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North Anna Unit 1 1992
Steam Generator Operating Cycle Evaluation

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TABLE OF CONTENTS

TABLE OF CONTENTS

1.0 INTRODUCTION

This report provides a tube integrity assessment to Reg. Guide 1.121 criteria for end-of-Cycle-9 conditions of the North Anna Unit 1 steam generators. The 1992 mid-cycle inspection results are adjusted to obtain expected end-of-Cycle-9 (EOC-9) maximum crack sizes and crack distributions. Considerations of reduced T_{hot} and the demonstrated effects of an initial RPC inspection (called an "inspection transient") on subsequent cycle indications are used to adjust the mid-cycle inspection results to EOC-9 conditions. Assessments are provided to demonstrate EOC-9 margins against tube burst and tube vibration-induced crack propagation. Potential leak rates under SLB conditions are also evaluated for the EOC-9 crack distributions.

The 1992 mid-cycle inspection program included full length testing with bobbin probes of 100% of the available tubes in each steam generator, RPC examination of all hot leg WEXTEX transitions and all hot leg TSP intersections, and RPC testing of all Row 2 U-bends. The results of the inspection program are evaluated along with planned changes in operating conditions for the remainder of the current fuel cycle to determine the expected end-of-cycle (EOC) crack distributions, including the number and sizes of circumferential cracks. The expected circumferential crack distribution is based on operating cycle length considerations, planned changes in operating conditions for the second half of the fuel cycle, and inspection transient considerations. Although the first and second halves of the current fuel cycle have approximately the same number of effective full power days of operation, a reduction in T_{hot} of 3°F for the second half of the cycle and a coastdown to lower power levels during the last four months of the cycle are expected to result in a reduction in the number and size of circumferential indications at the end of the current cycle. Furthermore, based on industry experience with inspection transients, the number and sizes of TSP circumferential indications at the end of the current cycle are expected to be smaller than the indications observed during the first 100% RPC inspection of the hot leg TSPs performed during the1992 mid-cycle inspection.

The WEXTEX transition and TSP circumferential cracks can be considered "strong" for tube burst considerations in that throughwall crack angles of [ ]b,c meet three times normal operating pressure differentials and throughwall angles greater than [ ]b,c meet SLB burst pressure conditions. North Anna inspection practices and plugging of all circumferential cracks reduce the likelihood of tube burst at SLB conditions to extremely low levels. During the 1992 inspection program, two cracks which exceeded the 226° crack angle for $3\Delta P$ burst capability were found. Thus, one of the principal objectives of this report is to demonstrate that the EOC circumferential crack distributions will satisfy $3\Delta P$ and ΔP_{SLB} burst pressure requirements. The EOC-9 crack distributions are developed from the 1992 mid-cycle 100% RPC inspections of the hot leg WEXTEX and TSP regions. Evaluations of multiple circumferential cracks and mixed mode (axial and circumferential) cracking are performed to demonstrate tube integrity for the EOC-9 conditions. The evaluation of circumferential cracks also includes an assessment of the potential for crack propagation by tube vibration under normal operating and SLB flow conditions.

Tube vibration assessments are particularly sensitive to throughwall crack angles, as small ligaments such as 10% remaining wall or ligaments between microcracks add substantially to the tube stiffness and can effectively eliminate tube vibration concerns. The RPC data provide very limited data on crack depth and generally overestimate the length of the throughwall portion of the indicated circumferential crack length. The tube vibration analyses to assess potential propagation of corrosion cracks are most confidently performed for assumed throughwall cracks. Thus it is necessary to bridge the information gap between RPC crack angles and potential throughwall crack angles which, if present, would be considerably smaller than the RPC crack angles. Based on the extensive North Anna inspections for circumferential cracks, it is reasonable to expect little throughwall crack penetratic [illegible] the remainder of Cycle 9, particularly with operation limits on leakage of 50 g[illegible]. However, it is the goal of this evaluation to provide conservative but realistic assessments of potential crack propagation due to tube vibration. To this end, assessments of the potential for vibration induced crack propagation in the WEXTEX and TSP regions are made using the tube vibration analysis methodology of WCAP-13034.

In the very unlikely event that throughwall or near throughwall cracks may be present that do not leak during normal operation but may leak during a postulated steam line break, SLB leak rates are calculated based on end-of-cycle crack distributions. The SLB leak rates for axial and circumferential cracks are calculated for the expected EOC crack distributions, which are based on reductions in the number and sizes of indications expected at the EOC-9 when compared to those found in the February 1992 mid-cycle inspections. In addition, bounding SLB leak rates are calculated based on the crack distributions found in the 1992 inspections.

Section 2 of this report integrates the detailed results of this report into a summary tube integrity assessment and provides the overall conclusions of this evaluation. The 1992 inspection results for North Anna Unit 1 are described in Section 3. Changes in operating conditions are evaluated in Section 4 to determine relative corrosion rates between the first and second half of the fuel cycle. A summary of crack sizes satisfying Reg. Guide 1.121 is presented in Section 5. The tube integrity assessments for tube burst, LBB, and vibration-induced crack propagation are developed in Section 6. Section 7 summarizes the steam line break leak rate analyses.

2.0 SUMMARY AND CONCLUSIONS

During January - February 1992, mid-cycle inspections of the steam generator tubes were performed for Cycle 9 of North Anna Unit 1. The eddy current inspections included RPC testing of 100% of the hot leg TSP intersections and WEXTEX expansion transitions. The number of tubes plugged for indications at the TSPs was significantly higher than the number plugged in previous inspections. The increase in the number of TSP indications and the large crack angles observed have been attributed to the initial application of RPC probes to all of the HL TSP intersections; it is judged that a significant number of the indications detected in 1992 existed during previous inspections, but were not detected due to denting at the TSPs until the use of the more sensitive RPC probes. This report evaluates the acceptability of continued operation for the remainder of Cycle 9, and updates the Cycle 9 operating cycle evaluation performed in WCAP-13034. Cycle 9 prior to the mid-cycle inspection included 254 effective full power days (EFPD) at essentially 100% power. The remainder of Cycle 9 includes 252 EFPD with about 2/3 of the cycle at 95% power and the remaining time in a coastdown mode at lower power levels.

2.1 Overall Conclusions

From the results of this evaluation, it is concluded that:

- Operation of the North Anna Unit 1 SGs to the end of the second half of Cycle 9 is acceptable and Reg. Guide 1.121 criteria will be met at the end of the cycle. This conclusion is based on the expected fewer and smaller indications at EOC-9 compared to the mid-cycle inspection results, which satisfy Reg. Guide 1.121.

- Based on the reduced power level and four month coastdown period planned for the second half of Cycle 9, it is expected that there will be at least a 7% reduction in both the the number of newly initiated cracks and the growth rates of existing cracks which were undetected during the 1992 mid-cycle inspections.

- The use of RPC probes to inspect 100% of the hot leg TSP intersections in all three SGs during February 1992 produced a significant increase in the number of tubes plugged for indications at the TSP elevations. Industry experience has shown that during the next inspection following the initial application of more restrictive eddy current analysis guidelines or the use of the more sensitive (at tube diametral changes such as dented intersections) RPC probe, there is a significant decrease in both the number and size of indications observed. Based on such inspection transients for the WEXTEX regions of the North Anna steam generators and for tubesheet and TSP regions of other operating plants, the number of axial and circumferential indications at the TSPs at the end of the current cycle are expected to be reduced to about 2/3 of the mid-cycle inspection results. The inspection transient is also expected to result in a reduction of about 8% in the circumferential crack angles at the TSPs. The 8% reduction in crack angles is based on North Anna Unit 1 experience for WEXTEX indications.

- The 7% reduction in crack growth from the reduced power conditions would apply to both growth in depth and in crack angle. However, the RPC probes can only measure crack angle with confidence. Thus, the 7% reduction is only applied to the crack angle growth rate. The largest crack growth rates found at the TSPs were 39° and 45° for the first half of the current fuel cycle. A 7% reduction in the largest crack growth rates would reduce growth by about 3°. Hence, the reduced power operating conditions are expected to result in a reduction in crack angles of about 3° in comparison to those measured in the 1992 mid-cycle inspection. This reduction is applied for circumferential indications at the WEXTEX transition and at the TSPs.

- The largest WEXTEX circumferential indication observed in the 1992 mid-cycle inspection was 199°, which is less than the 226° and 297° required to meet 3ΔP burst capability for throughwall and segmented cracks, respectively. Two circumferential indications at the TSPs had overall crack lengths (240° and 239°) which exceeded the 226° limiting crack angle for 3ΔP for a uniform, throughwall crack. However, the deepest parts of these cracks measured 134° and 96°, much less than the 226° limiting throughwall crack angle. Furthermore, applying the 8% and 3° reductions in TSP crack angles expected for the end of the current cycle results in maximum expected TSP circumferential crack angles of 218° and 217°. Therefore, all EOC circumferential indications are expected to meet the 3ΔP burst capability guideline of Reg. Guide 1.121.

- The TSP intersections of the North Anna Unit 1 SGs have experienced denting to the extent that axial cracks within the TSP thickness are judged not to open, even during a postulated SLB event. The denting would prevent the TSPs from moving relative to the tubes during a SLB. Therefore, only axial cracks extending above or below the TSP edges are accounted for in the tube integrity and SLB evaluations. The maximum axial crack length measured outside the TSPs during the 1992 mid-cycle inspection was 0.49 inch; this is less than the crack length of 0.72" which meets $3\Delta P$ burst criteria for the segmented crack morphology. The axial crack lengths from the 1992 mid-cycle inspection are conservatively applied for the expected EOC crack distribution. Therefore, all EOC axial indications are expected to meet $3\Delta P$ burst capability for Reg. Guide 1.121.

- Potential leakage at SLB conditions can be bounded by leakage from the estimated crack distributions at EOC conditions. The SLB leak rate for the expected EOC crack distribution is [ ]^{b,c}. The bounding SLB leak rate, assuming the crack distributions from the 1992 inspection apply for the EOC, is calculated to be [ ]^{b,c}.

- The administrative leak rate limit of 50 gpd provides large leak before break margins against tube burst at $3\Delta P_{N.O.}$ for assumed throughwall cracks and against burst at SLB conditions, even for leak limiting segmented crack morphologies.

- Corrosion crack propagation due to tube vibration is not expected for the range of circumferential crack sizes expected at the end of the current cycle. Even in the very unlikely event that crack propagation should occur, the North Anna leakage monitoring system and administrative procedures would provide detection and plant shutdown prior to a large leakage event approaching tube rupture. The North Anna leakage monitoring procedures would initiate plant shutdown following leakage exceeding 50 gpd in a single SG; plant shutdown would be completed within 2 hours.

2.2 Summary of Principal Results

The January - February 1992 mid-cycle inspection at North Anna Unit 1 encompassed full length testing with bobbin probes of 100% of the available tubes in each steam generator. The bobbin data was used to evaluate the condition of all free length tubing, including all U-bends with the exception of Row 2. The Row 2 U-bends were inspected with RPC probes. 100% of the available hot leg WEXTEX regions were also inspected with RPC probes; this marked the second time 100% RPC inspection of the hot leg tubesheet region was performed at North Anna Unit 1, the first being in Spring 1991 prior to Cycle 9 operation. During January 1992, comparison testing of the 8x1 arrayed pancake probe and the RPC probe on indications at the TSPs showed that in most cases, it was necessary to make conservative and probably false 8x1 calls to achieve more than 90% detection of the signals identified by RPC testing. This was attributed to the inability to discriminate effectively between liftoff signals at the dented TSP intersections and crack indications at the TSP edges. Therefore, an inspection program encompassing RPC testing of 100% of the TSP intersections was undertaken. This represented the first application of 100% RPC inspection to the TSPs at North Anna Unit 1.

Table 2-1 summarizes the tube plugging summary for the January - February 1992 inspection program. Three tubes were plugged for free span bobbin indications. 36 tubes were plugged for axial or circumferential RPC indications in the WEXTEX transition region. 469 tubes were plugged for RPC indications at the hot leg TSP intersections. 19 tubes were plugged preventively.

Of the 36 tubes plugged for WEXTEX indications, 31 were classified as circumferential cracks and 5 were classified as axial cracks. These indications were similar in appearance and EC characteristics to indications observed in prior inspections. The crack morphology is predominantly PWSCC. Tube pulls in prior outages have shown the cracks to be comprised of numerous microcracks with aspect ratios (length/depth) of 4/1 to 6/1, separated by nearly full depth ligaments. The segmentation of the WEXTEX cracks enhances the strength and stiffness of the tube with respect to an entirely throughwall crack; this segmentation is accounted for in the assessment for vibration induced crack propagation (Section 6.6) and the SLB leak rate analyses (Section 7.0).

A total of 212 tubes were identified with circumferential crack indications at the TSP elevations. The phase angles observed in the 1992 TSP circumferential crack population are consistent with the behavior observed in prior inspections, and are indicative of ODSCC. Pulled tube examinations during the 1991 inspection showed that 60% of the total RPC arc length was throughwall. A similar crack morphology is expected for the 1992 TSP circumferential indications. Since the detectable threshold depth for RPC probes is about 50% depth for OD circumferential cracks, the model for TSP circumferential cracks has 60% of the total RPC measured crack angle as through wall and the portion of the tube circumference apparently free from degradation has 50% deep undetected cracking. While this model is applied for SLB leakage analysis, tube burst capability for EOC-9 is conservatively demonstrated assuming the total RPC angle is throughwall.

