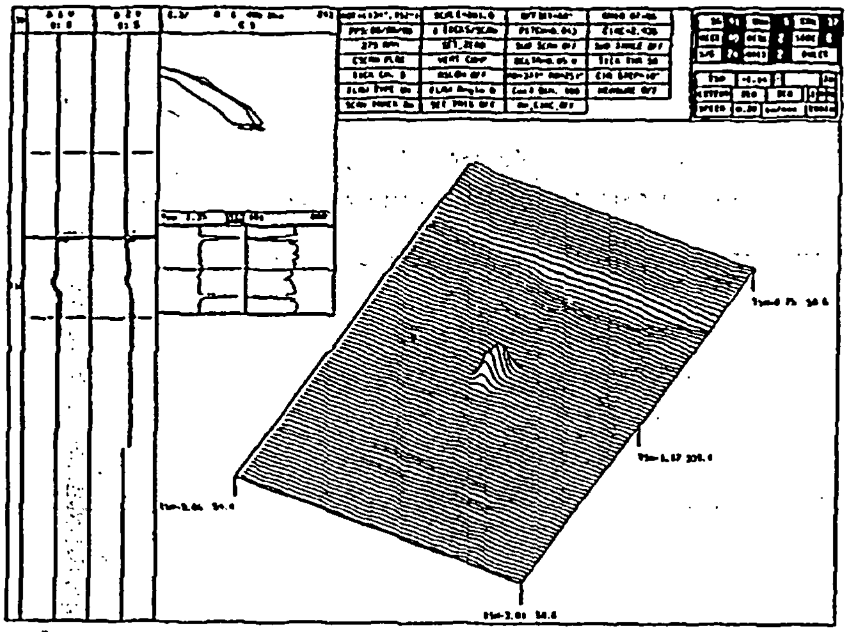


Figure 7.1.7-2a
Slanted SAI in Plant Y2 SG-24 R6C37 (Scan Line Plot)

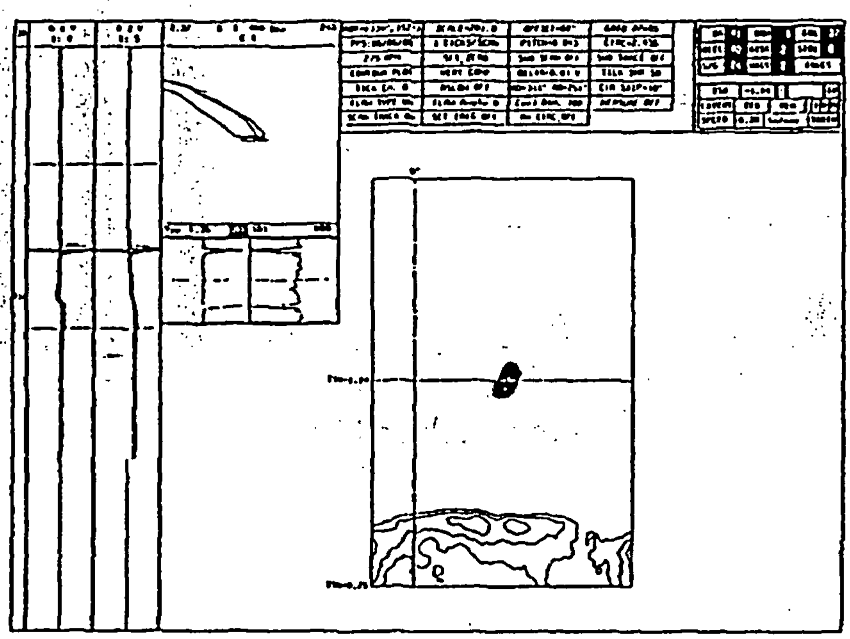


Figure 7.1.7-2b
Slanted SAI in Plant Y2 SG-24 R6C37 (Contour Plot)

Figure 7.1.8-1
Location of BWT below Top of Tubesheet

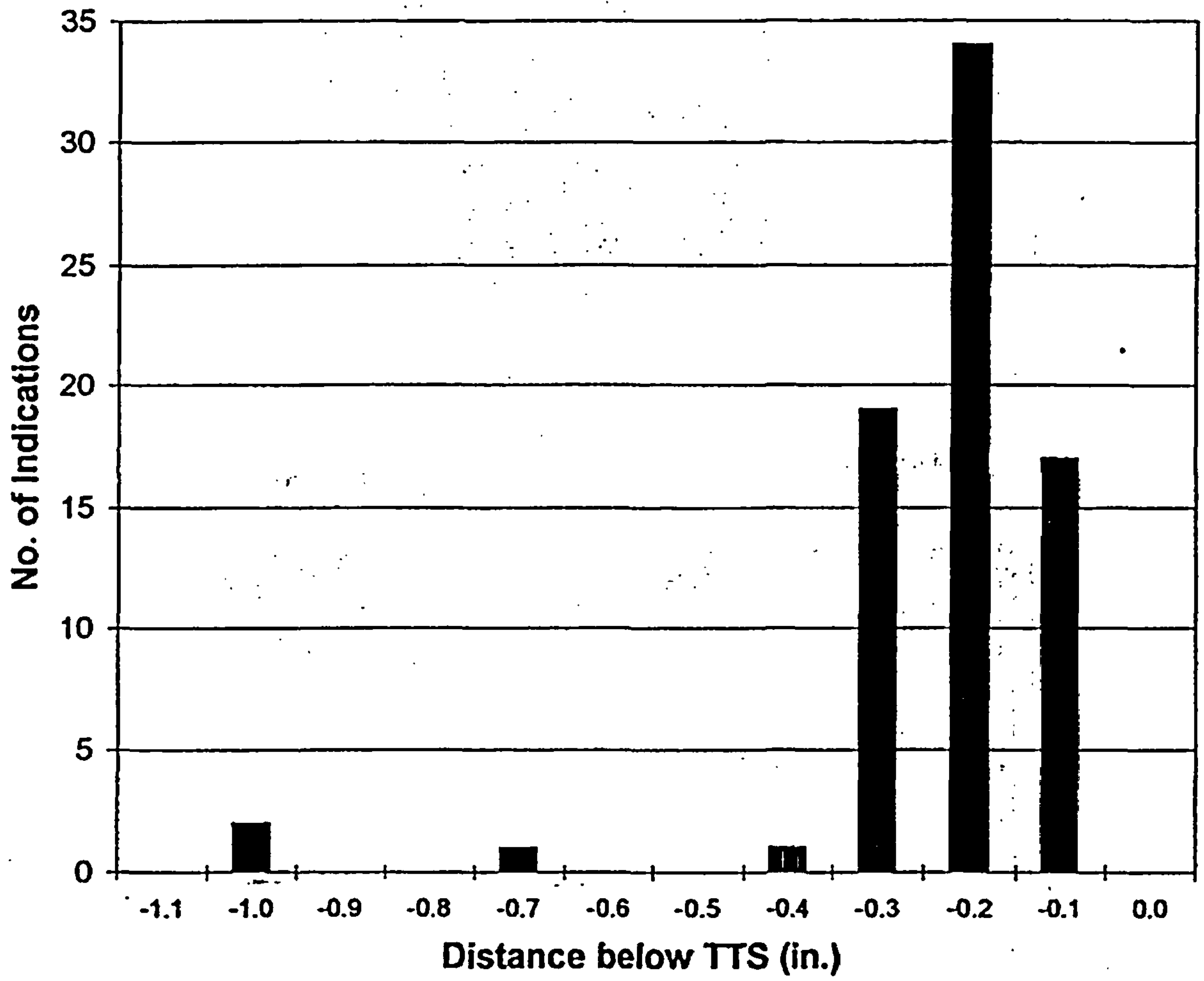
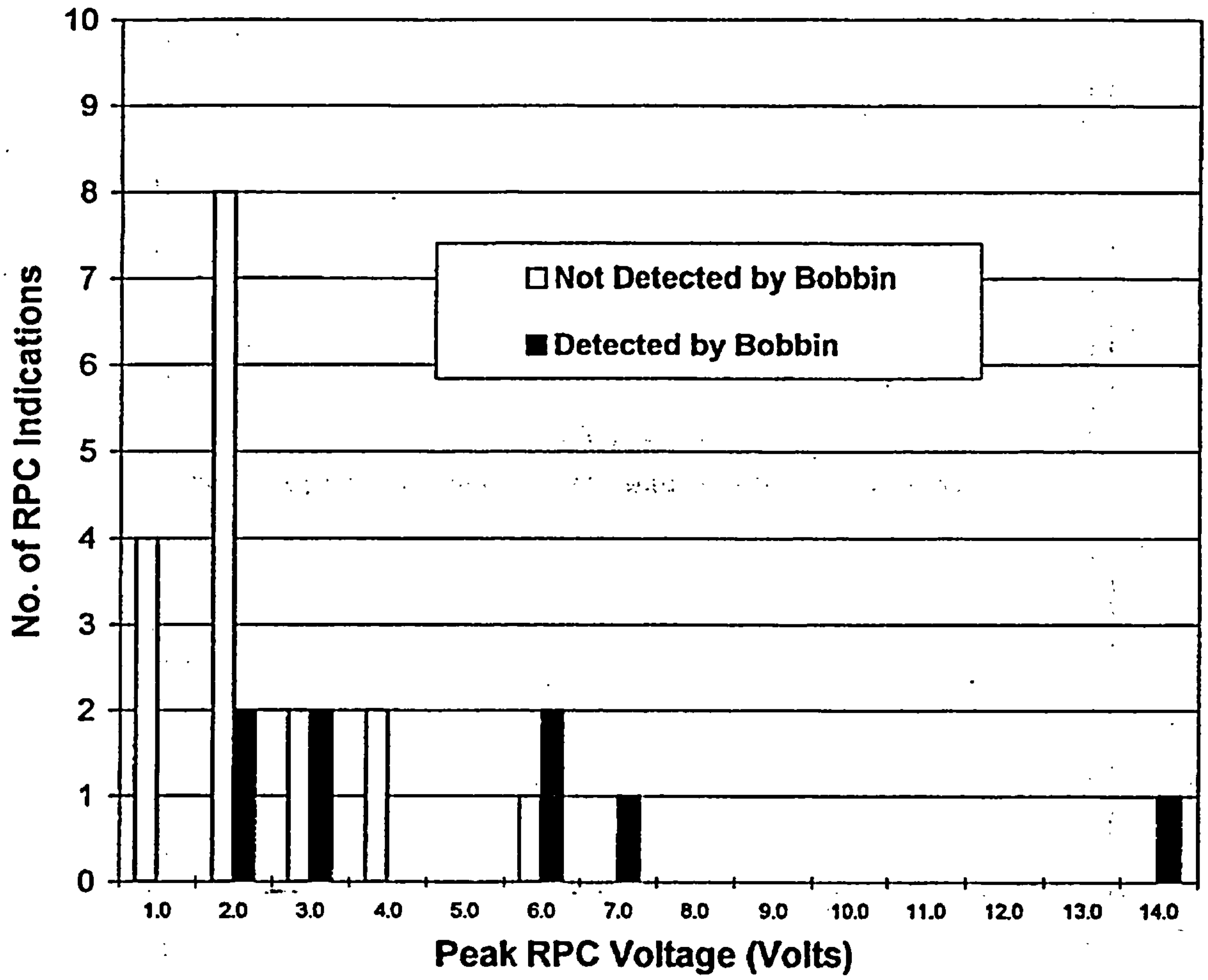


Figure 7.2-1
Bobbin Detection of RPC-Confirmed SAIs vs. Peak RPC Voltage



a,c

Figure 7.3-1
C-Scan Display for NDE Specimen 115 mil (300 kHz) Rotating Coil

a,c

Figure 7.3-2
C-Scan Display for the NDE Specimen PlusPoint (300 kHz) Rotating Coil

a,c

Figure 7.3-3a
C-Scan Display for the NDE Specimen 80 mil (300 kHz) Rotating Coil

a,c

Figure 7.3-3b
C-Scan Display for the NDE Specimen 80 mil (600 kHz) Rotating Coil

Figure 7.4-1
Cumulative Probability Distribution for Growth of W* Region Axial Indications

a,c

8.0 W* TUBE PLUGGING CRITERIA

This section integrates the results obtained in prior sections to summarize the W* tube plugging criteria for eddy current indications in the tubesheet region of the WEXTEX expansion. The W* criteria provide the basis for disposition of indications found by bobbin coil or RPC inspections below the bottom of the WEXTEX transition.

8.1 GENERAL APPROACH TO W* CRITERIA

The approach taken to develop the W* criteria is to utilize the general methodology of the L* criteria for hardroll expansions and adapt the methods for WEXTEX expansions. The hardroll L* criteria utilize an L* length of undegraded tubing to limit leakage and permit a flexible length (F*) to resist pullout forces, with the length increased if degradation is present within the minimum F* length. Since WEXTEX expansions have lower tube-to-tubesheet contact forces than hardroll expansions, limited leakage is possible under SLB conditions and the L* length is replaced in W* by the requirement to calculate SLB leakage for indications left in service. The SLB leakage for a given indication is dependent upon the distance of the top of the crack below the bottom of the WEXTEX transition (BWT). A flexible W* length patterned after the flexible F* length of the L* criteria is applied in W*. The general approach taken for W* can be applied to indications within the tubesheet for alternate types of tubesheet expansions. The principal *difference between the type of tubesheet expansion (hardroll, explosive, hydraulic, partial depth)* is that the methods for calculating SLB leakage must be specialized for the method of expansion.

The general approach taken to develop the W* tube plugging criteria includes:

1. Prevention of Tube Burst

   - Tube burst is precluded for cracks within the tubesheet by the constraint provided by the tubesheet.

2. Prevention of Axial Separation Due to Pullout Forces

   - Axial separation (tube pullout is precluded by requiring that undetected degradation be at least a distance W* below the bottom of the WEXTEX transition such that the pullout forces under normal operating or accident conditions are exceeded by the elastic preload between the tube and tubesheet. A flexible W* length approach is applied whereby the minimum W* length is increased by the length of any axial indications left in service to obtain an undegraded length equal to the minimum W* length.

   - *Circumferential indications within the flexible W* distance are repaired.*

3. Limit SLB Leakage Within Allowable Limits

   - SLB leakage is limited by leakage flow restrictions resulting from the crack and tube to tubesheet contact pressures which provide a restricted leakage path above the indications and also limit the degree of crack face opening compared to free span indications.

- The requirements for allowable leakage under accident conditions are satisfied by demonstrating that the leakage from indications within the W* distance, when combined with leakage from other implemented alternate repair criteria, is less than the plant specific allowable leakage limit.

4. Negligible Leakage Expected Under Normal Operating Conditions

- Extensive operating experience in Europe with PWSCC axial cracks left in service has demonstrated negligible operating leakage even for thousands of free span cracks remaining in service.

- Operating leakage is further limited for cracks within the tubesheet by the tube to tubesheet contact forces.

8.2 W* LENGTH

As developed in Section 4, the tube to tubesheet contact force resisting axial pullout forces is comprised of: radial contact pressure from the WEXTEX expansion process, radial contact pressure from local tube thermal expansion and pressure differentials at operating conditions, and the axially dependent radial contact pressures resulting from the tubesheet deflection due to pressure and thermal differentials across the tubesheet. The radial contact pressures from tubesheet deflection are a function of the radial distance from the tubesheet centerline. Consequently, the minimum W* distance for the tube to tubesheet contact forces to exceed the pullout forces is also a function of the radial position of a tube in the tube bundle.

Two zones have been defined, W* Zone A and W* Zone B, corresponding to inspection zones currently in use for inspection of the expansion transition. The W* lengths for W* Zone B and W* Zone A are 7.0 and 5.2 inches, respectively. The W* distance is defined as the distance below the bottom of the WEXTEX transition (BWT). Only hot leg values are given in this section as cold leg WEXTEX indications have not been found in operating SGs. Figure 4.5-1 provided a tubesheet map defining the two W* length zones.

Below the flexible W* distance, any degradation including a 360° circumferential crack is acceptable since the tube to tubesheet contact force integrated over the W* distance precludes tube pullout under normal operating or accident conditions. As developed in Section 4.4, Regulatory Guide 1.121 margins against rupture at normal operating conditions are limiting in determining the W* length.

Allowable degradation within the W* length is developed in Section 8.4.

8.3 APPLICATION OF GROWTH AND NDE UNCERTAINTY

8.3.1 Flexible W* Length

Since the required length of tubing to be inspected depends upon the presence or absence of indications and must include allowances for NDE uncertainty and growth of an indication, a variable or "Flexible W* Length" has been defined. The Flexible W* length is the distance from the bottom of the WEXTEX transition (BWT) to the bottom of the required inspection zone and includes: the minimum W* length, the length of indications if present within the W* length, conservative additional length for measurement uncertainty, and modifications to account for potential growth of indications.

The flexible W* length below the BWT is defined as:

$$\text{Flexible W* Length} = W^* + \Delta NDE_{W^*} + \Sigma CL_i + N_{CL} \bullet \Delta NDE_{CL} + N_{CL} \bullet \Delta CG$$

where,

W* is the W* length (7.0" for W* Zone B and 5.2" for W* Zone A).

ΔNDE_{W^*} is the NDE uncertainty in measuring the W* depth.

ΣCL_i is the total axial length of tubing in which axial cracking is present below the BWT and down to the adjusted W* length. For axial cracks which share the same elevation over a portion of their length, (e.g., parallel cracks) the contribution to CL from that band of axial cracks is the distance from the uppermost crack within the band to the lowermost crack within the band. CL may include contributions from both parallel cracks and single axial cracks.

N_{CL} is the number of enveloped groupings of indications (either of single cracks or parallel cracks) as described in CL, above.

ΔNDE_{CL} is the NDE uncertainty associated with measurement of the length of axial cracks.

ΔCG is the allowance for crack growth in length for each of the N_{CL} crack groups.

The eddy current data analysis guidelines of Appendix A of this report are to be applied for W* inspections. These guidelines are consistent with the development of NDE uncertainties.

8.3.2 Leakage Analysis

SLB leak rate analyses are required for condition monitoring (analysis of as-found inspection results) and operational assessments (projections to the next EOC). NDE uncertainties are included in the leak rate evaluation for both assessments while an allowance for crack growth is required only for operational assessments. The leak rates are dependent on the distance from the BWT to the uppermost tip of the crack. NDE uncertainties and crack growth are applied to the uppermost tip of the crack to conservatively reduce the distance of the crack tip below the BWT. It is possible that the application of uncertainties and growth can result in the crack tip estimated to be above the BWT. The applicable NDE uncertainty, ΔNDE_{CT}, is the uncertainty on the measurement of the distance between the crack tip and the BWT. The total growth rate, ΔCG, as described in Section 8.3.1, is conservatively assumed to all occur at the uppermost crack tip.

The estimated growth rate from Section 7.4 is added to each crack prior to the operational assessment leak rate calculation for each tube. At 95% cumulative probability, the growth rate is 0.25 inch per EFPY. This growth rate was conservatively developed from available data. As an option in applying the W* repair criteria, plant specific growth data can be developed and applied for W* applications. NDE uncertainty and growth are added to beginning of cycle (BOC) RPC crack tip positions to calculate the leakage contribution at end of cycle (EOC).

Section 6.4 provides tabulated SLB leak rates for Zone A and the four sub-zones of Zone B as a function of the distance between the BWT and the crack tip. These tabulated leak rates are based on deterministic analyses which are shown in Section 6.5 to be conservative relative to Monte Carlo analyses. The tabulated leak rates are provided to reduce the effort required to calculate the SLB leak rate for comparisons with allowable limits. As an option, the Monte Carlo methods of Section 6.5 can be used for the leak rate analysis when the conservatism of the deterministic methods may be considered to be unacceptable.

8.3.3 NDE Uncertainties

NDE uncertainties are developed in Section 7.3 and summarized in Table 8.3-1. The uncertainties were developed using prototypic, robotic measurements in a SG mockup and analyses by two field analysts using the NDE guidelines of Appendix A. NDE uncertainties are given for the + Point coil, 80 mil pancake coil and 115 mil pancake coil. The uncertainties for W* application are developed at the one-sided +95% confidence limit on the data. Differences in the NDE uncertainties between coils are modest. The + Point coil, which has the largest field spread of the coils tested, shows the largest uncertainties. It is seen that the uncertainty on crack length measurement is negative, that is, the measured length must be reduced by the applied NDE uncertainty due to overestimation of the length of significantly deep flaws (50% tested) by the NDE techniques. The uncertainty on locating the BWT relative to the TTS is approximately independent of whether the distance is measured with a bobbin or RPC coil.

The limiting NDE uncertainties, as obtained for the + Point coil, are: distance of upper crack tip relative to the BWT, [

]a,c

8.4 ALLOWABLE TUBE DEGRADATION IN W* LENGTH

Tube degradation within the flexible W* length is limited to provide adequate tube strength to transmit axial pullout forces through the W* distance. Allowable degradation within the W* distance is limited to:

- Axial indications left in service shall have the upper crack tip below the BWT by at least the NDE uncertainty, ΔNDE_{CT}, on locating the crack tip relative to the BWT.
- Resolvable, single axial indications (multiple indications must return to the null point between individual cracks) within the flexible W* distance can be left in service. RPC or equivalent coils or a UT inspection can be used to demonstrate return to null between multiple axial indications or the absence of circumferential involvement between the axial indications.
- Tubes with inclined axial indications less than 2.0 inches long (including the crack growth allowance) having inclination angles relative to the tube axis of < 45° minus the NDE uncertainty, ΔNDE_{CA}, on the measurement of the crack angle can be left in service. That is, the measured crack angle must be less than (45° - ΔNDE_{CA}). Tubes with two or more parallel (overlapping elevation), inclined axial cracks must be repaired. The limit of 2.0 inches for inclined axial indications is conservatively applied to limit the circumferential involvement of the indication. For application of the 2.0 inch limit, an inclined indication is an axial crack that is visually inclined on the RPC C-scan, such that an angular measurement is required and the measured angle exceeds the measurement uncertainty of ΔNDE_{CA}. There is no length limit on axial indications that are not inclined by this definition.
- All circumferential or volumetric indications within the flexible W* distance and axial *indications with inclination angles greater than (45° - ΔNDE_{CA}) are to be repaired.*
- Any type or combination of tube degradation below the W* length is acceptable.