A total of 286 tubes were identified with axial cracks at the TSP elevations. Almost half of these indications were at the first TSP, and 77% were at the first two TSPs; this distribution was similar to those found in earlier inspections when detection was accomplished by bobbin probes. The dominant crack morphology of the TSP axial indications is PWSCC, based on tube pulls performed in 1985 and 1987. The TSP PWSCC axial cracks exhibit multiple initiation sites with numerous microcracks comprising the macrocrack lengths identified in the RPC inspection. As observed in the WEXTEX PWSCC circumferential cracks, the microcracks comprising the TSP axial cracks exhibit aspect ratios of 4/1 to 6/1 and are separated by nearly full depth ligaments. Due to the presence of denting at nearly all of the TSP intersections, the axial cracks within the dented TSP crevices are not expected to open up, even during postulated SLB conditions; the denting would keep the TSPs from moving relative to the tubes during a postulated SLB event. For the tube burst and steam line break leak rate analyses, only the portions of the axial cracks extending above or below the edges of the TSP are considered. All of the axial indications detected at the TSP elevations have been plugged.

The largest WEXTEX circumferential indication, measuring 199°, was observed in R25C36 of SG B. Throughwall crack angles of up to 226° and segmented crack angles of up to 297° are shown to meet the 3ΔP burst capability requirement of Reg. Guide 1.121. Therefore, all of the WEXTEX indications observed satisfied the 3ΔP burst requirement.

Two circumferential indications at the TSP elevations had RPC crack angles which exceeded 226° for a uniform, throughwall crack; these tubes were R34C42-2H (240°) and R18C39-1H (239°), both in SG A. The deepest parts of these cracks measured ~134° and ~96°, respectively. Hence, the potential throughwall portions of these cracks were less than the 226° throughwall angle required for 3ΔP burst capability.

Based on operating cycle considerations and inspection transient considerations, the largest crack angles for the crack distribution at the end of the current operating cycle would be smaller than found at the last inspection and are expected to meet 3ΔP burst capability even if the RPC crack angles are very conservatively assumed to be uniformly throughwall cracks. These considerations are discussed below.

During the second half of the current fuel cycle, the North Anna Unit 1 steam generators will be operated at reduced load (95% power) with a lower primary coolant temperature than during the first half of the cycle. During the final four months of the fuel cycle, the plant will be in a coastdown mode at progressively lower power levels to conserve fuel. The durations of the first half of the current cycle (254 EFPD) and the second half of the cycle (252 planned EFPD) are approximately the same. Based on this data, the relative corrosion rates during each half of the current fuel cycle have been evaluated. Assuming that the operating chemistries for the two periods are comparable, the variation in relative corrosion for normalized corrosion activation energies ranging from 160 kcal/mole to 50 kcal/mole has been determined. For the highest activation energy evaluated, the total corrosion during the second half of the fuel cycle is expected to be 63% of that observed during the first half of the cycle. Using the lowest, most conservative activation energy evaluated, the total corrosion during the second half of the fuel cycle is expected to be approximately 93% of that observed following the first half of the cycle. The variation in relative corrosion based on the most conservative activation energy is applied for the EOC crack distribution, even though the reduction in the number of indications with TSP elevation would imply a larger activation energy. Hence, the reduced power and EOC coastdown for the second half of the current fuel cycle are expected to lead to at least a 7% reduction in the number of newly intitiated cracks and in the growth rates of existing cracks which were undetected during the mid-cycle inspection. For the circumferential cracks at the WEXTEX region and TSPs, the 7% reduction in growth rates would result in a reduction of the largest crack angles by about 3°.

In addition to a reduction in the sizes and number of indications due to operating cycle considerations, the TSP crack distribution for the end of the current cycle is also expected to show a reduction in the number and size of TSP indications based on the first time application of RPC testing at 100% of the hot leg TSPs in 1992. Industry experience has shown that during the first use of revised EC analyst guidelines or the initial application of the more sensitive RPC probe to 100% of the tubesheet region, the number of indications increases substantially over the indications observed during previous inspections. During the first inspection after the initial application of the revised analyst guidelines or more sensitive probe, both the number and size of indications decrease substantially when compared to the previous outage. This phenomenon is called an "inspection transient". Section 3.11 presents inspection transient data for the tubesheet regions of five plants, including North Anna Units 1 and 2, and for the TSP regions of three plants, including North Anna Unit 1. Based on the data presented, it is judged that many of the tubes plugged for indications during the inspection transients had cracks which existed during prior inspections, but were not detected until the use of the more sensitive probe or revised analysis guidelines. Furthermore, it is judged that the significant level of denting in the North Anna Unit 1 SGs has contributed to the inability to detect the cracks at the TSPs until the use of the more sensitive RPC probe at all TSP intersections. The number of TSP circumferential indications at the end of the current cycle is expected to be less than 2/3 of the indications observed during the mid-cycle inspections.

The first RPC inspection of 100% of the WEXTEX region at North Anna Unit 1 occurred in the Spring 1991 inspections prior to Cycle 9 operation. Hence, the second 100% RPC inspection of the WEXTEX transitions during January - February 1992 resulted in fewer tubes plugged for WEXTEX circumferential indications; therefore, no change in the number of WEXTEX indications is expected for the end of the current cycle, other than that associated with the lower T_{hot} as described above.

For the TSP axial indications, the crack lengths observed during the 1992 inspections are conservatively applied for the end-of-cycle crack distribution. However, based on the significant increase in the number of axial indications at the TSPs as the result of the 100% RPC inspection transient, the number of axial indications at the end of the current cycle is expected to be 2/3 of that observed in the 1992 mid-cycle inspection. The crack distributions expected at the end of the current fuel cycle, based on operating cycle considerations and inspection transient considerations, are based on modifying the 1992 mid-cycle distributions as follows:

WEXTEX Circumferential indications

- reduction in crack angles by 3°
- no change in the number of indications

TSP Circumferential Indications

- reduction in crack angles by both 3° and 8% of the last inspection results
- number of indications reduced to 2/3 of last inspection

TSP Axial Indications

- no change in crack length
- number of indications reduced to 2/3 of last inspection.

The reduction in WEXTEX indications for EOC-9 is negligible and acceptable burst capability has been demonstrated for the indications found at the mid-cycle inspection. For the TSP circumferential indications, the reduced T_{hot} and the RPC inspection transient lead to expected EOC crack angles less than 218°. Since the expected cracks are less than the 226° for 3ΔP burst capability of throughwall cracks, the EOC-9 conditions satisfy Reg. Guide 1.121 even if the total RPC angle is assumed to be throughwall.

Steam line break leak rate analyses have been performed for the expected end-of-cycle crack distributions. The leak rate contributions from the expected WEXTEX circumferential, TSP circumferential and TSP axial crack distributions are calculated to be 0.6 gpm, 12.8 gpm, and 3.4 gpm, respectively. Axial cracks in or above the WEXTEX region are not considered to contribute to the SLB leak rate, since all axial cracks exceeding 40% through wall depth are plugged before returning to power and throughwall cracks are not expected during the remaining one-half cycle of operation. The total SLB leak rate for the expected EOC crack distribution is estimated to be 16.8 gpm. In addition, a bounding SLB leak rate is calculated by conservatively applying the1992 crack distributions for the WEXTEX and TSP regions for the end-of-cycle. The bounding SLB leak rate would be approximately 30.5 gpm.

A tube vibration assessment has been performed to determine the potential for crack propagation driven by turbulent and fluidelastic tube vibration. The minimum crack angles for crack propagation are calculated for circumferential cracks at the WEXTEX transition and at the TSPs. None of the WEXTEX circumferential cracks observed after the first half of the current cycle had crack angles which were subject to crack propagation due to tube vibration. For the TSP regions, the potential for tube vibration induced crack propagation is significant only for indications at the bottom edge of the first TSP. None of the circumferential indications observed at the bottom of the first TSP during the 1992 mid-cycle inspection program had crack angles which exceeded those required for crack propagation. As previously described, the crack angles for the WEXTEX and TSP regions at the end of the current cycle are expected to be smaller than those observed during the 1992 mid-cycle inspection. Therefore, none of the circumferential indications at the TSPs or WEXTEX transitions are expected to experience tube vibration-induced crack propagation.

Table 2-1

North Anna Unit 1 Tube Plugging Summary - February 1992

Indication	Probe Type	Number of Tubes Plugged SGA	SGB	SGC
WEXTEX (Hot Leg)	RPC	15	10	11
TSP (Hot Leg)	RPC	143	148	178
Free Span	Bobbin	1	0	2
Preventive		7	2	10
Total 1992 Plugging		166	160	201
Cumulative SG Plugging		629	585	851
		(18.6%)	(17.3%)	(25.1%)

3.0 EDDY CURRENT DATA REVIEW

3.1 Inspection Summary

The 1992 North Anna Unit 1 steam generator inspection program encompassed full length testing with bobbin probes of 100% of the available tubes in each steam generator. The data from this program was used to evaluate the condition of all free length tubing, including the U-bend portions, except for Row 2 U-bends. Comparison testing of the 8x1 arrayed pancake probe and the RPC probe was conducted on indications at the TSPs. The comparison tests showed that in most cases, it was necessary to make conservative and probably false 8x1 calls to achieve more than 90% detection of the signals identified by RPC testing. This was attributed to the inability to discriminate effectively between liftoff signals at the dented TSP intersections and crack indications at the TSP edges. Utilization of the 8x1 probes with a high overcall rate and RPC verification was judged to be less efficient than RPC testing alone. Therefore, an inspection program encompassing RPC testing of 100% of the TSP intersections was undertaken. All hot leg (HL) WEXTEX transitions and HL tube support plate intersections, whether dented or not, were inspected with RPC probes. Additionally, all Row 2 tubes were tested through the U-bends with RPC probes.

The eddy current (EC) analysts were required to pass site specific examinations approved by the Virginia Power NDE Level III. All data was analyzed independently by two analysts. Resolutions of conflicts arising between primary and secondary analysts were performed by Westinghouse lead analysts, in concert with procedures jointly established with the Virginia Power NDE Level III and overseen independently by Virginia Power Quality Assurance.

3.2 Tube Plugging Summary

Through the end of 1991, cumulative tube plugging of 15.1% (1538 tubes) had accrued; this was distributed among the steam generators as follows: SG A, 13.67% (463); SG B, 12.54% (425); SG C, 19.18% (650). The incremental plugging resulting from the January-February 1992 inspection is summarized in Table 3-1. Of the 527 tubes plugged during this outage, most were identified by RPC inspection at the tube support plates (469) and the WEXTEX transition zones (36); 3 were identified on free length tubing by bobbin probes and 19 were preventively plugged. After completion of the 1992 plugging, 2065 tubes (20.31%) have been plugged cumulatively; these are distributed among the three steam generators as follows: SG A, 18.6% (629); SG B, 17.3% (585); SG C, 25.1% (851).

3.3 WEXTEX Indications

All flaw indications identified by RPC testing in the WEXTEX region were regarded as sufficient basis for plugging the tubes on which they were found. Of the 36 such tubes, 31 were classified as circumferential cracks and 5 as axial cracks. On five of the tubes, more than one circumferential crack was reported; these were designated MCI (multiple circumferential indication) as distinguished from SCI for single circumferential indications; there were no multiple axial indications (MAI) reported. Table 3-2 summarizes the distribution of the WEXTEX RPC indications by type for each steam generator. Figures 3-1, 3-2 and 3-3 present the plan views for steam generators A, B, and C respectively; these show the distribution of the WEXTEX indications.

3.3.1 Location of WEXTEX Indications

By far, the predominant location of the circumferential indications observed in the North Anna Unit 1 WEXTEX region is within the first 0.2" below the top of the tubesheet (TTS); only 2 of the 31 circumferential indications reported were above this, and those were within 0.1" of the TTS. One circumferential indication was more than 0.2" below (0.28") the TTS. By contrast, 3 of the 5 axial indications were more than 0.1" above the TTS, while 2 were within the 0.1" just below the TTS.

3.3.2 Crack Morphology

The WEXTEX crack indications recorded in the February 1992 inspection are similar in appearance and EC characteristics to the prior indications. The predominant aspect of these signals from EC data is the ID origin, indicated by the phase angle data associated with the RPC signals which, were classified mainly as circumferential, with a small number appearing axial in orientation. Although the phase angles are typically offset in combination with the transition effects, the WEXTEX phase angle observations as a group lie in the ID range of flaw behavior, distinctly different from the phase angles associated with the TSP/dent circumferential signals which are grouped in the OD range of flaw behavior. The ID-originated cracks in the WEXTEX zone are characterized as cracks with multiple initiation sites, with resulting numerous microcracks comprising the macrocrack detected by the RPC probe. Tube pulls in 1985 and 1987 examined ID-originated cracks of this type and established that the individual microcracks detected have aspect ratios of 4/1 to 6/1 separated by nearly full depth ligaments. The deepest cracks are typically within a macrocrack or adjacent microcracks for which the separating ligament may have been lost by corrosion. No significant cracking is found other than the essentially continuous macrocrack. As for the 1991 analysis, the PWSCC cracks are represented by a ligament model with 0.2 to 0.3 inch long, deep (assumed throughwall) segments separated by ligaments (assumed wall thickness). An elastic ligament model is used to size the width of the ligaments such that the ligaments remain elastic under normal operating pressure differentials, which results in ligaments with about 0.050 inch width for 0.2 inch throughwall segments.

3.3.3 WEXTEX Circumferential Arc Lengths

Individual SCI's exhibit lengths measured in degrees arc length, ranging from less than 60° (very few) to 199°. By contrast, the 1991 inspection results included WEXTEX crack arc lengths up to 247° and the 1989 inspections included arc lengths up to 300°. Figure 3-4 compares the size distributions for the 1991 and 1992 inspections. The smaller number of circumferential cracks reported in 1992 (31) compared to 1991 (216) reflects the shorter operating period prior to shutdown but more importantly, the effect of the 1991 inspection transient; i.e., the 100% RPC inspection performed in the WEXTEX region in 1991 was the first such inspection applied in North Anna Unit 1 (see Section 3.11).