Based on the above requirements, axial indications below the BWT by at least the NDE uncertainty are permitted to remain in service although crack growth over the subsequent operating cycle could result in an EOC indication crack tip above the BWT. This repair requirement assures that the dominant length of the crack remains in the fully expanded tube which limits crack opening for SLB leakage and the SLB leakage model is applicable to this crack location. Leakage is essentially the same for a crack tip just below the BWT or somewhat above the BWT since the tube expansion limits the crack opening but there is no tight crevice above the crack tip to further limit leakage. In addition, the repair requirement prevents an axial tube burst since the potential crack length above the BWT is limited to the crack growth and would be too short for burst at SLB conditions.

8.5 SLB LEAK RATE EVALUATION

The SLB leakage from the tubesheet region is limited by the contact pressure between the tube and tubesheet as developed in Section 6. The contact pressure is the result of the WEXTEX expansion process, thermal expansion mismatch between the tube and tubesheet and from the differential pressure between the primary and secondary side. The contact pressure is also influenced by the dilation or contraction of the tubesheet hole resulting from tubesheet deflection caused by the primary to secondary side ΔP acting on the tubesheet. Since the deflection effect is a function of radial distance from the tubesheet center, the tube-to-tubesheet contact pressure varies with tubesheet radius also. For the purpose of the SLB leakage evaluation, the contact pressure from the WEXTEX expansion process is not included in the determination of the total contact pressure. The leak rate model is based on tests for constrained crack openings and for leakage through the expanded crevices. The WEXTEX contact pressure was inherent in the test samples for the crevice leak rate tests, is considered representative of that in steam generator tubes, and therefore is not accounted for separately in the SLB evaluation. For the leak rate tests with constrained crack openings, the test specimens were ground to produce small tube to collar gaps or contact pressure and the WEXTEX contact pressure is not included in the tests. It is conservative to ignore the WEXTEX contact pressure for the constrained crack opening model since inclusion in the analysis would further reduce the effective crack opening.

The SLB leak rate model is applicable to both the hot leg and cold leg. The model assumes a free span crack in series with a flow resistance for the tube-to-tubesheet crevice (Section 6). An effective free span crack length is determined from leak rate tests with crack openings constrained by the tubesheet. Equating the test leak rates for constrained cracks to an effective free span crack length is performed to permit pressure drop analyses for the series model. The crevice flow resistance is based on test results of prototypic WEXTEX joints. Knowing the distance between the uppermost tip of the crack and the BWT together with the radial position of the tube in the tubesheet, the leakage rate can be predicted from the leak rate models. As shown in Section 6, the leak rate is independent of crack length due to the tubesheet constraint on the effective crack opening length. For cracks within 0.7 inch of the BWT for which the WEXTEX expansion diameter may be tapered (tube-to-tubesheet gap < 1 mil), the leakage model includes the crevice restriction of leakage due to small tube-to-tubesheet gaps and the effective crack length for zero contact pressure. If the tip of the crack is above the BWT, the leak rate is based on no crevice and the effective crack length for zero contact pressure. Even with the tip of the crack above the BWT, as potentially possible with crack growth, the center of the crack is below the BWT and the tubesheet constraint limits the crack opening.

The leakage analysis methods and leak rates as a function of the crack tip distance below the BWT are the same for condition monitoring (analysis of as-found indications) and operational assessments (projected to next EOC). The difference in application is that the operational assessment reduces the crack tip distance below the BWT by the crack length growth rate. It is conservatively assumed that the total crack growth occurs at the uppermost crack tip.

The resulting SLB leakage for tubes with indications in the tubesheet region in the current inspection, is to be added to the SLB leakage from other tubes returned to service under additional alternate plugging criteria, if appropriate. The total must be less than the plant specific allowable SLB leakage limit. If the leakage exceeds the allowable limit, an appropriate number of the indications must be repaired to satisfy the allowable leakage limit.

8.6 INSPECTION REQUIREMENTS

The W* repair criteria provide for disposition of indications found by bobbin coil or RPC inspections. In this context, RPC applies to a rotating pancake coil or an equivalent coil such as the + Point coil. The extent of the bobbin and RPC inspections are determined by Technical Specification requirements and plant specific RPC inspection guidelines for the WEXTEX transitions. Application of the W* criteria does not mandate a specific inspection sample size. For implementation of W*, indications within the flexible W* length that are found by bobbin coil inspection must also be RPC inspected to characterize crack lengths and elevations. All indications left in service within the flexible W* length must be RPC inspected at each planned refueling outage. When RPC inspections are performed for the WEXTEX transition region, the inspection shall include the full length of the flexible W* region.

Recording of results for the bobbin coil inspection shall include, as a minimum: the tube location, the elevation of each indication relative to the top of the tubesheet, the peak-to-peak voltage of each indication and the phase angle and/or depth of the indication. The recorded results shall include all indications in the tubesheet region and are provided for information only since the bobbin data are not used in W* applications except to identify indications for RPC inspection.

Recording of results from the RPC inspection shall include:

- Tube location
- Length of RPC inspection relative to the TTS on either an inspection basis if kept the same for all tubes inspected or on a tube basis if not the same for all inspected tubes. The length to be RPC inspected below the BWT is defined as the "Flexible W* length".
- Location of the BWT relative to the TTS
- Elevation below the TTS to the uppermost crack tip of each indication.
- Crack length of each axial indication. Axial length shall be reported separately for each indication.
- For axially oriented cracks clearly inclined relative to the tube axis, the inclination angle of the crack relative to the tube axis shall be reported. A value of 0° may be reported for crack inclination angles that are less than about 20° and the angles do not require individual sizing.
- For multiple axial indications within the flexible W* distance, the inspection record shall distinguish between indications which can be individually resolved and those which cannot be

individually resolved (RPC amplitude does not return to null level between indications). This feature may be entered as a separate data entry in the inspection record or as an alternate classification of the indication (i.e., instead of MAI, MAR or MAU could be used). The total circumferential angle spanning the unresolved axial indications or each resolved axial indication shall be reported in addition to the axial lengths of each separate indication.

- For circumferential cracks, the elevation of the indication relative to the TTS or BWT and the circumferential arc length or angular extent shall be reported. Tube repair would be required if within the flexible W* distance.
- Maximum RPC voltage (peak-to-peak) of each indication (for information only, not used in W* criteria).
- RPC phase angle and/or depth of each indication (for information only, not used in W* criteria).

Reviews of WEXTEX expansions by profilometry analyses have shown full expansions below the BWT for lengths considerably larger than the required W* distances of about 6 inches. Thus, identification of the BWT is adequate to confirm expansion over the W* length and further confirmation of the expanded length is not required. The elevation of the BWT below the TTS is typically variable within a few tenths of an inch. Lack of an expansion near the TTS would be identified by the inability to locate the BWT. If the bottom of the expansion transition is above the TTS, the TTS is applied as the BWT for application of the W* criteria.

For application of the W* criteria, location of the BWT could be performed at one time for all tubes and the data entered into the inspection record when an indication is found within the flexible W* distance. Alternately, the BWT measurement can be performed on an inspection basis when an indication is found that requires application of the W* criteria.

8.7 SUMMARY OF W* TUBE PLUGGING CRITERIA

As developed in the above sections, the W* plugging criteria can be summarized as follows:

<u>W* Length</u>

The W* length in the hot leg shall be 7.0 inches in W* Zone B and 5.2 inches in W* Zone A. The W* length is the length of tubing below the bottom of the WEXTEX transition (BWT) which must be demonstrated to be undegraded in accordance with the following criteria. If cracks are found within the W* region, the flexible W* length must be applied to account for the assumed lack of axial restraint over the length of the crack (Section 5.4). The flexible W* length is the total RPC-inspected length as measured downward from the BWT, and includes NDE uncertainties and crack lengths within W* as adjusted for growth. For most inspections, it is expected that the RPC inspection length will be measured from the top of tubesheet (TTS). In this case, the distance of the BWT below the TTS must be subtracted from the inspected length for comparisons with the flexible W* length. Below the flexible W* length any type or combination of tube degradation is acceptable.

The following are the length requirements to be applied in the two zones across the tubesheet with and with degradation within the flexible W* distance:

Central Zone B

- Without degradation

  W* Length below BWT = 7.0" + ΔNDE_{W^*}

- With degradation in W* length

  Flexible W* Length below BWT = 7.0" + ΔNDE_{W^*} + ΣCL_i + $N_{CL} \bullet \Delta NDE_{CL}$ + $N_{CL} \bullet \Delta CG$

Outer Zone A

- Without degradation

  W* Length below BWT = 5.2" + ΔNDE_{W^*}

- With degradation in W* length

  Flexible W* Length below BWT = 5.2" + ΔNDE_{W^*} + ΣCL_i + $N_{CL} \bullet \Delta NDE_{CL}$ + $N_{CL} \bullet \Delta CG$

The definitions for the NDE uncertainties and crack growth rates are given in Section 8.3 and further discussed later in this section.

<u>Allowable Tube Degradation Within W* Length</u>

Tube degradation within the W* length shall be limited as follows:

- Axial indications left in service shall have the upper crack tip below the BWT by at least the NDE uncertainty, ΔNDE_{CT}, on locating the crack tip relative to the BWT.

- Resolvable, single axial indications (multiple indications must return to the null point between individual cracks) within the flexible W* distance can be left in service. RPC or equivalent coils or a UT inspection can be used to demonstrate return to null between multiple axial indications or the absence of circumferential involvement between the axial indications.

- Inclined axial indications less than 2.0 inches long (including the crack growth allowance) having inclination angles relative to the tube axis of < 45° minus the NDE uncertainty,

ΔNDE_{CA}, on the measurement of the crack angle can be left in service. That is, the measured crack angle must be less than (45° - ΔNDE_{CA}). Tubes with two or more parallel (overlapping elevation), inclined axial cracks must be repaired. The limit of 2.0 inches for inclined axial indications is conservatively applied to limit the circumferential involvement of the indication. For application of the 2.0 inch limit, an inclined indication is an axial crack that is visually inclined on the RPC C-scan, such that an angular measurement is required and the measured angle exceeds the measurement uncertainty of ΔNDE_{CA}. There is no length limit on axial indications that are not inclined by this definition.

- All circumferential or volumetric indications within the flexible W* distance and axial indications with inclination angles greater than (45° - ΔNDE_{CA}) are to be repaired.

- Any type or combination of tube degradation below the W* length is acceptable.

<u>SLB Leakage Evaluation</u>

The SLB leakage evaluation shall be based upon:

- Deterministic leakage analyses (Section 6.4) utilizing leak rates for Zone A and each of the four sub-zones of Zone B as a function of the distance of the upper crack tip below the BWT. The total leak rate is obtained as a sum of the leak rates from individual indications in the SG. As an option, Monte Carlo SLB leak rate analyses may be performed to reduce conservatism in the deterministic analysis method.

- For a condition monitoring assessment (analysis of as-found inspection results), the RPC measured distance of the crack tip below the BWT shall be reduced by the measurement uncertainty (ΔNDE_{CT}).

- For an operational assessment (analysis of projected EOC conditions), the RPC measured distance of the crack tip below the BWT shall be reduced by the measurement uncertainty (ΔNDE_{CT}) and the crack growth allowance (ΔCG).

- The total leak rate from RPC-inspected tubes in the W* region will be divided by the percent of tubes inspected using RPC or equivalent probes to obtain the total leak rate from all indications.

- The combined predicted leakage from all tubes with indications, including those which have been returned to service previously, must be compared to the plant specific allowable SLB leakage limits. The leakage from W* indications shall be added to the predicted leakage for indications left in service based on other implemented ARCs. If the predicted leakage is less than the allowable limit, the tubes with indications may be returned to service provided that all other W* criteria are met. If the allowable leakage limit is exceeded, tubes shall be plugged until the allowable leakage limit is met. Priority for repair to meet leakage limits shall be the indications having the largest leakage contribution.

Inspection Requirements

The inspection requirements for implementing the W* repair criteria, given in more detail in Section 8.6, can be summarized as follows.

- The W* criteria provide for disposition of indications found by bobbin or RPC inspections and do not mandate a specific inspection sample size.
- Indications within the flexible W* length found by bobbin coil inspection must also be inspected by RPC (or equivalent coil such as + Point) to characterize crack lengths and elevations.
- All indications left in service within the flexible W* length must be RPC inspected at each subsequent planned inspection.
- When RPC inspections are performed for the WEXTEX transition region, the inspection shall include the full length of the flexible W* region.
- Bobbin coil inspection results shall include, as a minimum: the tube location, the elevation of each indication relative to the top of the tubesheet, the peak-to-peak voltage of each indication and the phase angle and/or depth of the indication. The recorded results shall include all indications in the tubesheet region.
- Recording of results from the RPC inspection shall include: tube location; length of RPC inspection relative to the TTS (or BWT) on either an inspection basis if constant for all tubes inspected or on a tube basis if not consistent for all inspected tubes; location of the BWT relative to the TTS; elevation below the TTS (or BWT) to the uppermost crack tip of each indication; crack length of each axial indication; the inclination angle of the crack relative to the tube axis for axially oriented cracks clearly inclined relative to the tube axis; the inspection record shall distinguish between multiple axial indications which can be individually resolved and those which cannot be individually resolved (RPC amplitude does not return to null level between indications); the elevation of circumferential indications relative to the TTS or BWT and the circumferential arc length or angular extent; maximum RPC voltage (peak-to-peak) of each indication; and RPC phase angle and/or depth of each indication.

Application of the W* criteria permits measurements of the crack tip and W* distances either relative to the BWT or to the top of the tubesheet (TTS). Specific applications of either option may depend on the coil used in the inspection and its ability to identify the BWT reliably. NDE uncertainties in determining the crack tip and W* distances relative to the BWT, as required for W* application, may be different between the two options as discussed in Section 8.3.3.

NDE Uncertainties

NDE uncertainties are developed in Section 7.3 and further discussed in Section 8.3.3 and Table 8.3-1. For W* applications, the NDE uncertainties are applied at the 95% confidence level. NDE uncertainties are provided for: distance of upper crack tip relative to the BWT, ΔNDE_{CT}; crack length measurement, ΔNDE_{CL}; crack angle measurement, ΔNDE_{CA}; and distance of W* below the BWT, ΔNDE_{W*}. Specific values for the NDE uncertainties are moderately dependent upon the type of rotating coil used for the inspection as shown in Table 8.3-1. The uncertainties ΔNDE_{CT} and ΔNDE_{W} for measurements relative to the BWT include the uncertainties for locating the BWT relative to the TTS since all measurements are made relative to the TTS.

Crack Growth Rates

A conservative crack growth rate for axial indications is developed in Section 8.3 as the 95% cumulative probability value for data from three plants. Difficulties in sizing the prior cycle tend to result in underestimates of the length and an overestimate of the growth rate. The resulting crack growth rate, ΔCG, is 0.25 inch per EFPY. This value can be generically applied for all W* applications. In general, the influence of crack growth uncertainties on either the flexible W* length or the SLB leak rate is small. As an option, plant specific growth rates can be developed and applied for the W* criteria as an alternative to using the generic value.

Conservatisms in the W* Criteria

The W* criteria have been conservatively developed relative to providing a lower bound on tube pullout force capability and an upper bound on SLB leak rates. Conservatisms in the criteria include:

- The W* lengths are the most limiting length of any tube in each of the two zones and bound all other tubes in the zone.
- Lower bound tube pull forces for WEXTEX expansions, based on a smooth tubesheet hole, have been used to maximize the W* distance and bound variability in WEXTEX expansions.
- The length of a crack within the flexible W* length is assumed to provide no contribution to pullout force even though the contact pressures from thermal expansion and pressure differential would apply.
- All expansions are assumed to have a small gap over the upper 0.7" of distance below the BWT for both pullout force and leakage analyses.
- The W* length is developed for a generically low steam pressure of 760 psia which bounds all operating Model 51 SGs with WEXTEX expansions.

- All circumferential indications within the W* distance are conservatively repaired as well as closely spaced axial indications for which the absence of a circumferential indication between the axial cracks cannot be demonstrated by RPC or UT inspection.

- All axial indications are assumed to be throughwall for SLB leakage analyses.

- The SLB leak rates are the most limiting of any tube in each of the two zones and bound all other tubes in the zone.

- All crack growth in length is assumed to be toward the BWT for leakage analyses.

Table 8.3-1. Summary of NDE Uncertainties for W* Applications

W* Measurement	Probe	NDE Uncertainty		W* Application Value[2]
		Mean[1]	Std. Dev.	

a,c

a,c

Figure 8.2-1 W* Zone A and B1-B4 Boundaries

9.0 REFERENCES

9-1. WCAP-11857, "Tubesheet Region Tube Alternate Plugging (L*) Criteria for Steam Generators in the V. C. Summer Nuclear Station", June 1988. (Proprietary).

9-2. EPRI NP-6864-L, PWR Steam Generator Tube-Plugging Limits: Technical Support *Document for Expansion Zone PWSCC in Roll Transitions, December, 1990.*

9-3. WCAP-11228, Rev.1, "Tubesheet Region Plugging Criterion for the South Carolina Electric and Gas Company V. C. Summer Units 1 and 2 Steam Generators", October 1986. (Proprietary).

9-4. Smith, R. E., "Series 51 Generic Seismic Analysis", Calculation Note SM-91-97, NSD Structural Mechanics, Westinghouse, Pittsburgh, Pa., October 1991. (Proprietary).

9-5. FWDC 9-61-5427, 'Expansion of Alloy 600 Tubes Into Carbon Steel Collars Using The WEXTEX Process, Foster Wheeler Development Corporation, May 16, 1991. (Proprietary).

9-6. Thurman, A. L., "Series 51 Tube/Tubesheet Contact Pressures", Calculation Note SM96-39, NSD Steam Generator Design and Analysis, Westinghouse, Pittsburgh, PA, May 1996. (Proprietary).

9-7. ASME Boiler and Pressure Vessel Code, Section III, "Rules for Construction of Nuclear Power Plant Components", The American Society of Mechanical Engineers, New York, NY, 1989.

9-8. Slot, T., "Stress Analysis of Thick Perforated Plates", PhD Thesis, Technomic Publishing Co., Westport, CN, 1972.

9-9. WNET-142, Vol. 8, "Model D4-2 Steam Generator Stress Report, Divider Plate Analysis," Westinghouse Tampa Plant, Florida, September, 1977. (Proprietary).

9-10. Thurman, A. L., "Doel 4 Elevated Tubesheet Sleeve - ASME Code Evaluation and Effect of Tubesheet Rotations on Contact Pressures", Calculation Note SM-94-58, Revision 1, NSD Steam Generator Design and Analysis, Westinghouse Electric Corporation, Pittsburgh, PA, October 1994. (Proprietary).

9-11. Timoshenko, S., Strength of Materials Part II, Third Edition, Von Nostrand Company, Princeton, N. J., 1956.

9-12. NRC Generic Letter 95-05, " Voltage-Based Repair Criteria for Westinghouse Steam Generator Tubes Affected by Outside Diameter Stress Corrosion Cracking," USNRC, August 3, 1995.

9-13. WCAP-14277, Revision 1, "SLB Leak Rate and Tube Burst Probability Analysis Methods for ODSCC at TSP Intersections," Westinghouse Electric Corp., December, 1996.

9-14. NSD-RMW-91-026, "An Analytical Model for Flow Through an Axial Crack in Series with a Denting Corrosion Medium," Westinghouse Electric Corporation, February, 1991. (Proprietary).

9-15. NSD-RMW-91-058, "DENTFLO, Rev. 1," Westinghouse Electric Corporation, March 1991. (Proprietary).

9-16. NSD-E-SGDA-99-006, "NRC RAI on Diablo Canyon W*Loss Coefficient", from R. F. Keating to W. Rice, dated January 11,1999 (Proprietary).

Appendix A

NDE Guidelines
for Application with W* Criteria

1.0 SCOPE

These guidelines are intended to support the measurement of axial lengths associated with point to point differences between the bottom of the WEXTEX transition (BWT) or the top of the tubesheet (TTS) and the uppermost tip of axial crack indications, as well as crack length measurements for axial PWSCC (primary water stress corrosion cracking) detected in the expanded tube sections of certain Westinghouse 51 Series steam generators. The acceptability of off-axis cracks is supported by measurement of the angle of inclination of such cracks from the tube axis.

2.0 ENGINEERING DATA REQUIREMENTS

The WEXTEX expansion zone alternate repair criteria (W*) impose special engineering data requirements on eddy current data analyses in order to ascertain the structural condition of the tube. These requirements include:

1. Measurement of crack lengths
2. Inclination angle between axial crack(s) and the tube axis
3. Number of axial cracks in a band
4. Measurement of the length of sound tubing measured from

    a) the bottom of the WEXTEX transition (BWT) or from the top of the tubesheet (whichever is lower) to the uppermost tip of an axial crack or crack band

    b) the bottom of the axial crack or crack band to the lowest point inspected or to the top of the next lowest crack band, if any.

Both axial and circumferential cracks are of interest. This section defines and describes the engineering data requirements for detailed crack characterization.

2.1 Crack Characterization

2.1.1 Circumferential Cracks

The detection of circumferential cracks in the region below the top of the tubesheet shall disqualify the tube from application of W*. Normal data reporting requirements shall apply. As a reminder, circumferential cracks above the bottom of the WEXTEX transition should be evaluated with respect to the need for tube stabilization as well as for structural integrity.

2.1.2 WEXTEX Transition Location

The position of the point at which full expansion is reached occurs at the bottom of the transition. This position is typically located within the first 0.25 inches below the top of the tubesheet. Graphically this point is obtained by identifying the intersection obtained by extending the expanded tube profile in the tubesheet until it crosses the extended trace of the unexpanded tube above. Some plants have obtained this point by bobbin probe profilometry in the past; this value may be used to anchor the rotating probe analyses. Identification may be made with either type probe if satisfactory data is available; caution should be employed in using the +Point coils for this purpose, since its differential character may minimize the visibility of the transition.