3.4 TSP Circumferential Indications

RPC examination of the assumed dented TSP's in the North Anna 1 steam generators resulted in identification of 212 tubes with circumferential crack indications (SCI & MCI) Table 3-3 provides a breakdown of the distribution of these cracks for each of the steam generators with respect to TSP elevation. Figures 3-5, 3-6 and 3-7 display the planar composite distribution of these indications for steam generators A, B and C respectively.

The arc length distribution of the observed TSP circumferential crack population is presented in Figure 3-8, together with the comparable 1991 distribution. It is seen that the 1992 population is much larger than that observed in 1991; this is a manifestation of the inspection transient resulting from the first application of 100% RPC testing to the support plate intersections. The 1991 population (93 tubes) represents only those cracks confirmed by RPC examination after detection by bobbin or 8x1 probe testing. Because prior detection by bobbin or 8x1 probes was required before RPC testing, only ~540 intersections were tested with RPC. This excludes those 7th support plate locations RPC tested in conjunction with NRC Bulletin 88-02 concerns. The 1992 inspection on the affected support plates (1-5) encompassed more than 50,000 intersections, a nearly 100-fold increase in RPC scope.

The 1992 inspection transient resulted in increased numbers of indications as well as longer arc lengths. Cracks which were previously undetected were reported in the 1992 initial 100% RPC inspection, including some with long arc lengths. The largest arc lengths found were in SG A at R34C42-2H and R18C39-1H, with RPC crack angles of 240° and 239°, respectively; these were the only two indications exceeding 226° for 3ΔP burst capability. The characterization of 8x1 signals observed in 1991 was apparently unable to discriminate effectively between liftoff signals at the dented intersection and crack indications at the TSP edges. This effect was confirmed in 8x1 vs. RPC comparison tests performed at North Anna 1 in January 1992. In these tests, it was necessary to make conservative and probably false 8x1 calls to achieve ≥90% detection of the signals identified by RPC testing.

3.4.1 Crack Morphology for Tube Integrity Assessments

The TSP circumferential crack population observed in 1992 exhibits phase angles usually associated with OD origin degradation. This is consistent with the behavior of the 1991 population, as well as the findings of the tube examination (R11C14-1H) for the circumferential cracks. In that examination, it was observed that 60% of the total arc length associated with the main crack at the upper edge was throughwall. For the 1992 evaluation, it is assumed that the observed circumferential cracks are similar to those found in 1991, i.e., ODSCC consisting of macrocracks formed by linkup of individual microcracks followed by corrosion of the separating ligaments. The portion of the tube circumference apparently free from degradation based on RPC results is assumed to have 50% deep undetected cracking.

3.5 TSP Axial Indications

The RPC examination of 100% of the hot leg support plate intersections in S/G's A, B and C resulted in identification of 286 tubes with axial cracks, with 98, 87 and 101 indications in each SG, respectively. As indicated in Table 3-4, these indications were distributed with almost half at the 1H level and 77% at the first two plates. This distribution is similar to those found in earlier inspections (e.g. 1985, 1987, 1989, 1991) when detection was accomplished by bobbin probes. Figures 3-9, 3-10 and 3-11 display the planar composite distributions for the TSP axial indications. Again, the pattern is similar to those observed in prior inspections. Neither the circumferential ODSCC indications nor the axial (PWSCC) indications display any preference for localized clustering at the TSP elevations. Comparing 1992 inspection results with those from 1991 shows that the tubes plugged for axial cracks in 1992 arise mainly (63%) from cracks not detected by bobbin at the edges of dented intersections while cracks in this category accounted for only 13% of 1991's tube plugging for axial cracks. Therefore it is likely that the 286 tubes plugged in 1992 for axial cracking reflect the RPC inspection transient described above rather than accelerated PWSCC during the 9 month operating interval just prior to the inspection. Cracks undetected by the bobbin probe are masked by denting at the TSP and the RPC probe is better suited to detect them because its surface-riding feature reduces the influence from the dent interference. It is estimated that the "new" axial crack population identifiable by bobbin in the 1992 inspection accounts for ~120 of 287 tubes, approximately half the number plugged on that basis in 1991, during an inspection that followed an uninterrupted operating cycle.

3.6 Crack Morphology

Tube pulls performed in 1985 and 1987 have characterized the dominant morphology associated with axial cracks in the dented TSP intersections of North Anna 1 as PWSCC with multiple initiation sites and numerous microcracks adding up to the macrocrack lengths typically identified in RPC inspections. Aspect ratios (length/depth) of 4/1 to 6/1 are associated with the individual microcracks which are separated by nearly full thickness ligaments. The deepest cracks are typically within a macrocrack or adjacent microcracks for which the separating ligament may have been lost by corrosion. No significant cracking is found other than the essentially continuous macrocrack. For analysis, the PWSCC cracks can be represented by a ligament model with 0.2 to 0.3 inch long, deep (assumed throughwall) segments separated by ligaments (assumed full thickness). An elastic ligament model is used to size the width of the ligaments such that the ligaments remain elastic under normal operating pressure differentials, which results in ligaments of about 0.050 inch width for 0.2 inch throughwall segments.

3.6 Multiple Circumferential Indictions (MCI's)

3.6.1 WEXTEX MCI's

Of the 31 tubes identified with circumferential cracks in the WEXTEX expansion zone, there were 5 which exhibited MCI's. Table 3-5 provides a listing of the individual tubes, along with the elevation of indications, the arc lengths and ligaments observed, and the total crack arc lengths. The smallest ligament observed was 12° on S/G A R24C33 which, adjusted for RPC resolution capability (see Section 3.8), represents ~42° separation between cracks. The apparent total crack arc length is 234° (149° + 85°); with resolution corrections for coil lead-in and lead-out effects assuming deep cracks, this is reduced to about 174°. On this basis, all MCI ligaments observed exceed the 30-35° ligament size required for MCI burst capability to exceed that of a single crack with a 70° ligament (see Section 5.4). All the observed WEXTEX MCI's meet the 3ΔP burst capability (see Section 6.2).

3.6.2 TSP MCI's

A total of 212 tubes were plugged for TSP circumferential cracks; of these 13 exhibited MCI signals on the same elevation (i.e. support plate edge). Table 3-6 provides a list of these tubes, the elevations, and the crack and ligament lengths observed. The minimum ligament observed in these MCIs was ~41°, which amounts to ~71° after RPC resolution adjustment for lead-in/lead-out coil effects. Thus the observed ligaments exceed the 60-70° size required to establish MCI burst capability at 3ΔP conditions (Section 5.4); hence, all of the TSP MCI's meet the 3ΔP burst capability requirements (Section 6.3).

3.7 Potential Combined Axial and Circumferential Indications

Of the 469 tubes plugged for axial and circumferential indications at support plates, there were 13 tubes (14 TSPs) which displayed both axial and circumferential indications at the same TSP. Seven (7) of these instances involved axial cracks either entirely within the TSP dimensions or on the opposite edge from the circumferential indication. The other seven (7) occurrences involved situations in which the axial crack intersected the same elevation on which the circumferential indication was observed; the locations of these tubes are shown in Table 3-7 and Figure 3-12. The data for all 14 TSP locations is summarized in Table 3-8; given are the tube, the elevation, the arc length of the circumferential indication, the distance between the indications' centers (expressed in degrees), the derived ligament arc length, and the sum of ligament angle measured plus 1/2 of the axial indication arc length. The derived ligament angle is obtained from the center line to center line separation minus half the circumferential angle; this provides a ligament angle comprised of the ligament plus half the RPC resolution capability for the single axial crack. The actual measured ligament plus half the RPC resolution capability for the axial crack provides a check against the derived arc length. It is seen that either the derived or the measured arc length provides sufficiently long ligaments even before adjustment for RPC lead-in/lead-out effects, except for R30C67; after adjustment this tube also is shown to possess sufficient ligament separating the two crack modes to meet the burst pressure requirements. All the ligaments in the potential mixed mode degradation cases observed exceed 30° and are expected to meet 3ΔP burst capability requirements (see Section 6.5).

3.8 RPC Resolution Considerations

Limitations on RPC resolution do not permit accurate sizing of ligaments between closely spaced cracks. RPC resolution tests performed for a ligament between two throughwall circumferential indications were described in WCAP-13034 and are summarized in this section for application to the structural assessment of MCIs. RPC resolution tests were also performed for the ligament between a throughwall circumferential crack and a throughwall axial crack to support the assessment of potential combined circumferential and axial indications at TSP intersections (Section 3.7).

RPC resolution for a ligament between two circumferential indications was evaluated using EDM notch simulations for circumferential cracks. Ligament sizes of 0.125 and 0.250 inches between throughwall EDM notches were inspected with an RPC probe. The results are shown in Figure 3-13. It is seen that a ligament of 0.125 inch between the EDM circumferential notches cannot be resolved by the RPC probe. A ligament of 0.25 inch, corresponding to an angle of about 35°, is required to clearly separate the circumferential indications based on the RPC amplitude returning to the "null point" for which the amplitude returns to the background level.

The North Anna RPC data analysis guidelines require the amplitude to return to the null point to call a circumferential indication a MCI. The ligament size or angle is then defined as the width of the null point response between two circumferential indications. Because of the limited resolution, the RPC measured ligament at null point response significantly underestimates the actual ligament between two deep circumferential cracks. The actual ligament between two closely spaced, throughwall circumferential cracks can be expected to exceed the measured RPC ligament plus 30°. This RPC resolution limitation results from the RPC coil lead-in and lead-out effects on measuring a crack size such that the crack angles for deep indications are overestimated. The RPC lead-in or lead-out effects are each typically found to be about a RPC coil diameter of about 0.1 inch diameter or about 15° each. Therefore, if it is assumed that the measured RPC crack angles are deep or throughwall cracks, the measured angles should be decreased by 30° and the measured ligaments between cracks should be increased by 30°.

RPC resolution tests were also performed for a ligament between a circumferential and an axial crack. Again the cracks were simulated by throughwall EDM notches. Ligament sizes of 0.125, 0.250 and 0.400 inch were evaluated. The RPC inspection results for these tests are shown in Figure 3-14. For a 0.125 inch ligament, the ligament between the axial and circumferential indications cannot be resolved by RPC. For the 0.250 inch (~37°) ligament, the RPC amplitude returns to the null point with a 0.040 inch (~7°) ligament detectable by RPC. Thus the ligament angle is underestimated by about 30°. For the 0.400 inch ligament, the RPC measured ligament is between 0.110 (16°) and 0.150 inch (22°) compared to the actual ligament angle of 59°. Thus the ligament size is underestimated by >35° and at least 30° must be added to the RPC measured ligament to obtain the minimum actual ligament size.

The ligament size between axial and circumferential cracks can also be estimated by alternate methods which ignore the RPC crack angle obtained for axial indications, as given in Table 3-8. In Table 3-8, two methods are applied to estimate the ligament size. The first method derives the ligament angle as the centerline to centerline distance between the axial and circumferential cracks minus half the circumferential angle. The second method utilizes the RPC measured ligament size plus half the RPC measured angle for the axial crack. Both of these methods tend to underestimate the ligament size by the overestimate of the circumferential angle resulting from the RPC lead-in or lead-out effect. Thus the ligament sizes of Table 3-8 are general conservative underestimates of the actual ligament compared to adding 30° to the RPC measured ligament size.

3.9 WEXTEX Circumferential Crack Growth Rates

Tubes reported with WEXTEX circumferential cracks in 1992 were re-analyzed from the 1991 EC data, in order to establish an estimate of azimuthal crack propagation; the 1992 inspection represented the second consecutive in-service inspection of the WEXTEX transitions with RPC probes. Of the 31 tubes found with WEXTEX circumferential indications (see Table 3-2), 24 were evaluated on the basis of the 1992 data to exhibit visible circumferential features which were attributed to the precursor cracks. For these cases, the apparent azimuthal arc was calculated and compared to the arc lengths reported at the corresponding locations in 1992; these differences yielded an average change for WEXTEX crack growth of 12.8° ± 12.2° for the operating interval (see Table 3-9). To compare with the prior cycles growth rate determined from 8 x 1/RPC correlations, the observed value is doubled to account for the shortened operating interval to yield a cycle average growth rate of approximately 26° for 1991-1992 compared to the 1989-1991 growth rate of 30°. Figure 3-15 compares the cumulative and interval growth rates for 1991 and 1992. The 95% cumulative growth rate value for twice the 1992 result (66°) compares favorably with the 1991 value (73°) which was based on the 8 x 1/RPC correlation. The operating interval completed prior to the 1992 inspection was 254 EFPD versus 506 EFPD preceding the 1991 inspection.

3.10 Tube Support Plate Circumferential Crack Growth Rates

There were 23 TSP circumferential indications reported in 1992 which had been RPC tested in 1991. Comparing the arc lengths from the 1992 calls with the corresponding features in the 1991 data (Table 3-10) yielded comparisons which amounted to 10.5° ± 12.2° growth for the short cycle; doubling this estimate to enable comparison with the previous, full cycle average growth rate again results in a favorable comparison -- 21% for the 1991 - 1992 period vs. 30% for the 1989 - 1991 period. Similarly the 95% cumulative probabilities for these periods were 63° and 67° respectively. Figure 3-16 presents the cumulative and interval growths compared between the 1992 RPC and 1991 8x1 data..

3.11 Inspection Transient Considerations

During the December 1990 and February 1992 inspection programs at North Anna Unit 1, RPC probes were used more extensively than in previous outages; this resulted in one time occurrences of a large number of tubes plugged due to indications in the WEXTEX transition region (1990) and at the TSP intersections (1992). This behavior is typical of plants which experience inspection transients. Specifically, the number of indications found during the first inspection using new NDE guidelines or a more sensitive probe type are typically much larger than in the preceding inspections. During the next inspection following the application of the revised guidelines or new probe, the number and size of indications have been observed to decrease substantially. Experience has shown that many cracks detected during the first application of more stringent guidelines or with a more sensitive probe would also have been found in the preceding inspection, had the guidelines or probe been applied at that time.

Inspection transients for the tubesheet and TSP regions have been observed in several plants in recent years, following the implementation of 100% RPC inspection in the hot leg tubesheet or the use of revised EC analysis guidelines for the TSP regions. The levels of tube plugging at North Anna Unit 1 have been consistent with the inspection transient behavior observed at other plants. Industry experience with inspection transients at several plants are compared to that of North Anna Unit 1 in the following sections.

3.11.1 WEXTEX Region Inspection Transient at Plant L

The first application of the RPC probe to 100% of the hot leg tubesheet regions in all four SGs at Plant L occurred during the 1989 inservice inspections. 100% RPC inspections of the hot leg tubesheet regions were also performed during subsequent inspections in 1990 and 1991. Table 3-11 summarizes the tube plugging results for tubesheet region cracking from 1987 through 1991. Prior to 1989, nine tubes were plugged for ODSCC in the tubesheet region. Upon implementation of 100% RPC inspection of the hot leg tubesheet in 1989, a total of 90 tubes were plugged for axial and circumferential indications in the WEXTEX transition region. Of this total, 41 tubes were plugged for axial cracks on the OD of the tubes, and 56 tubes were plugged for ID circumferential cracking. During the second 100% RPC inspection of the hot leg tubesheet region in 1990, a total of 29 tubes were plugged for cracking in the WEXTEX transition region; all but two of these tubes were plugged for axial indications. 28 tubes were plugged for tubesheet indications in 1991.

Similar to the trend in numbers of indications for inspection transients, crack sizes tend to be the largest in the first RPC inspection and smaller in subsequent inspections. For Plant L, the largest circumferential crack angles in the three sequential inspections were 263°, 20° and 158°.

The above results for Plant L clearly demonstrate the inspection transient experienced during the initial application of 100% RPC to the WEXTEX expansion region, when a significant increase in the number of both axial and circumferential indications occurred. Subsequent inspections using RPC to inspect 100% of the hot leg tubesheet have resulted in significantly lower numbers of tubes and smaller crack sizes for axial and circumferential cracking in the WEXTEX expansion region, compared to the first RPC inspection.

3.11.2 Inspection Transients at Plant A-1

Table 3-12 shows the tube plugging history for Plant A-1 from 1985 through 1991. A significant increase in the number of tubes plugged for tubesheet and TSP indications occurred in 1991. For the tubesheet region, this increase is the result of the first application of RPC to 100% of the tubesheet hot leg. The significant increase in the number of tubes plugged for indications at the TSPs is the result of a change in EC analyst guidelines. These inspection transients are described in detail below.

Prior to 1991, a modest number of tubes were plugged for OD indications above the tubesheet; sixteen of the 20 tubes plugged from 1985 to 1988 for ODSCC in the tubesheet region were for indications on the hot leg side in the sludge deposition region. During the October 1989 inspection program, 100% of the available tubes were inspected full length using a standard bobbin probe. Supplemental MRPC inspections were performed for distorted indications (DI's) at the TSPs and above the tubesheet. In addition, a random sampling of 9% of the tubes in one SG were inspected with an 8x1 probe for possible circumferential cracking in the WEXTEX transition region. A total of 22 tubes were plugged for ODSCC in the sludge deposition region.

In order to increase the detectability of circumferential indications in the WEXTEX region, 100% of the available tubes in the hot leg tubesheet region were inspected by RPC probes in April 1991; in addition, the bobbin inspection guidelines for indications above the tubesheet were altered (i.e., the voltage threshold for RPC inspection was eliminated). The resulting number of tubes plugged for ODSCC at the top of the tubesheet more than doubled, totalling 46 tubes plugged. Although no tubes had been plugged for PWSCC in the tubesheet in prior outages, 72 tubes were plugged for PWSCC in the WEXTEX expansion zone (37 axial indications and 35 circumferential indications). This behavior is typical of the inspection transients observed during first time application of 100% RPC or after changes in bobbin interpretation guidelines.

The number of tubes plugged for indications at the TSPs during April 1991 also increased as a result of the elimination of the bobbin voltage cutoff for requiring RPC inspection. The more stringent analyst guidelines and increased use of the RPC probe resulted in the plugging of 102 tubes for indications of ODSCC at the TSP elevations; only four tubes had been plugged for such indications during all prior inspections. Again, this clearly demonstrates the inspection transient effect of changes in analyst guidelines and more extensive use of the RPC probe.

The next inspection program for the Plant A-1 steam generators will occur during the September 1992 refueling outage; hence, there is no data to demonstrate a decrease in the number of indications observed during the first outage following the inspection transient. However, the steam generators at Plant A-2 recently completed the first inspection after a similar inspection transient; the results for Plant A-2 are described below.

3.11.3 Inspection Transients at Plant A-2

Table 3-13 shows the tube plugging history for Plant A-2 from 1985 through 1992. A significant increase in the number of tubes plugged for tubesheet and TSP indications occurred in 1990. For the tubesheet region, this increase was the result of the first application of RPC to 100% of the tubesheet hot leg. The significant increase in the number of tubes plugged for indications at the TSPs was the result of a change in bobbin coil analyst guidelines. These inspection transients are described in detail below.

At Plant A-2, PWSCC has been observed in the hot leg mechanical expansion region since January 1985. Prior to 1990, 86 tubes were plugged for PWSCC indications in the expanded region. During the inspection programs prior to 1990, 100% of the available tubes were inspected full length using a standard bobbin probe. Supplemental MRPC inspections were performed for distorted indications (DI's) at the TSPs and above the tubesheet. During the December 1990 inspection program, 100% of the available tubes in the hot leg tubesheet region were inspected using RPC probes; 328 tubes were plugged for indications of PWSCC at the roll transitions. 100% RPC inspection of the roll transition regions in March 1992 resulted in only 60 pluggable tubes, all with axial indications in the roll transitions.

From 1985 to 1989, a total of 112 tubes were plugged for ODSCC at the TSP elevations of Plant A-2. In December 1990, revised inspection guidelines for the TSP regions eliminated bobbin coil thresholds and 243 tubes were plugged for ODSCC at the TSP elevations. These revised guidelines were also responsible for the April 1991 inspection transient described above for Plant A-1. Again, this clearly demonstrates the inspection transient effect of changes in analyst guidelines and more extensive use of the RPC probe. In March 1992, only 18 tubes were plugged for ODSCC at the TSPs. However, this inspection implemented an alternate tube plugging criteria; thus, the reduction in plugging from 243 to 18 is a combination of the inspection transient and plugging criteria.

3.11.4 Inspection Transients and Conclusions for North Anna Units 1 and 2

Table 3-14 summarizes the tube plugging due to circumferential indications in the tubesheet and TSP regions of North Anna Units 1 and 2 through 1992. The table demonstrates that the North Anna steam generators have experienced similar inspection transient behavior to that seen in the other plants described above.

The first application of RPC to inspect 100% of the WEXTEX transitions in North Anna Unit 1 occurred in December 1991. The resulting inspection transient produced 216 circumferential indications. For the inspection following the first 100% RPC inspections, only 31 circumferential indications were found at Unit 1; hence, the number of indications were reduced by a factor of 7. The first application of RPC to inspect 100% of the WEXTEX transitions in North Anna Unit 2 occurred in September 1990. The resulting inspection transient produced 26 circumferential indications, up from 4 indications in the preceding outage . For the inspection following the first 100% RPC inspections, 13 indications were found at Unit 2. For Unit 1, the maximum circumferential crack angle found in the first RPC inspection was ~247°, compared to 199° in the subsequent inspection. Except for a large circumferential indication identified in the first Unit 2 RPC inspection but not called for plugging based on lack of phase angle response, the largest Unit 2 circumferential crack was reduced from 238° to 128° in the outage following the RPC inspection transient.

The first application of the RPC probe to 100% of the hot leg TSP intersections of North Anna Unit 1 occurred in February 1992. A total of 212 tubes were plugged for circumferential indications at the TSP elevations. This represented a significant increase over the number of tubes plugged during any of the prior outages. This behavior is consistent with the inspection transient behavior observed for the TSP axial indications of Plants A-1 and A-2.

Based on the data presented above for inspections following an outage in which revised inspection guidelines or more sensitive probes are used, it is judged that many of the tubes plugged for indications during the inspection transients had cracks which existed during prior inspections, but were not detected until the use of the more sensitive probe or revised analysis guidelines. The significant level of denting in the North Anna 1 steam generators has contributed to the limited detectability of the cracks at the TSP intersections until the use of the more sensitive RPC probe at all TSP intersections. Therefore, it is judged that the number and size of indications which will exist at the end of the current operating cycle will be smaller than the cracks found during the 2/92 inspection program.

Table 3-1

North Anna #1
February 1992

Tube Plugging Summary

	A	B	C
Through 1991	463	425	650
WEXTEX (HL) (RPC)	15	10	11
TSP (HL) (RPC)	143	148	178
Other (Bobbin)	1	0	2
Preventive	7	2	10
Total 1992	166	160	201
Cumulative	629	585	851
% Plugged	18.6%	17.3%	25.1%

Table 3-2

North Anna #1
February 1992

WEXTEX Inspection Results

# Tubes	Steam Generator A	B	C
Single Axial	3	0	2
Multiple Axial	0	0	0
Single Circumferential	10	9	7
Multiple Circumferential	2	1	2

- There were 0 tubes with mixed mode degradation identified in the WEXTEX transitions.

Table 3-3

NORTH ANNA #1
FEBRUARY 1992

TSP CIRCUMFERENTIAL CRACKS

ELEVATION	STEAM GENERATOR A SCI/MCI	B SCI/MCI	C SCI/MCI
1H	25/3	22/0	27/0
2H	15/0	33/3	42/3
3H	2/0	7/2	19/2
4H	3/0	0/0	3/0
5H	1/0	0/0	1/0
6H	0/0	0/0	0/0
7H	0/0	0/0	0/0

SCI - SINGLE CIRCUMFERENTIAL INDICATION
MCI - MULTIPLE CIRCUMFERENTIAL INDICATIONS

Table 3-4

North Anna #1
February 1992

TSP Axial Cracks

Elevation	Steam Generator A SAI/MAI	Steam Generator B SAI/MAI	Steam Generator C SAI/MAI
1H	36/0	53/4	37/5
2H	24/2	14/3	41/1
3H	7/0	6/0	5/1
4H	5/0	5/0	8/0
5H	21/0	1/0	1/0
6H	3/0	1/0	2/0
7H	0/0	0/0	0/0

SAI - SINGLE AXIAL INDICATION
MAI - MULTIPLE AXIAL INDICATIONS

Table 3-5

North Anna-1
WEXTEX MCIs

Tube	Location	Circ.1	Lig.1	Circ.2	Lig.2	Total Circ.
			St[illegible] Generator A			
R19C32	TS-.12	102°	24°(54°)$^{(1)}$	82°	152°	184°
R24C33	TS-.08	149°	114°	85°	12°(42°)$^{(1)}$	234°(174°)$^{(1)}$
			Steam Generator B			
R9C36	TS+.00	81°	17°(47°)$^{(1)}$	82°	180°	163°
			Steam Generator C			
R10C72	TS-.02	76°	38°	76°	170°	151°
R25C50	TS-.04	67°	46°	59°	178°	126°

Note 1. RPC measured ligament increased by 30° for resolution limitations (coil lead-in and lead-out effects) and each circumferential indication decreased by 30°.

Table 3-6

North Anna-1
TSP Multiple Circumferential Indications (MCIs)

Tube	Location	Circ. 1	Lig. 1	Circ. 2	Lig. 2
			Steam Generator A		
R6C6	1H+.39	81°	91°	78°	110°
R17C10	1H+.50	90°	86°	95°	~ 89°
R29C30	1H+.26	131°	75°	87°	~ 67°
			Steam Generator B		
R11C8	2H-.21	114°	68°	117°	61°
	2H+.23	108°	65°	81°	106°
R12C8	3H+.23	128°	75°	98°	59°
R22C24	2H-.30	132°	73°	101°	54°
R2C41	3H+.29	138°	66° (96°)(1)	115°	41° (71°)(1)
	3H-.25	91°	88°	101°	80°
R36C62	2H-.23	83°	69°	107°	101°
			Steam Generator C		
R20C9	3H-.27	130°	64°	79°	87°
R24C10	3H+.28	105°	92°	88°	~ 75°
R10C29	2H+.35	80°	83°	107°	90°
R18C44	2H+.35	99°	90°	109°	~ 62°
R27C71	2H-.30	79°	96°	82°	103°

Note 1. RPC measured ligament angles based on return of signal amplitude to background or null point. For deep circumferential indications, the actual ligament exceeds the measured ligament by about 30° or more (see Section 3.11 and Figure 3-15) due to RPC coil lead-in and lead-out resolution limits on crack angles.

Table 3-7

North Anna #1
February 1992

TSPs with Both Circumferential and Axial Cracks

No cases of mixed mode degradation were detected in S/G A and S/G B.

Seven (7) locations with mixed mode degradation at the same TSP edge were observed in S/G C.

Elevation	Tube Edge*	Circum.	Minimum Separating Ligament**
TSP #1:	R29C16 +	75°	> 25°
	R3C43 +	73°	> 39°
	R18C46 +	69°	> 69°
TSP #2:	R10C29 -	119°	>113°
	R8C33 +	76°	> 37°
	R29C64 -	91°	> 27°
	R30C67 +	133°	> 20°

Data was acquired with 2X RPC probe; for closest axial-circumferential proximity 3 coil Zetec probe was used; no apparent improvement in resolution.

All these intersections were judged to be acceptable against tube burst criteria.