2.1.3 Sound Expansion Length

Axial cracks are acceptable below the BWT, but the length of such cracks may not be used in satisfaction of the sound tubing length required to prevent pullout of the tube under accident loadings.

2.2 Analyst Training

Data analysts shall be given specific training in 1) industry experience with expansion zone cracking and 2) current industry analysis practices for crack detection and characterization.

Training data sets shall be prepared for analyst familiarization. These data sets shall include examples of WEXTEX expansion zone indications reflecting a diversity of test conditions including but not limited to; 1) large and small amplitude indications, 2) indications in the presence of extraneous test variables. i.e., secondary-side deposits, permeability, excessive expansion zone geometry changes, etc., and 3) indications which illustrate the engineering data requirements listed in Section 2. The training shall reinforce analyst facility to apply the software appropriate to perform these tasks.

2.3 Analyst Performance Demonstration

All data analysts shall successfully pass a site-specific practical examination. The examination should consist of data sets that demonstrate analyst ability to detect and size eddy current indications typical of those associated with WEXTEX expanded tube sections and specifically to perform the following tasks:

a. Determine distances between ends of indications and reference locations like the bottom of the WEXTEX transition or the top of the tubesheet
b. Lengths of indications
c. *Angles of inclination of indications relative to the tube axis.*

Analysts may qualify separately for detection and characterization.

3.0 ANALYSIS SETUP

The setup instructions provided in this section apply to rotating probes using coils qualified in accordance with Appendix H (Performance Demonstration for Eddy Current Examination) of the EPRI PWR Steam Generator Examination Guidelines (NP-6201 Rev. 4).

3.1 Channel Assignments

The normal assignment of channels for the individual frequencies from rotating probe coils, e.g., pancakes, shall be set up in such a fashion that the display of standard flaw signals are directed upwards. This convention promotes evaluation of all data displays consistent *with industry practice.*

3.2 Spans

Initial span settings may be established as required by the qualified procedure for the particular coil being used. It is recommended that the span setting be established such that the response from a 40% (OD) EDM notch in an expansion transition be displayed at 50% full *screen displacement.*

3.3 Rotations

The phase settings for pancake coils is established by setting probe motion horizontal in the prime reporting frequency channel; this is expected to yield 18-22° for a 100% axial EDM notch. For high frequency pancake coils, such as the 0.080" shielded coil, rotating the 20% ID notch to ~ 5° is recommended. Care should be exercised to avoid setting this value in a manner which results in shallow ID indications lying at phase angles indistinguishable from liftoff. To the extent that +Point coils are used for detection and sizing in the tubesheet region, the 100% axial EDM notch should be set between 30 and 35°.

3.4 Voltage Normalization

The response of the 100% axial notch shall be calibrated to give 20 volts peak to peak in the prime frequency channel for each coil; this voltage is acceptable for all supporting channels as well.

3.5 Calibration Curves

For the purposes of the W* alternate repair criteria all flaws detected in the WEXTEX region will be considered repairable. Phase angle-depth calibration curves are not required.

4.0 REPORTING REQUIREMENTS

4.1 Data Quality

Calibration Verification: The four EDM notches located within expansion transitions on the calibration standard shall all be visible.

Probe Noise: The collected data observed in the prime channel for degradation evaluation shall be monitored continuously; data which exhibits excessive noise shall be rejected and the affected tubes caused to be re-examined with a well-behaved probe.

Tube Noise: Positive measures for assessing noise levels arising from such variables as probe motion, tube deposits, and permeability should be taken; in the event separation of tube indications from interfering signals is questionable, consideration should be given to the need for alternative NDE methods less affected by the interference.

System Noise: Electrical influences which render the collected data useless should be investigated and eliminated; if the noise cannot be isolated and stopped, data collection may need to be scheduled at times when the source is not operative.

4.2 General Analysis Requirements

The potential for PWSCC is well documented for WEXTEX expansion transitions, including both axial and circumferential orientations. The presence of ODSCC in both orientations in and below WEXTEX expansion transition is rare but has some industry precedent.

With liftoff or probe motion set on the horizontal, the presence of signal trajectories in the upper impedance plane shall be regarded as reflecting possible degradation. While calibration standard signals exhibit predictable phase angle rotation with changing frequency, this behavior should not be relied upon for in-plant conditions. For example, clockwise vs counter-clockwise, ID to OD, or OD to ID shifts with frequency are within the expected patterns of behavior for flaw signals. Detection of flaw behavior in a degradation analysis channel should cause the signal to be evaluated as an indication of degradation, notwithstanding conflict with other channels or with other coils. If the signal in the context of its occurrence is more reasonably explained as arising from extraneous factors, analysts may cite these considerations as the basis for a non-flaw disposition. Care should be exercised to avoid nullifying a flaw signal call on the basis that a data channel more susceptible to interference does not present clear flaw behavior.

Filters and/or line nulling techniques are often used as an analysis aid to remove geometric or high frequency noise. However, the filtered data channel identification of a potential indication should only add to the observed population, not to eliminate an indication seen on a raw or unfiltered data channel.

Expansion transitions which are not symmetric and smoothly varying, may cause liftoff signals to follow a trajectory in the upper impedance plane. In these cases, a coordinated review of the C-scan and Lissajous behavior may resolve the signal as representing liftoff.

Similarly, interferences arising from the presence of metallic copper deposits or magnetite, which may be detectable in the upper impedance plane, should be screened carefully to avoid misidentification of flaws as extraneous variables.

4.3 Data Screening

Data acquisition test extent during WEXTEX expansion zone examination typically consists of 2 inches above the top of the tubesheet to at least 5 inches below the top of the tubesheet; in the event of an application of W* to a particular tube the inspection extent must include the W* length (e.g., 5 inches below the TTS) plus the length of axial indications observed. In the event the initial inspection did not cover the required length, the positive identification test can be used to correct the deficiency. All data acquired from this region shall be screened using *both* impedance plane and C-scan plot analysis techniques.

Strip Chart Analysis - *Strip chart evaluation techniques shall not be used in isolation for data screening, but as a supplement to C-scan and impedance plane evaluations.*

Impedance Plane Analysis - Primary, secondary, and process degradation channels (mixes, filters), if used, shall be scrolled for potential indications. The use of multiple-channel analysis software display features is encouraged to accomplish this *requirement in an efficient manner.*

Conservative analysis criteria shall be used for screening purposes. No voltage threshold shall be used. In addition, requirements for phase angle correlation between degradation analysis channels, and/or confirmation between different coils is not required for reporting an indication. Potential indications observed in any of the degradation analysis channels shall be a basis for reporting.

C-scan Analysis – C-scan plots shall be generated and reviewed for all primary degradation analysis channels; secondary, and process degradation analysis channels may be used as needed. Signal features observed on C-scan plots shall be reviewed in the impedance plane for evidence of degradation.

4.4 Reporting Requirements

Analysis Codes - Appropriate three-letter analysis codes that reflect indication orientation and frequency of occurrence shall be adopted. Typical industry codes for indications attributable to cracking include SAI and MAI for single and multiple axial indications, SCI and MCI for single and multiple circumferential indications, and MMI for mixed mode indications in which both orientations are present. The codes used shall be defined in the plant data analysis guidelines.

Final Report Entry - The record of each tube analyzed shall include the tube ID (Row, Column), the signal amplitude (VOLTS), the phase angle (DEG), the 3-letter analysis code, the channel (CH#) from which analysis was made, axial location and test extent for each detected flaw. The angle of inclination of the axial indications with respect to the tube axis will be calculated from the reported data as indicated in 5.3.6.

The axial location should be reported consistently with respect to the top of the tubesheet; this shall apply also to the axial location of the bottom of the explosive *transition and all other W* data requirements. There shall be a separate record for* each indication found at the same location (multiple axial indications) as well as for axial indications at different axial locations.

5.0 MEASUREMENT OF W* NDE PARAMETERS

These guidelines start with the knowledge that a flaw has been detected in the region below the top of tubesheet to which W* applies. The analysis modes chosen below should favor the channel(s), which are most effective in locating and sizing. For example, the pancake coil would measure oblique flaws more effectively over the +Point since the +Point may not reflect the true extent of the flaw.

5.1 Calibration Standards

5.1.1 Table A1 provides a listing of discontinuities suitable for calibration of eddy current systems for many purposes. For the w* application, only EDM notches are required;these are indicated by the shaded cells in Table A1.

5.1.2 Flat-bottom holes - Hole diameters and tolerances for flat-bottom holes (FBH) are as specified by current plant ASME Code requirements.

5.1.3 EDM notches - All EDM notches shall be at least 0.25" long with a width no greater than 0.006" for W* applications. Although not required for W*, it is recommended that new standards have all NDE notches at least 0.35" long and that the 100% EDM notch be 0.5" in length.

5.1.4 Process Channel Reference Signal Sources

In addition to the tube wall discontinuities listed in Table A2, a simulated tube sheet segment 270 degrees in circumferential extent, 0.75" thick, fabricated from SA-285 Grade C carbon steel or equivalent, shall be incorporated into the calibration standard for process channel suppression.

Other reference signal sources e.g., copper, ferrite, etc., may be incorporated into the calibration standard at the discretion of the user.

5.2 Analysis Setup

Rotating probes may employ pancake coils with diameters ranging from 0.080" to 0.125" on probe bodies suitably centered to establish surface-riding contact. For surface-riding coils, fill factor is not a relevant parameter. Probe diameters may be employed as needed to traverse the tube axially, so long as the probe design permits uniform surface contact of the sensing coils. Rotating probes may employ either impedance or transmit-receive technology. While the probe may deploy 1, 2 or 3 coils, it is recommended that voltage measurements be made with a pancake coil rather than a directionally wound coil. The combination of the probe pushing speed and the rotation speed shall be such as would result in a maximum pitch (displacement between scan lines) of 0.040". The NDE uncertainties developed for the

W* measurements were performed using 0.6" per sec pushing speed and 900 rpm rotation speed at a digitization rate of 1000 per second in order to satisfy the requirement for 30 samples per inch in both the circumferential and axial directions.

The setup parameters provided here are applicable to rotating coil probes, which may be fitted with such coils as the 0.115"and/or the 0.080" pancakes or a +Point paired configuration. A specific analysis technique sheet (ANTS) must be completed to show the actual setup parameters for the particular probe type and configuration used.

5.2.1 For each of the rotating coils to be used, establish the primary, support, and process channels required by the ANTS ; additional channels may be established at the discretion of the analyst, but those required by this procedure shall be set up. The lead analyst shall verify that all analysts have correctly established the required channels.

5.2.2 Configure the MRPC display as follows:

a) For left strip chart, select the vertical component of the primary frequency channel of the coil that is best suited to characterize the reported flaw location.

b) For right strip chart, select a low frequency locating coil channel.

c) For Lissajous, select the primary frequency channel for the coil used for the evaluation of the flaw.

5.2.3 Set channel rotation as follows:

Data analysis channels (0.115" Pancake, +Point Axial, 0.08"Pancake):

Set rotation such that the phase of the 40% ID circumferential EDM notch is at 15 Degrees (Peak to Peak).

Locator channel(s):

Set rotation such that the phase response of the TSP or the TTS is in the downward direction at 90°.