* + Upper Edge
  - Lower Edge

** Not adjusted for RPC resolution considerations

Table 3-8

North Anna-1

Mixed Mode Evaluation

Tube	Location	Circ. Angle	C.L. to C.L.	Derived(1) Lig.Angle	Measured(2) Lig.+ 0.5 Axial θ	Resolution
			Steam Generator C			
R29C9	3H-.27	$130^0/79^0$				Opposite Edges, No Concern
R14C10	2H+.20	101^0				Opposite Edges, No Concern
R5C11	1H-.27	96^0				Axial Inside TSP, No Concern
R29C16	1H+.26	75^0	62^0	25^0	6^0+28^0	Acceptable, large ligament
R10C29	2H-.29	119^0			90^0+23^0	Acceptable, large ligament
R6C33	1H-.30	85^0				Opposite Edges, No Concern
R8C33	2H+.18	76^0	82^0	44^0	10^0+27^0	Acceptable, large ligament
R6C40	3H-.26	104^0				Opposite Edges, No Concern
R3C43	1H+.31	73^0	75^0	39^0	17^0+20^0	Acceptable, large ligament
R18C46	1H+.33	69^0			36^0+33^0	Acceptable, large ligament
R29C64	2H-.33	91^0	75^0	30^0	10^0+17^0	Acceptable, large ligament
	2H+.47	63^0				Opposite Edges, No Concern
R30C67	2H+.26	$133^0 (103^0)^{(3)}$	86^0	$20^0 (35^0)^3$	5^0+19^0	Acceptable, large ligament
R30C70	2H+.31	95^0				Opposite Edges, No Concern

Notes:

1) Ligament angle obtained as circumferential crack centerline to axial crack centerline distance minus one-half the circumferential angle.
2) Ligament angle obtained as the measured ligament angle plus one-half the axial crack angle.
3) RPC measurements adjusted for resolution (coil lead-in and lead-out) in measuring deep crack angles. Resolution typically ~1 coil diameter (0.105", 15^0) at each end of crack.

Table 3-9

WEXTEX Circumferential Crack Growth from RPC Data (1991 - 1992)

SG	Tube	Location	Growth per Cycle* (degrees)
A	R21C23	TSH	30
A	R15C26	TSH	1
A	R24C33	TSH	16
A	R24C33	TSH	21
A	R20C45	TSH	1
A	R25C55	TSH	21
A	R15C56	TSH	29
A	R19C32	TSH	7
A	R10C71	TSH	11
A	R20C23	TSH	15
B	R9C36	TSH	0
B	R9C36	TSH	7
B	R25C36	TSH	24
B	R28C41	TSH	2
B	R14C54	TSH	5
B	R16C56	TSH	30
B	R16C22	TSH	0
B	R25C8	TSH	48
B	R12C74	TSH	0
C	R21C27	TSH	7
C	R19C45	TSH	10
C	R27C46	TSH	12
C	R25C50	TSH	11
C	R25C56	TSH	0

Average Change*: 12.8° ± 12.2°

* All negative changes set to zero.

Table 3-10

TSP Circumferential Crack Growth from RPC Data (1991 - 1992)

SG	Tube	Location	Growth per Cycle* (degrees)
A	R22C24	2H	6
A	R30C24	2H	10
A	R7C27	2H	20
A	R39C41	1H	0
B	R15C9	1H	13
C	R6C3	1H	1
C	R5C11	3H	39
C	R5C11	3H	29
C	R24C27	2H	14
C	R24C27	2H	0
C	R24C36	1H	13
C	R41C42	3H	11
C	R37C49	2H	4
C	R37C49	2H	0
C	R36C52	3H	5
C	R18C54	2H	12
C	R29C64	2H	0
C	R29C64	2H	12
C	R9C65	3H	0
C	R27C71	2H	5
C	R27C71	2H	0
C	R17C62	2H	3
C	R27C75	2H	45

Average Change*: 10.5° ± 12.2°

* All negative changes set to zero.

Table 3-11

Inspection Transient for WEXTEX Expansion Region of Plant L

Date of Inspection	Axial Indications	Circ. Indications	Total
April 1986	1	0	1
May 1987	0	0	0
May 1988	8	0	8
May 1989(1)	41	56	97
May 1990(2)	27	2	29
May 1991(2)	17	11	28

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(1) First application of RPC to 100% of active tubes in hot leg tubesheet region.

(2) 100% of active tubes in hot leg tubesheet region inspected with RPC.

Table 3-12

Tube Plugging History for Plant A-1 (1985 - 1991)

	Number of Tubes Plugged			
Date	Tubesheet PWSCC	Tubesheet ODSCC	TSP ODSCC	Other
5/85	0	0	0	1
10/86	0	3	2	1
4/88	0	17	0	0
10/89	0	22	2	0
4/91(1)	72	46	102	47

(1) Inspection transient resulting from first time application of RPC to 100% of available tubes in hot leg tubesheet region, as well as revised EC analyst guidelines and more extensive use of RPC at TSP elevations.

Table 3-13

Tube Plugging History for Plant A-2 (1985 - 1992)

	Number of Tubes Plugged			
	Tubesheet	Tubesheet	TSP	
Date	PWSCC	ODSCC	ODSCC	Other
1/85	1	0	0	13
4/86	40	0	28	2
11/87	29	1	74	5
4/89	16	0	10	1
12/90	328(1)	0	243	0
3/92	51(2)	0	18(3)	1

(1) Inspection transient resulting from first time application of RPC to 100% of available tubes in hot leg tubesheet region, as well as revised EC analyst guidelines and more extensive use of RPC at TSP elevations.

(2) Second application of RPC to 100% of available tubes in hot leg tubesheet region (hard roll expansion).

(3) Tube plugging reflected alternate tube plugging criteria and thus was not only dependent on inspection transient.

Table 3-14

Tube Plugging for Tubesheet and TSP Circumferential Indications at North Anna Units 1 and 2

North Anna Unit 1			North Anna Unit 2	
Date	WEXTEX Transition	TSP	Date	WEXTEX Transition
4/89	31	--	2/89	4
12/90	216(1)	93	9/90	26(1)
2/92	31	212(2)	3/92	13

---

(1) Inspection transient resulting from first time application of RPC to 100% of available tubes in hot leg tubesheet region.

(2) Inspection transient resulting from first time application of RPC to hot leg TSP intersections in 100% of available tubes.

Figure 3-1

NORTH ANNA UNIT 1 S/G A 2/27 PLUG LIST

WEXTEX INDICATIONS (RPC PROBES)

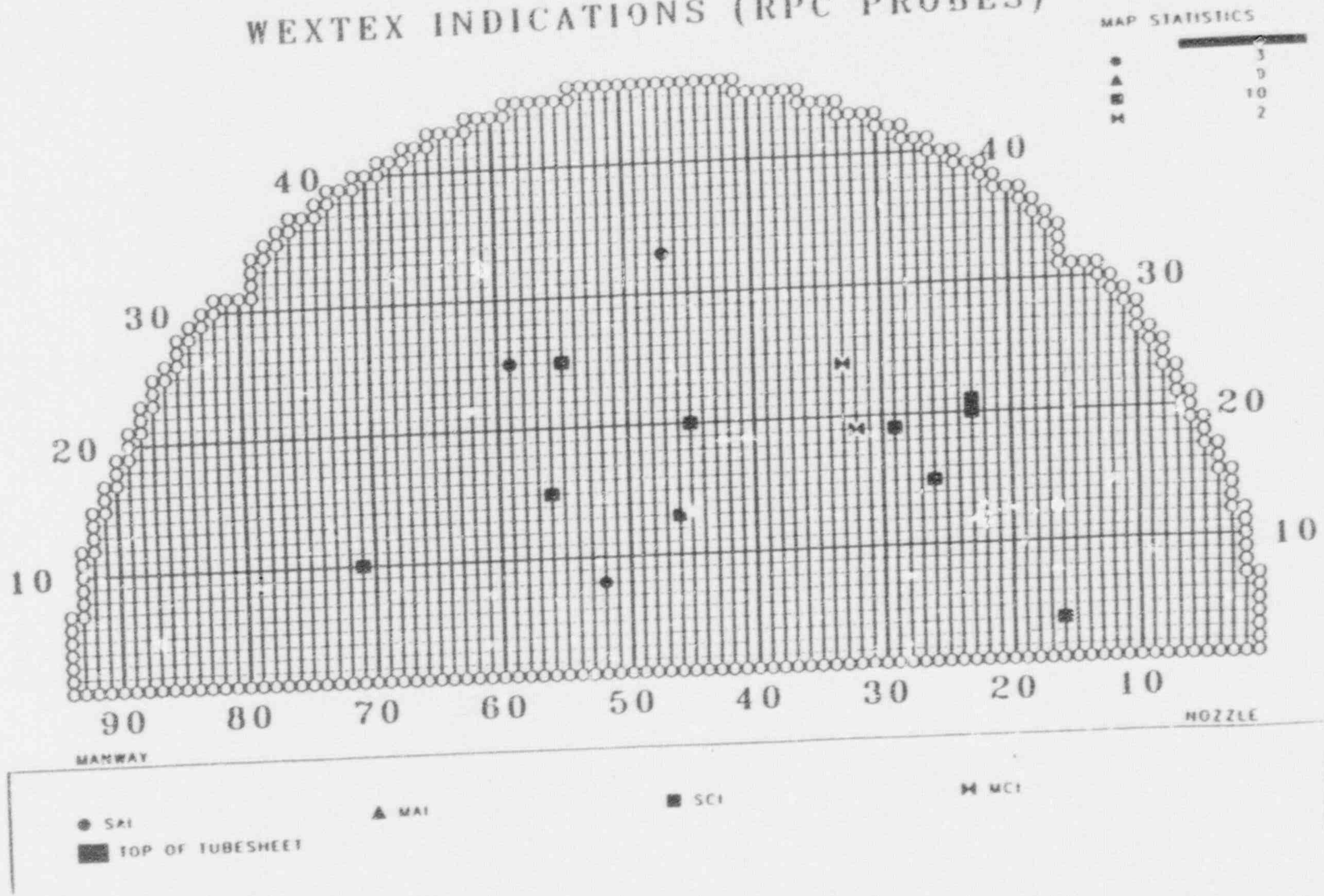


Figure 3-2

NORTH ANNA UNIT 1 S/G B 2/27 PLUG LIST

WEXTEX INDICATIONS (RPC PROBES)

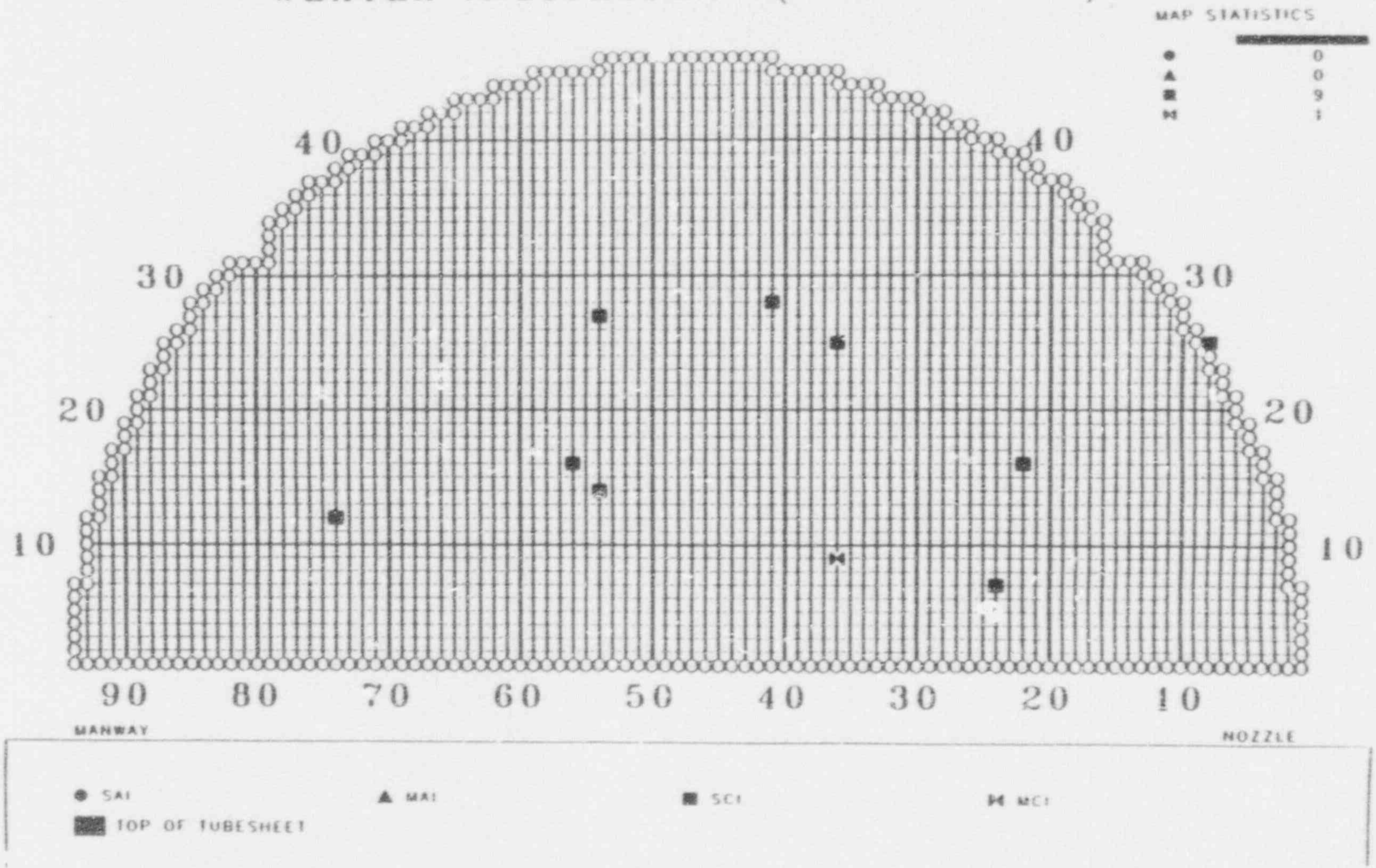


Figure 3-3

NORTH ANNA UNIT 1 S/G C 2/27/92 PLUG LIST

WEXTEX INDICATIONS (RPC PROBES)