Trigger channel:

Set rotation such that the minor pulses are horizontal and the major pulse is upward.

5.2.4 *Set the axial scale between two known artifacts, such as through-wall holes on the calibration standard (refer to the drawing for the as-built dimension).*

5.2.5 *Verify axial speed is consistent with acquisition parameters.*

5.2.6 Select the primary frequency channel, and locate the response of the *center of the 100% axial EDM notch. Set voltage on this signal to 20.00 volt (Peak to* Peak), and repeat for all 3 coils. The voltage may be set on non-analysis channels using the values established for the +Point axial channel.

5.2.7 Establish phase vs. depth curves as described, using ACTUAL percentage values from the appropriate standard drawing for the calibration standard.

a. Establish a 3-point OD curve using the primary frequency channel response from the 100%, 60%, & 40% nominal OD axial EDM notches.

b. Establish a 3-point ID curve using the primary frequency response from the 100%, and 40%, nominal ID axial EDM notches (ID point 3 is 0 degrees = 0%).

If a process channel, such as a mix or filter application, is being used, perform an independent calibration curve as described above.

5.2.8 Adjust the span such that the Lissajous response of the 40% OD axial EDM notch is 50% of full screen (main Lissajous window) height for all applicable analysis channels.

5.2.9 Store setup to disk and media.

5.3 Axial Length Measurement

Axial lengths and distances are critical parameters for engineering evaluation of indications found in the region below the BWT. In principle crack lengths and distances between BWT or the top of the tubesheet are measured by identical processes; only the endpoint features which must be identified differ, e.g., BWT to STR (uppermost crack tip or start of crack), STR to STP (lower crack tip).

5.3.1 Load the tube to be measured and establish TSH + 0.0" reference using the low frequency locating channel. (Figure A5.1)

5.3.2 Locate the bottom of the WEXTEX transition using the best suited channel, (typically the 0.115" mid-range pancake coil at 300 kHz) and enter BWT with the corresponding location into the report. (Figure A5.2)

5.3.3 Locate the null point at the starting end (uppermost crack tip) of the indication, which is the furthest away from the tube end, and enter STR along with the corresponding location into the report. (Figure A5.3)

5.3.4 Locate the null point at the ending end (lower crack tip) of the indication, which is the closest to the tube end, and enter STP along with the corresponding location into the report. (Figure A5.4) The axial length is the difference between the STR and STP scan lines divided by the cosine of the inclination angle.

5.3.5 Measure the circumferential extent in degrees between the start, STR, (corresponding to the uppermost crack tip) and stop, STP (corresponding to the lower crack tip), of the indication. Choose the positions corresponding to the points of maximum amplitude on the STR scan line and the STP scan line. A true axial indication should be close to 0 degrees. Enter this measurement along with the appropriate call (SCI, MCI, SAI, MAI) into the report. (Figure A5.5)

5.3.6 Calculate the inclination angle based on the axial length of the indication and the circumferential extent from start to end.

A = ARCTAN ((D x Pi x C) / 360 / L)

where: A = inclination angle
D = the diameter of tubing
P = 3.14159
C = circumferential extent of the indication from section 5.3.5
L = the axial length of the indication

The diameter used should be appropriate for the type of cracking observed.

5.3.6 Repeat 5.3.3 to 5.3.5 for each axial indication in the tube.

5.3.7 Graphics are required for all locations recorded.

5.4 Depth Measurement of Axial Indications

<u>This guidance is provided in the event that crack profiling is needed. All axial indications will be regarded as repairable upon detection.</u>

5.4.1 Axial crack indications identified in the WEXTEX expanded region from 0.7" or more below the top of the tubesheet or the BWT, whichever is lower, are potentially eligible for retention in service provided they satisfy the W* criteria.

5.4.2 Using the arrow place the cursor at the beginning of the indication (STR, as identified in 5.3.3). Assign 0% to the NDD scan line outside the apparent start of the indication. Move the cursor one line toward the finish (STP) of the indication.

5.4.3 Isolate the signal within the Lissajous window, and perform Peak to Peak measurement. Enter the percentage value, the phase angle, percent depth, and amplitude (voltage) into the report. (Figure A5.6)

If the indication cannot be assigned a depth measurement, the depth for this scan line will be interpolated from the two adjacent scan lines.

5.4.4 Move the cursor to the next scan line of the indication and repeat 5.4.3.

5.4.5 Repeat step 5.4.4 until all scan lines for the axial indication have been entered to the report. Assign 0% to the scan line outside the apparent end (STP) of the indication.

5.4.6 Repeat 5.4.1 through 5.4.5 until all subject axial indications in the tube have been entered to report. Figure A5.7 presents a sample report of a complete data set for a tube with one axial indication.

6.0 APPLICATION OF CRACK PROFILES FOR AVERAGE DEPTH CALCULATION

6.1 Crack Length Averaged Depth

Calculations for crack length average depth are based on the area under the depth/angular position curve divided by the total length of the crack between the leading and trailing endpoints.

6.2 Calculation of Average Crack Depth

From the profile measurements along the axial crack length, perform a weighted average calculation using the individual depth estimates for each scan line.

$$\text{Average Depth} = \frac{\text{Sum}\,(\text{Depth}_i \times \text{Segment}_i\ (\text{inches}))}{\text{Total Length (inches)}}$$

where i = index identifying successive scans of the profile

Engineering calculations to be performed using this approach require that the source of degradation (ID/OD) be known, as well as nominal tube OD, tube wall thickness, % depth estimates from NDE or destructive examination, and the rotation pitch to be applied between successive % depth data points.

Table A1
Calibration Standard Reference Discontinuity Configuration

Orientation	Surface	Location	Depth, %				Comments
			20	40	60	100	
Circ	ID	Freespan	x				
Circ	OD	Freespan	x				
Axial	ID	Freespan	x				
Axial	OD	Freespan	x				
FBH	OD	Freespan	x		x	x	ASME
Circ	ID	Exp		x			
Circ	OD	Exp		x			
Axial	ID	Exp		x			
Axial	OD	Exp		x			

Table A2
3-Coil Probe Head
Test Frequencies

Coil	Primary	Aux 1	Aux 2	Locator
+Point	300 kHz	Optional	100-150 kHz	NA
0.115" Pancake Coil[1]	300 kHz	Optional	100-150 kHz	10-30 kHz
0.080" Pancake Coil[2]	600 kHz	Optional	100-150 kHz	NA

Notes:
[1] Unshielded.
[2] Shielded (800 kHz may be used if the coil design supports it.)