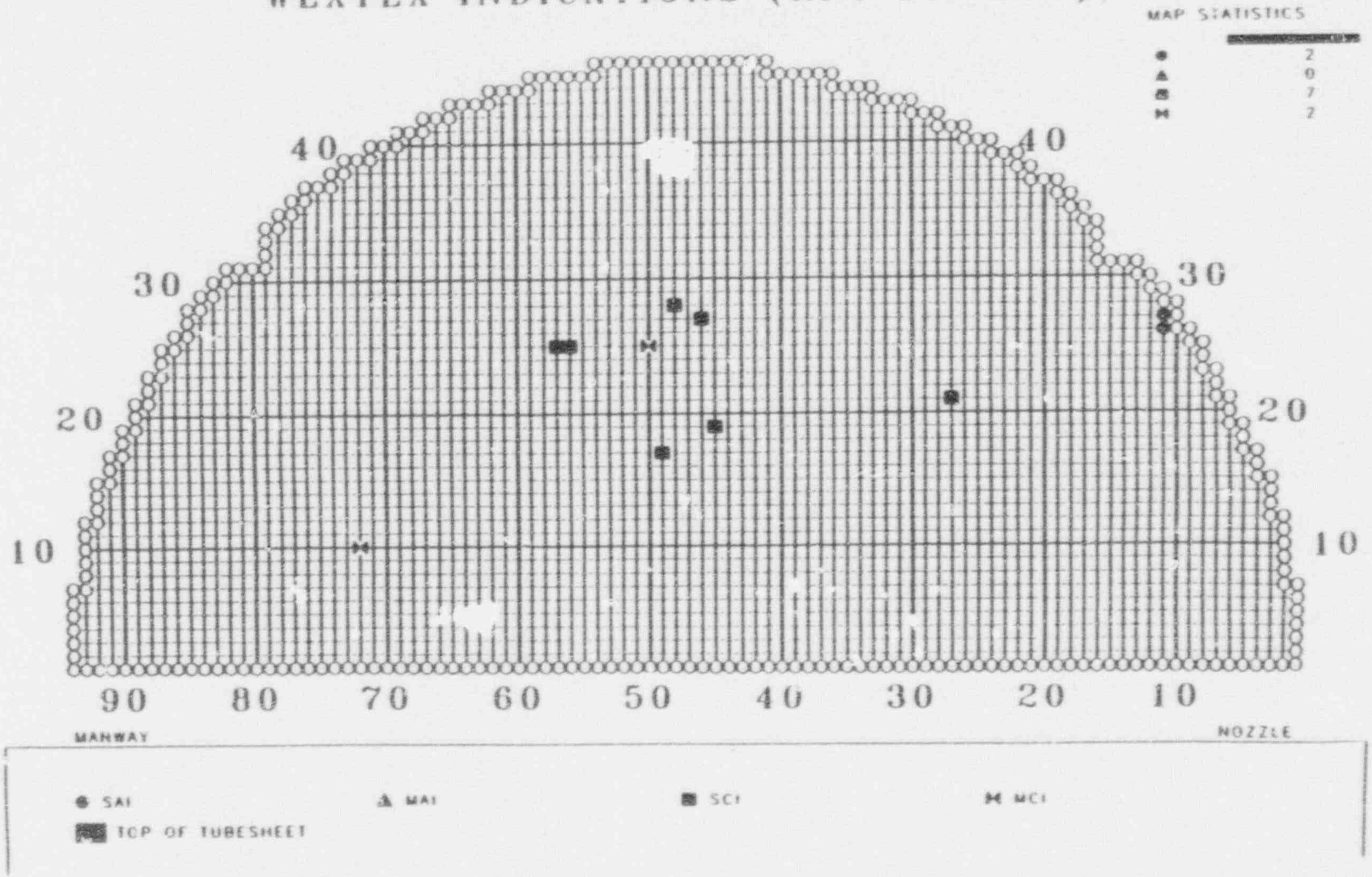


Figure 3-4

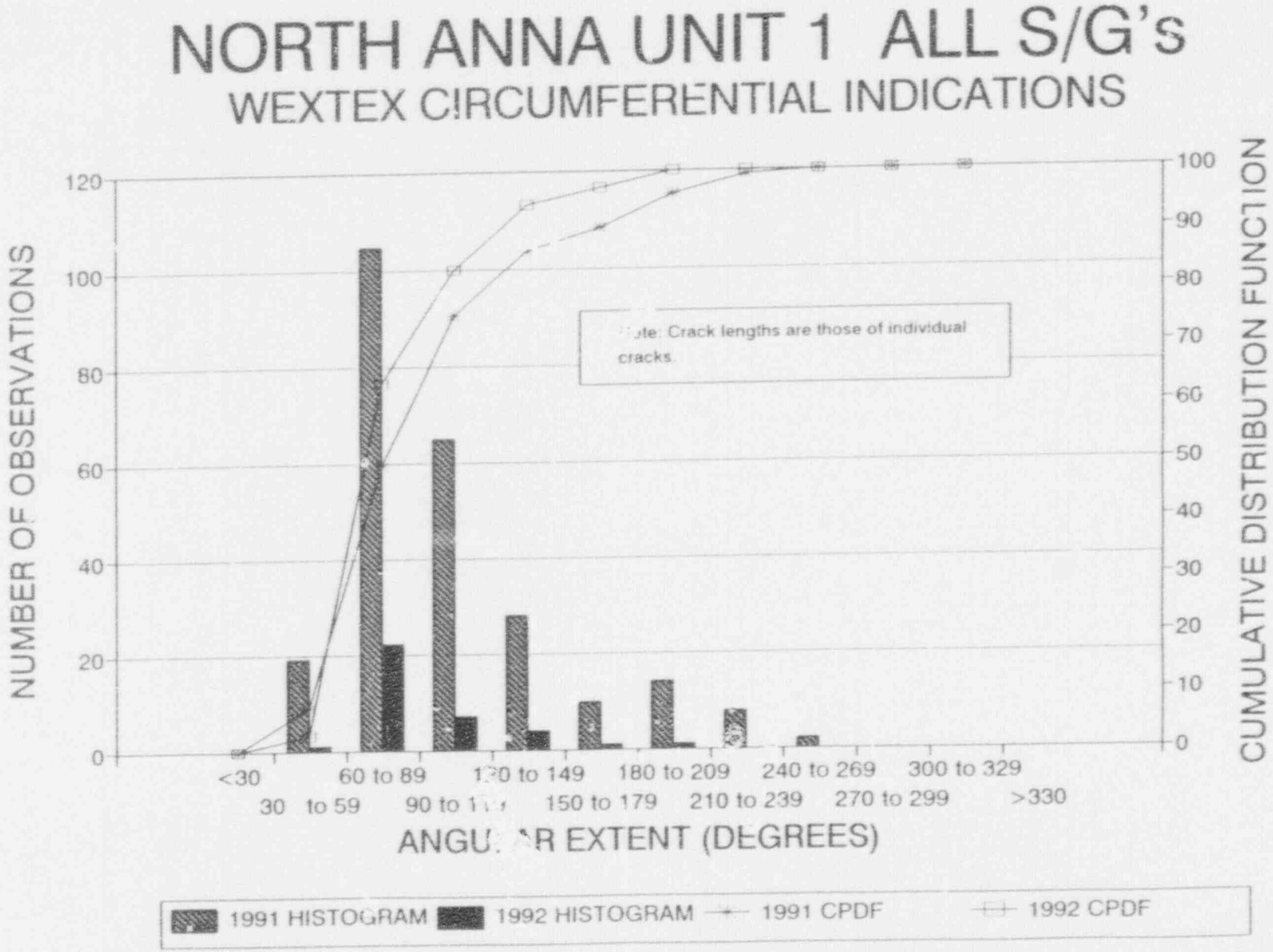

NORTH ANNA UNIT 1 ALL S/G's
WEXTEX CIRCUMFERENTIAL INDICATIONS
NUMBER OF OBSERVATIONS
CUMULATIVE DISTRIBUTION FUNCTION
ANGULAR EXTENT (DEGREES)
<30
30 to 59
60 to 89
90 to 119
120 to 149
150 to 179
180 to 209
210 to 239
240 to 269
270 to 299
300 to 329
>330
Note: Crack lengths are those of individual cracks.
1991 HISTOGRAM
1992 HISTOGRAM
1991 CPDF
1992 CPDF

Figure 3-5

NORTH ANNA UNIT 1 S/G A 2/27 PLUG LIST

SUPPORT PLATE CIRCUMFERENTIAL INDICATIONS (RPC)

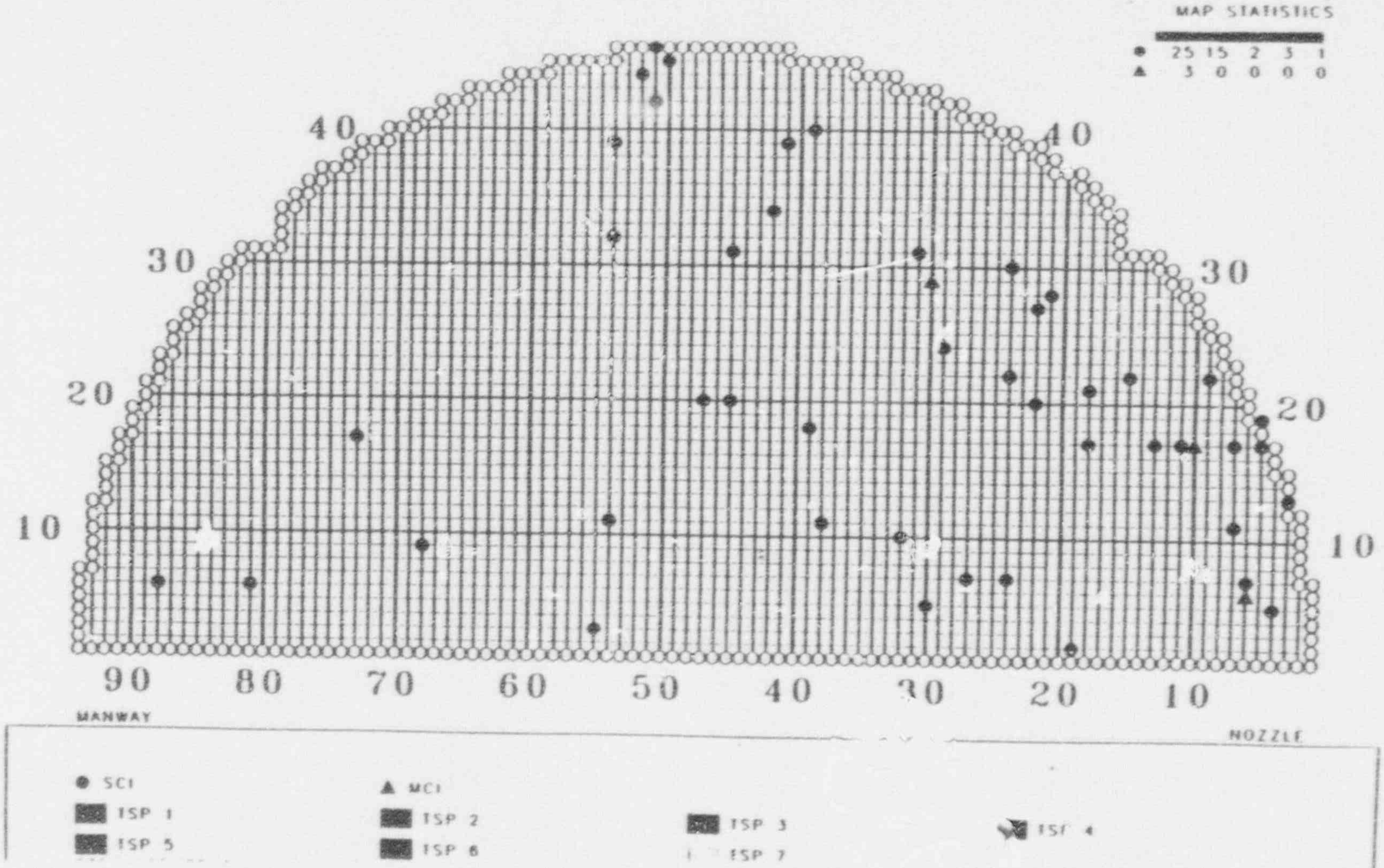


Figure 3-6

NORTH ANNA UNIT I S/G B 2/27 PLUG LIST

SUPPORT PLATE CIRCUMFERENTIAL INDICATIONS (RPC)