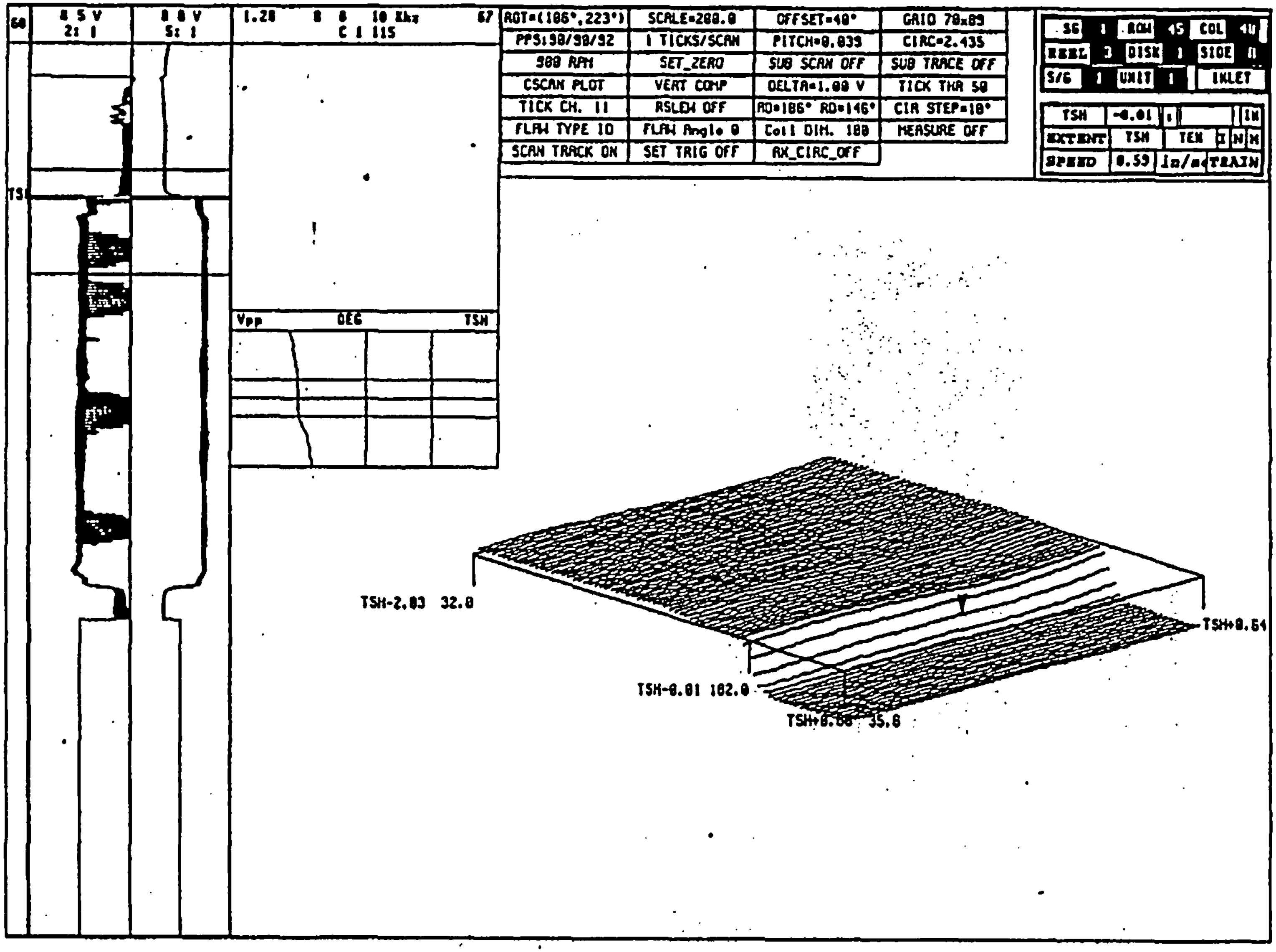


Figure A5.1
Location of the Top of the Tubesheet

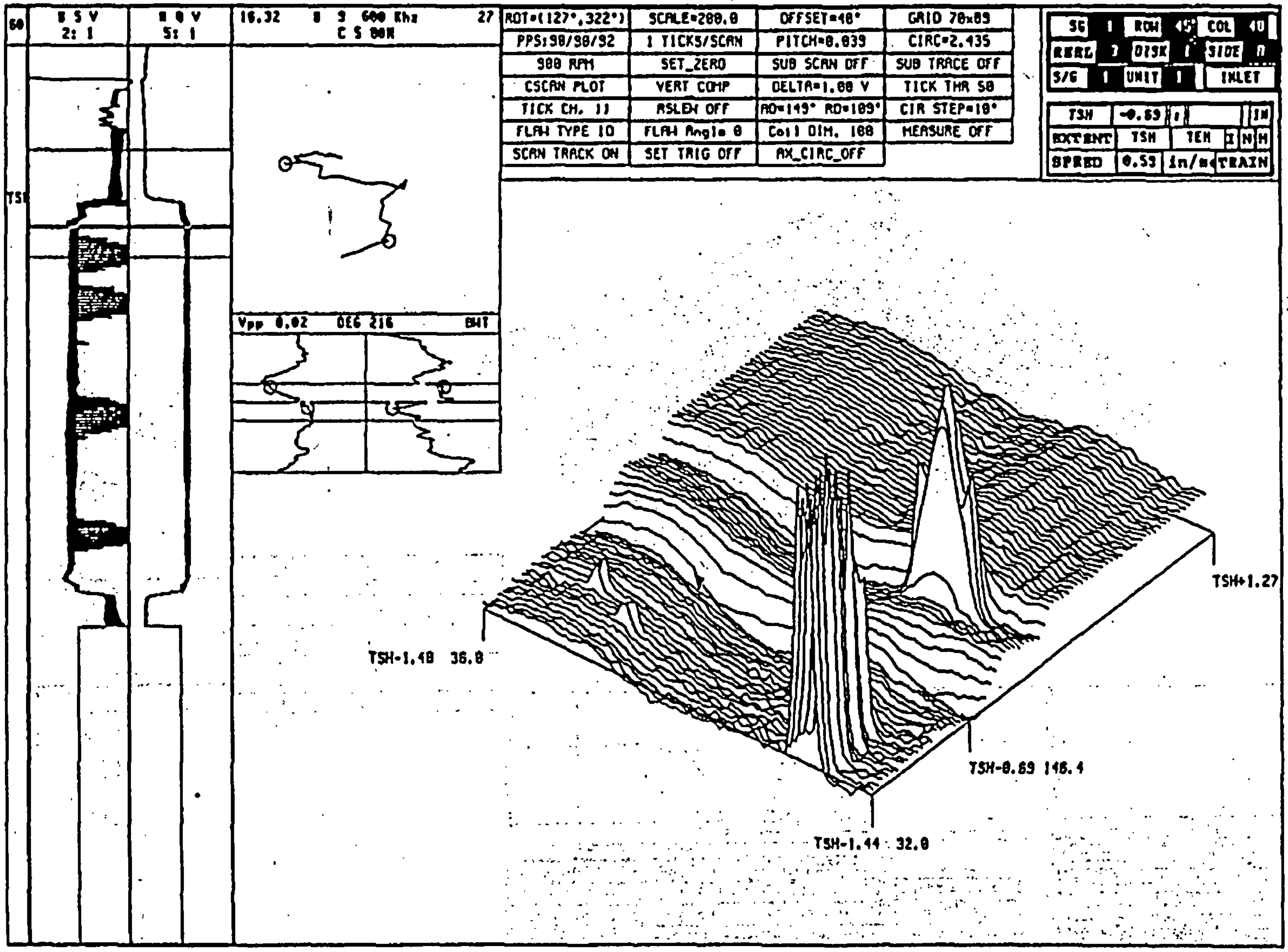


Figure A5.2
Location of the Bottom of the WEXTEX Transition (BWT)

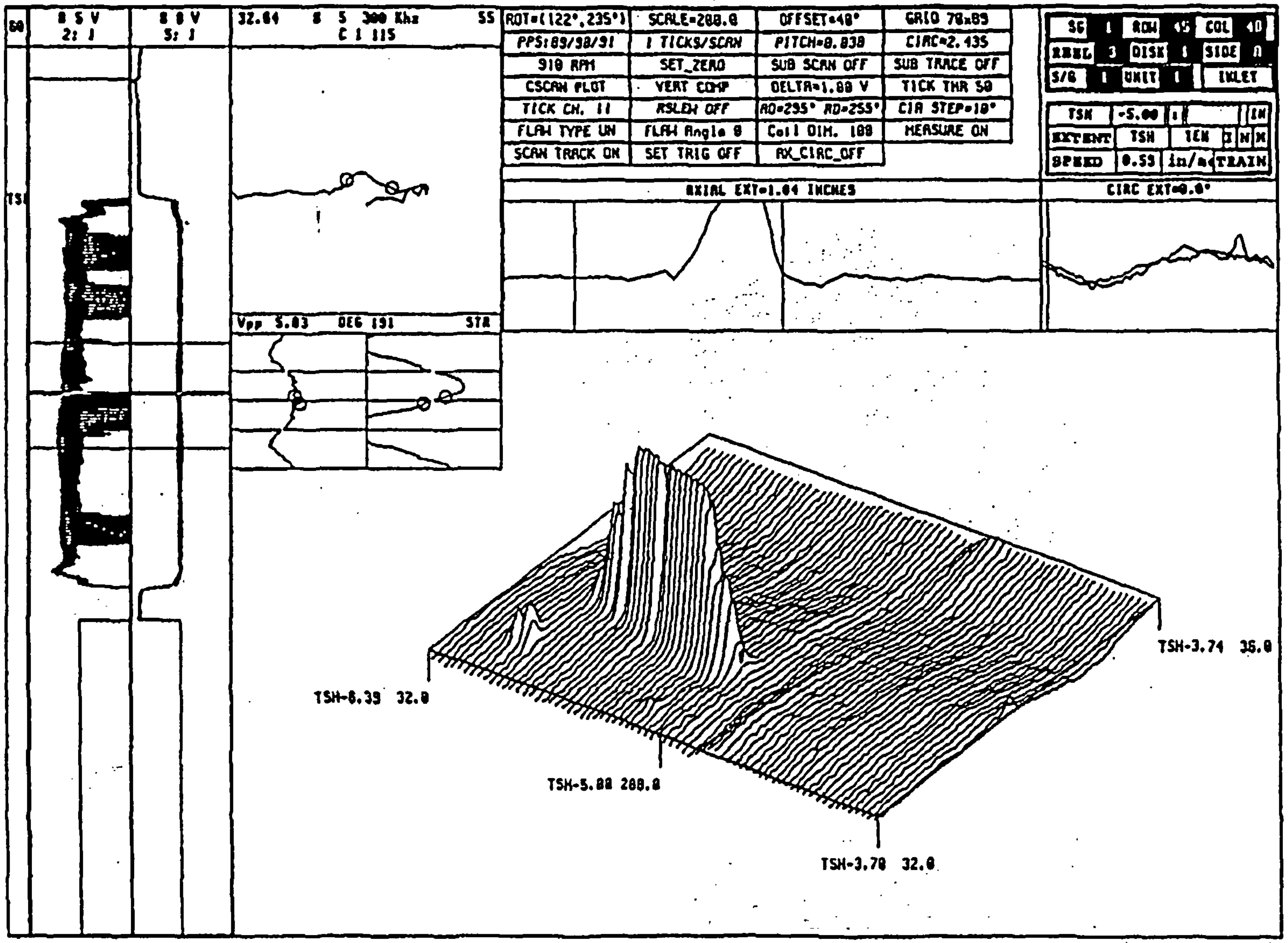


Figure A5.3
Identification of the Uppermost Crack Tip (STR)

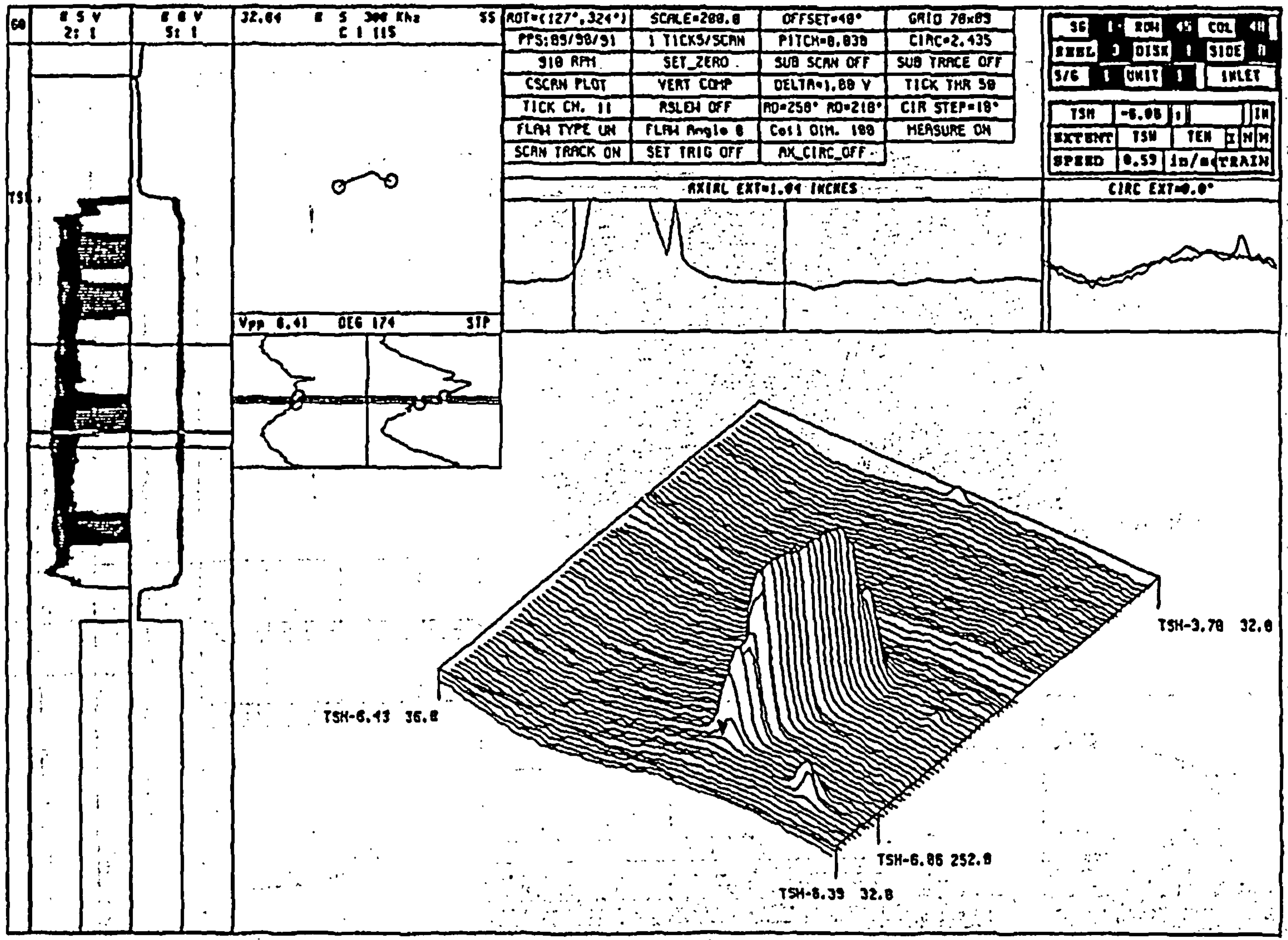


Figure A5.4
Identification of the Lower Crack Tip (STP)