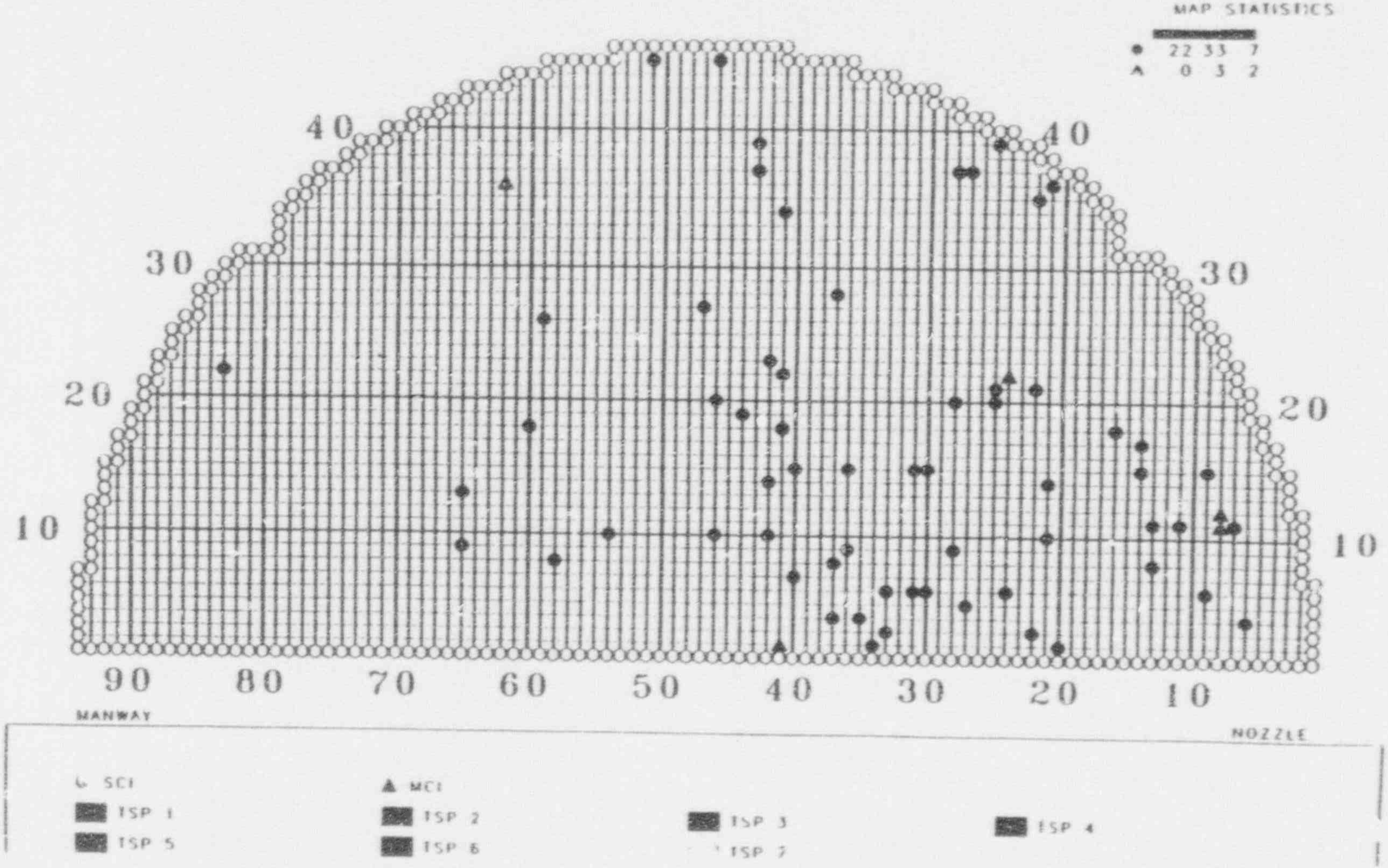


Figure 3-7

NORTH ANNA UNIT 1 S/G C 2/27/92 PLUG LIST

SUPPORT PLATE CIRCUMFERENTIAL INDICATIONS (RPC)

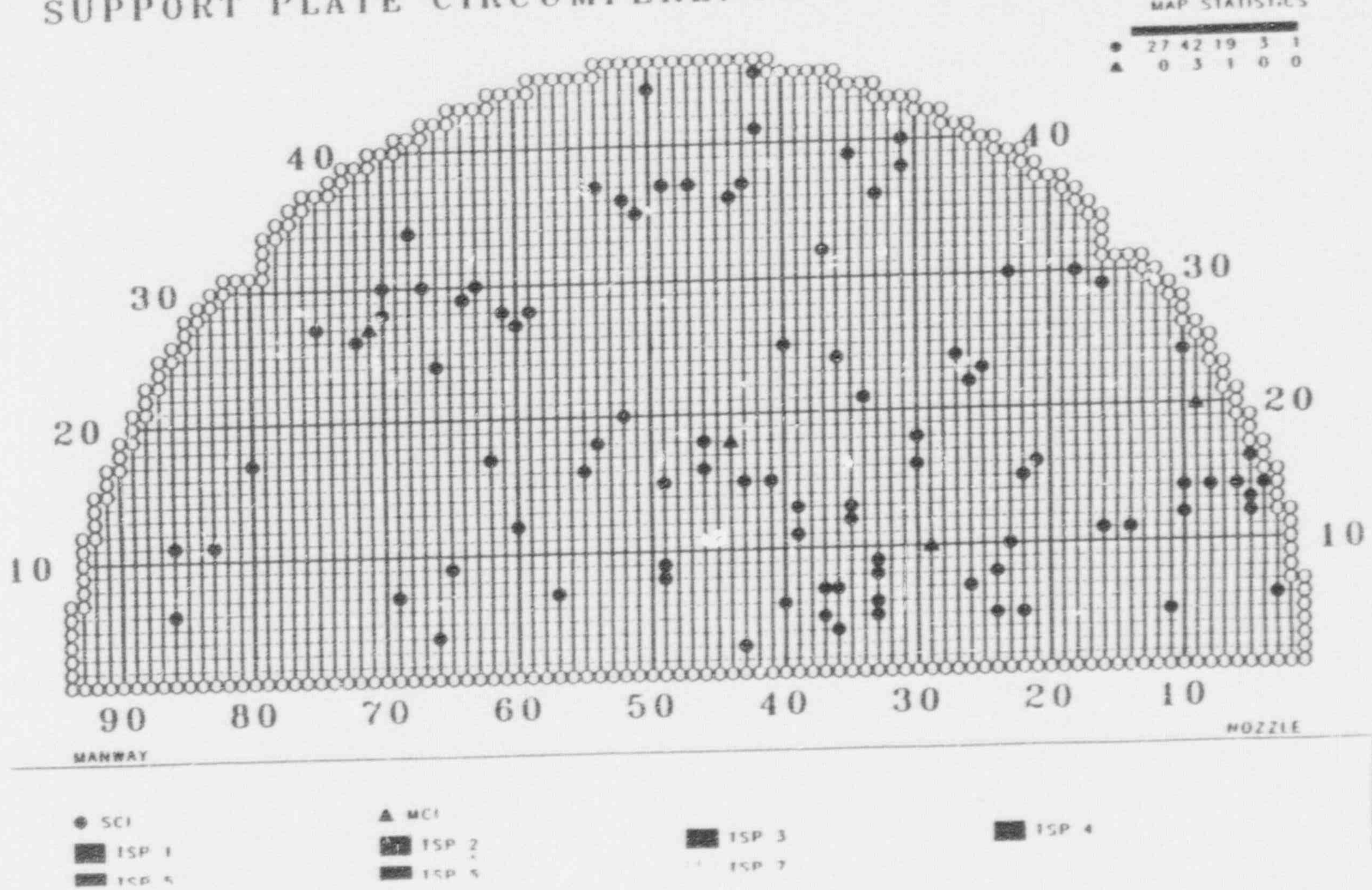


Figure 3-8

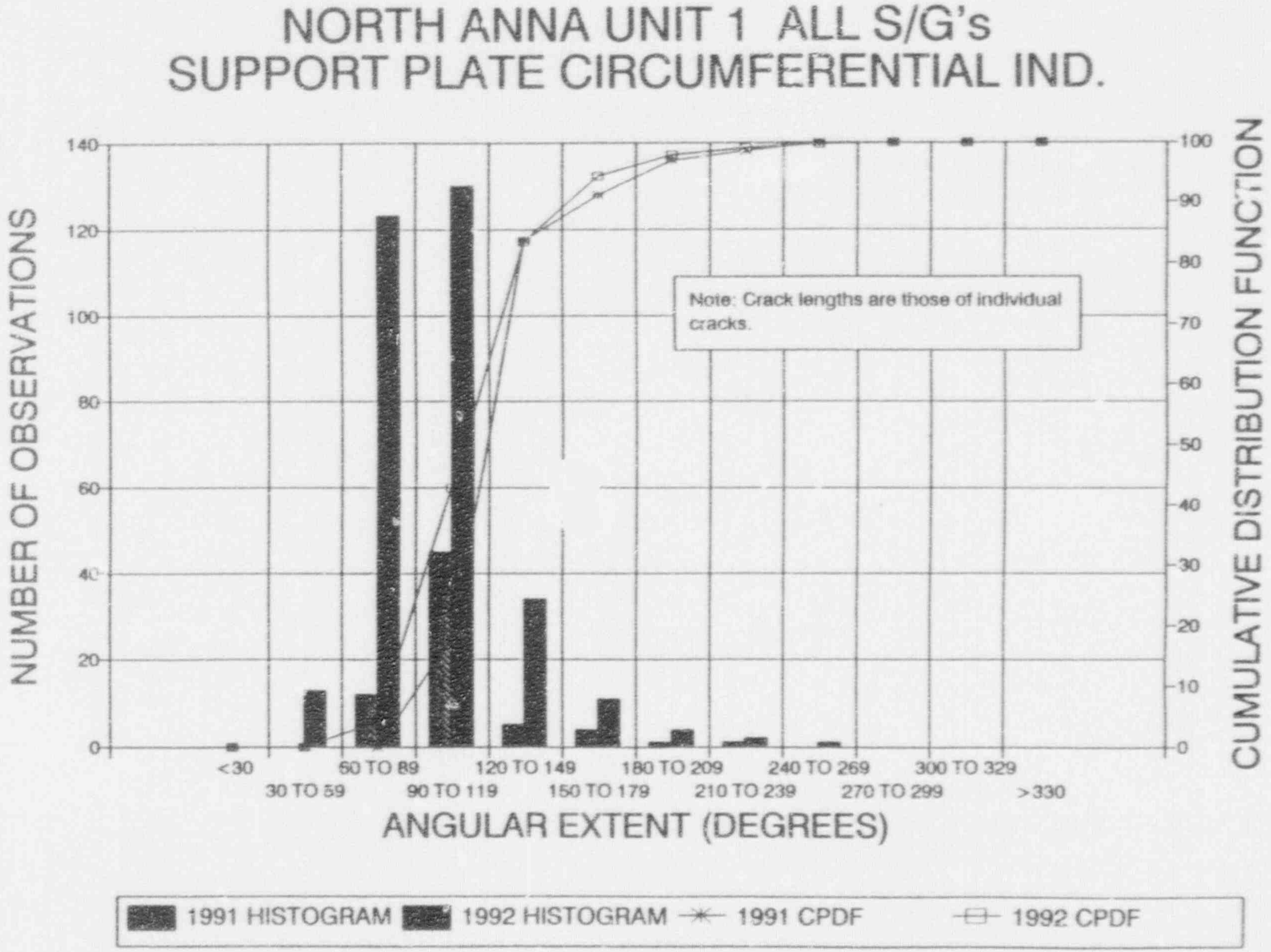

NORTH ANNA UNIT 1 ALL S/G's
SUPPORT PLATE CIRCUMFERENTIAL IND.
NUMBER OF OBSERVATIONS
CUMULATIVE DISTRIBUTION FUNCTION
0
20
40
60
80
100
120
140
10
30
50
70
90
Note: Crack lengths are those of individual cracks.
<30
30 TO 59
60 TO 89
90 TO 119
120 TO 149
150 TO 179
180 TO 209
210 TO 239
240 TO 269
270 TO 299
300 TO 329
>330
ANGULAR EXTENT (DEGREES)
1991 HISTOGRAM
1992 HISTOGRAM
1991 CPDF
1992 CPDF

Figure 3-9

NORTH ANNA UNIT 1 S/G A 2/27 PLUG LIST

SUPPORT PLATE AXIAL INDICATIONS (RPC)

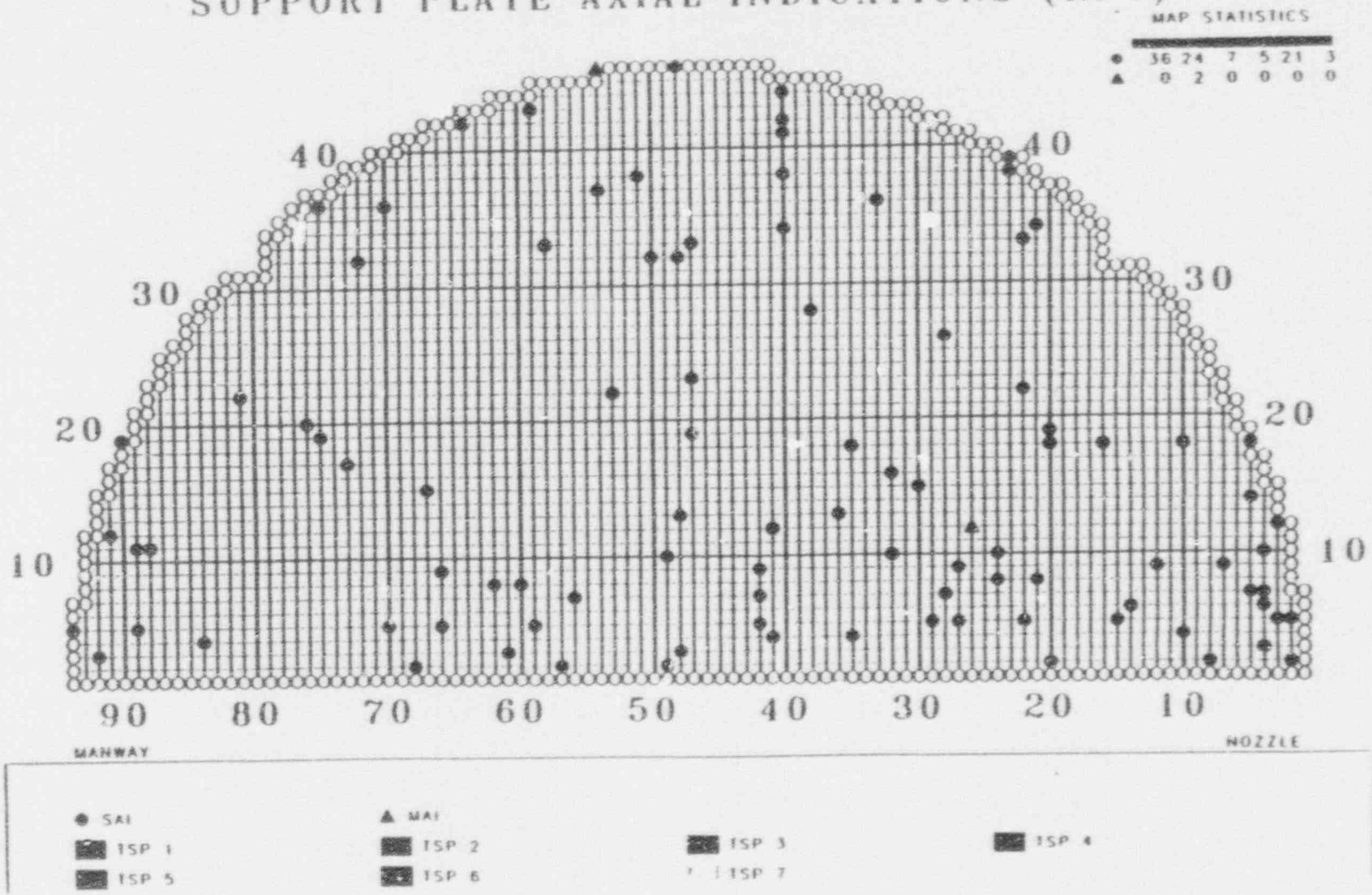


Figure 3-10

NORTH ANNA UNIT 1 S/G B 2/27 PLUG LIST

SUPPORT PLATE AXIAL INDICATIONS (RPC)