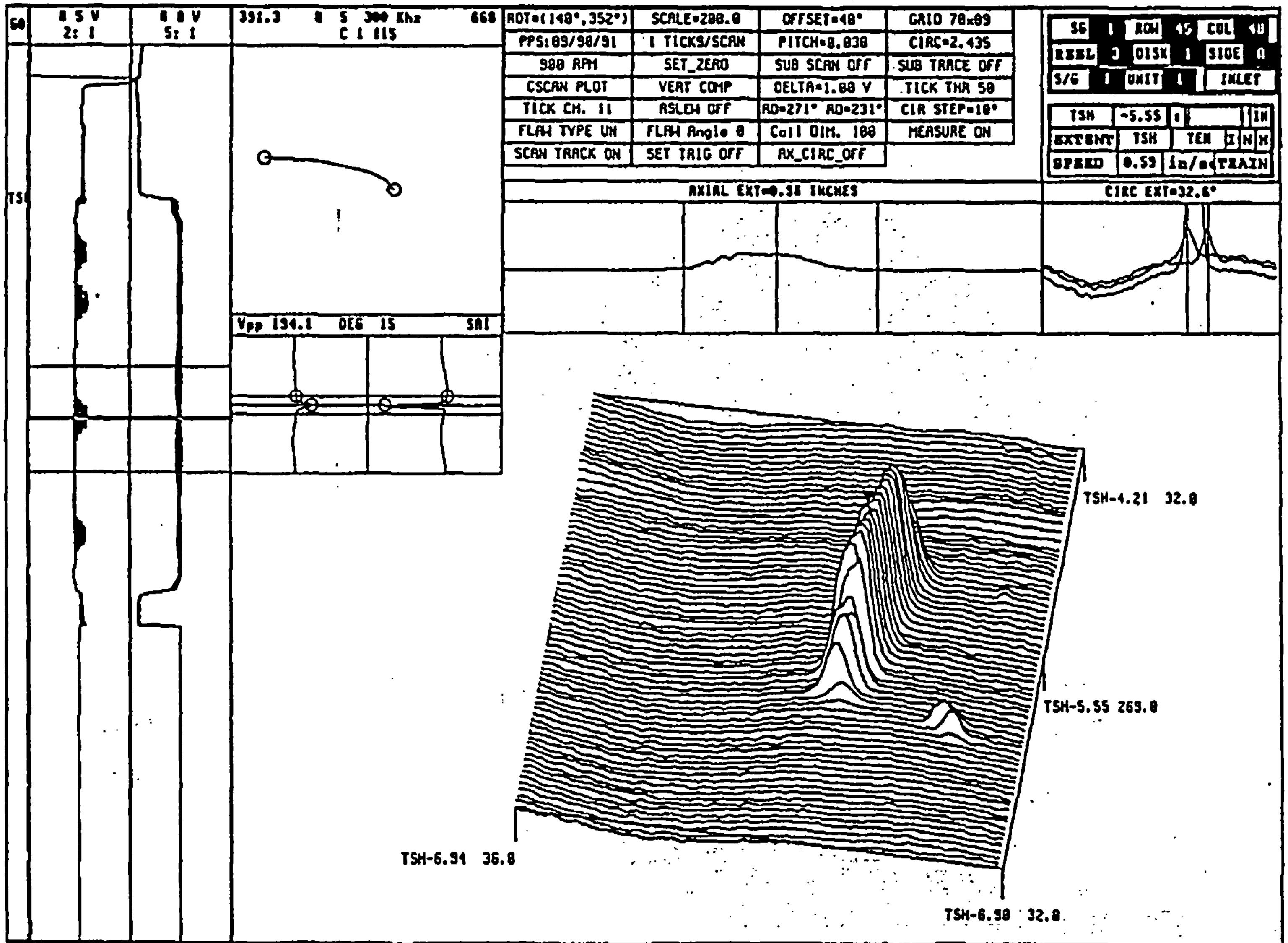


Figure A5.5
Measurement of the Circumferential Extent of the Indication

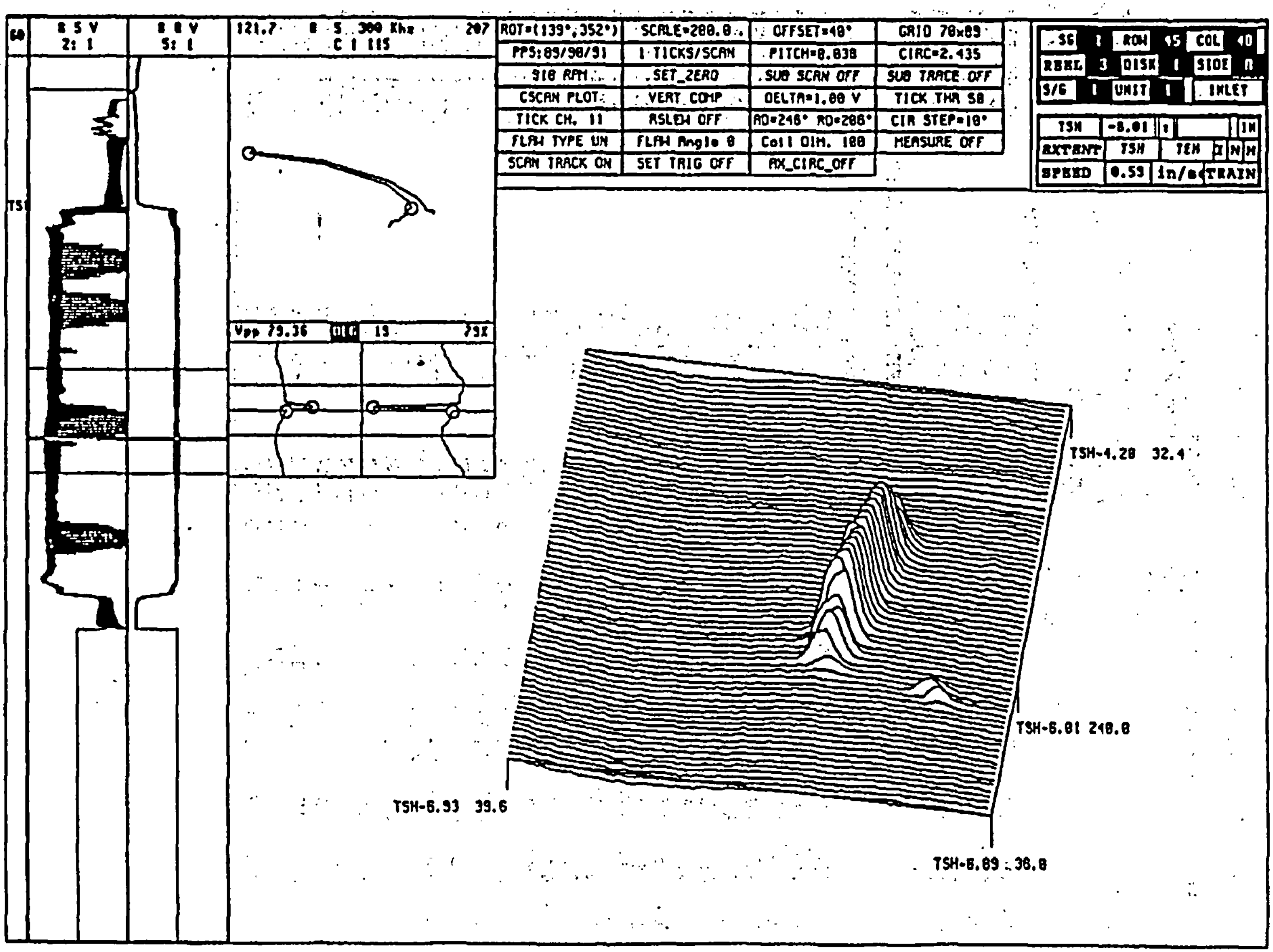


Figure A5.6
Individual Scan Line Depth Measurement for Profiling

PLANT: WALTZ MILL______ UNIT: 1 S/G: 1 LEG: INLET DATE: 11/16/96
REEL: 3

LINE	SG	ROW	COL	VOLTS	DEG	%	CH	LOCATION	BEG	END
1	ANSER 8.1 Rev 64				11/04/96 14			START REEL 3 WPS 1A	PRI	
2						PROBE		115/+PT/80HF		
3						REEL		3		
4								POCRATSKY RJ III	12/07/96	
5								DAWSON FD II	OPERATOR	
6						STD		MGT04294		
7						CAL		0739	11/16/96	
8								START LENGTH MEASUREMENT		
9	1	45	48	8.02	216	BWT	9	TSH -0.69	TSH	TEH
10	1	45	48	7.11	179	STR	5	TSH -5.00	TSH	TEH
11	1	45	48	6.41	174	STP	5	TSH -6.06	TSH	TEH
12	1	45	48	194.1	15	SAI	5	TSH -5.55	TSH	TEH
13	1	45	48	100	33	DIM ID		TSH +962.0	TSH	TEH
14								END LENGTH MEASUREMENT		
15										
16								START DEPTH MEASUREMENT		
17	1	45	48	0.28	95	0	5	TSH -5.12	TSH	TEH
18	1	45	48	0.95	42	88	5	TSH -5.16	TSH	TEH
19	1	45	48	2.86	17	71	5	TSH -5.20	TSH	TEH
20	1	45	48	3.63	9	37	5	TSH -5.23	TSH	TEH
21	1	45	48	5.01	11	46	5	TSH -5.27	TSH	TEH
22	1	45	48	6.43	12	50	5	TSH -5.31	TSH	TEH
23	1	45	48	6.20	14	58	5	TSH -5.35	TSH	TEH
24	1	45	48	6.66	13	54	5	TSH -5.39	TSH	TEH
25	1	45	48	6.54	13	54	5	TSH -5.43	TSH	TEH
26	1	45	48	6.19	14	58	5	TSH -5.47	TSH	TEH
27	1	45	48	6.52	13	54	5	TSH -5.51	TSH	TEH
28	1	45	48	6.17	14	58	5	TSH -5.55	TSH	TEH
29	1	45	48	6.48	13	54	5	TSH -5.59	TSH	TEH
30	1	45	48	6.11	15	62	5	TSH -5.63	TSH	TEH
31	1	45	48	6.55	13	54	5	TSH -5.67	TSH	TEH
32	1	45	48	6.23	14	58	5	TSH -5.71	TSH	TEH
33	1	45	48	6.49	13	54	5	TSH -5.74	TSH	TEH
34	1	45	48	6.32	15	62	5	TSH -5.78	TSH	TEH
35	1	45	48	6.47	14	58	5	TSH -5.82	TSH	TEH
36	1	45	48	6.22	14	58	5	TSH -5.86	TSH	TEH
37	1	45	48	6.33	12	50	5	TSH -5.90	TSH	TEH
38	1	45	48	4.96	10	42	5	TSH -5.94	TSH	TEH
39	1	45	48	3.48	13	54	5	TSH -5.98	TSH	TEH
40	1	45	48	2.59	19	79	5	TSH -6.02	TSH	TEH
41	1	45	48	0.95	51	80	5	TSH -6.06	TSH	TEH
42	1	45	48	0.26	106	0	5	TSH -6.10	TSH	TEH
43								END DEPTH MEASUREMENT		

SIGNATURE ______________________ DATE 12/07/96 09:10:56 PAGE 1/1 EC177

Figure A5.7
Final Report Data for W* Axial Crack Characterization