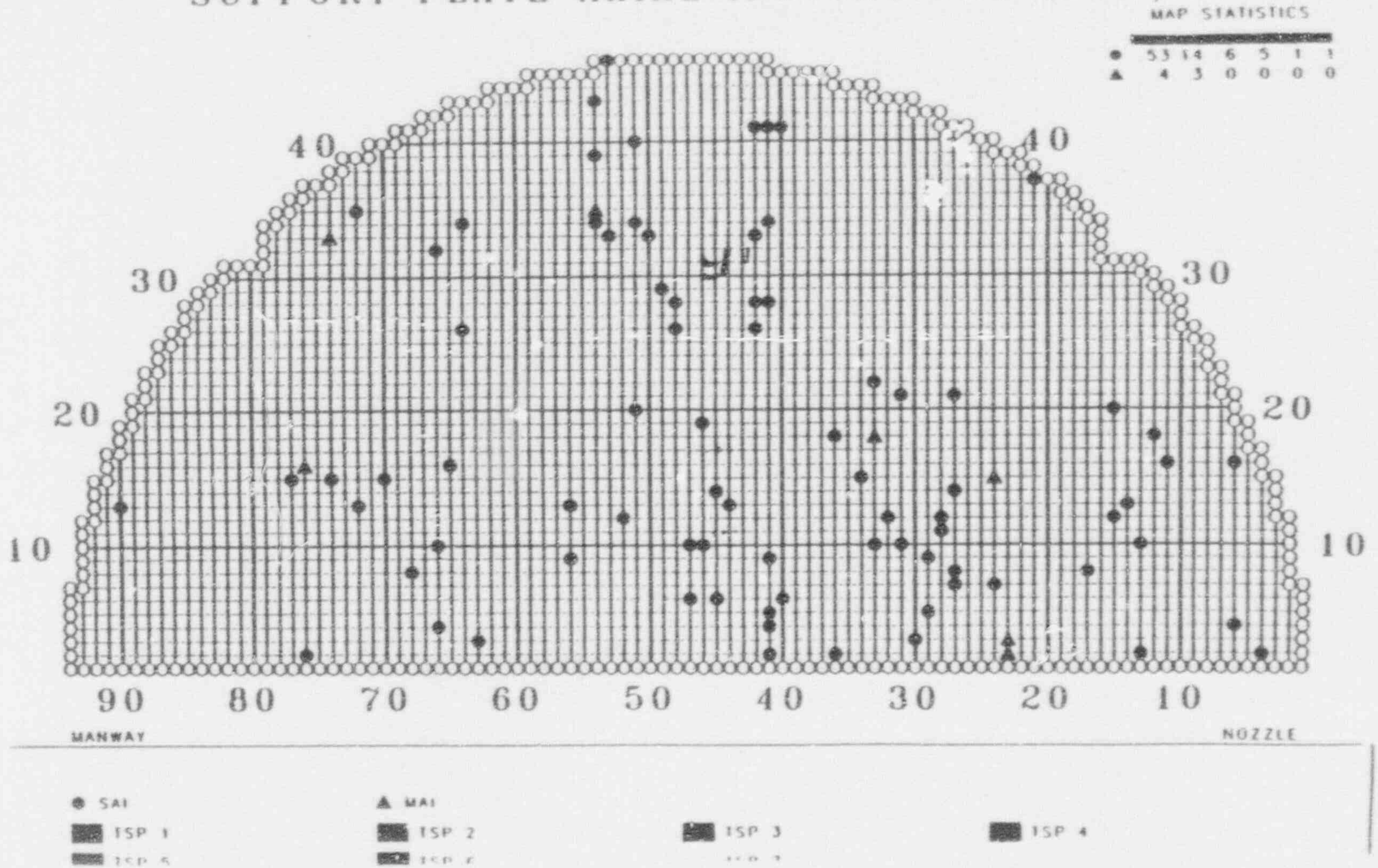


Figure 3-11

NORTH ANNA UNIT 1 S/G C 2/27/92 PLUG LIST

SUPPORT PLATE AXIAL INDICATIONS (RPC)

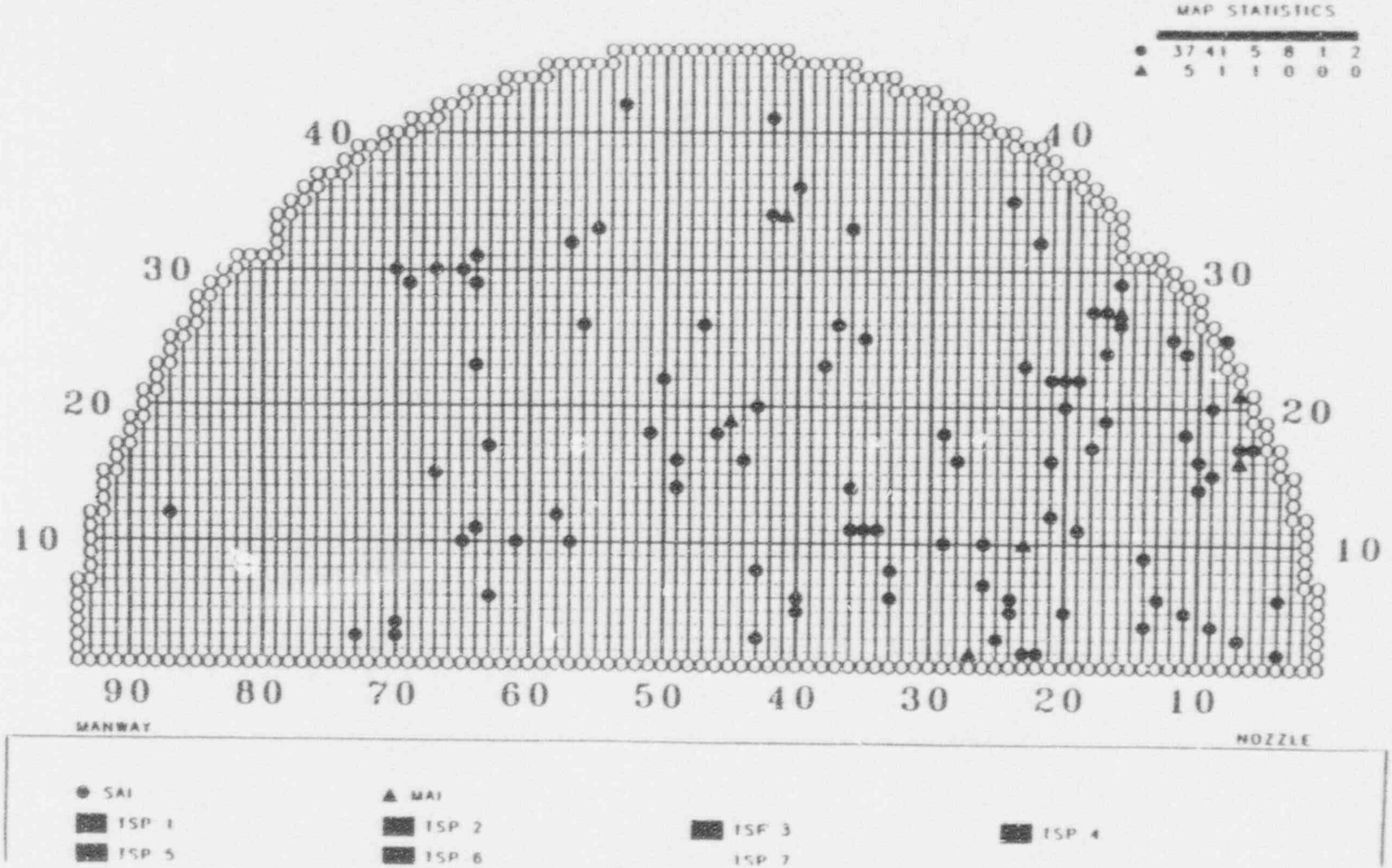


Figure 3-12

NORTH ANNA UNIT 1 S/G C FEB 1 '92 INSPECTION

POTENTIAL MIXED MODE INDICATIONS

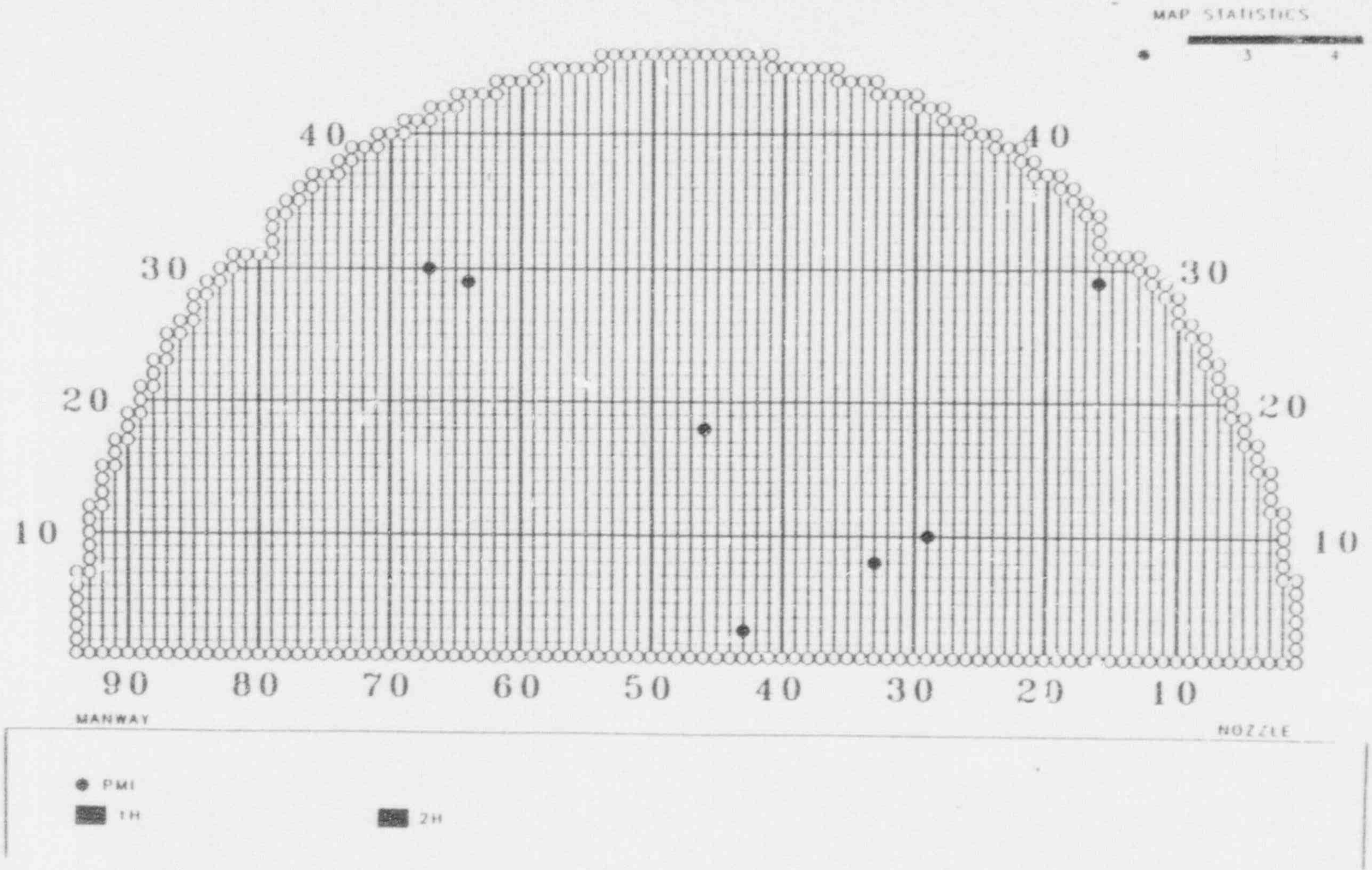
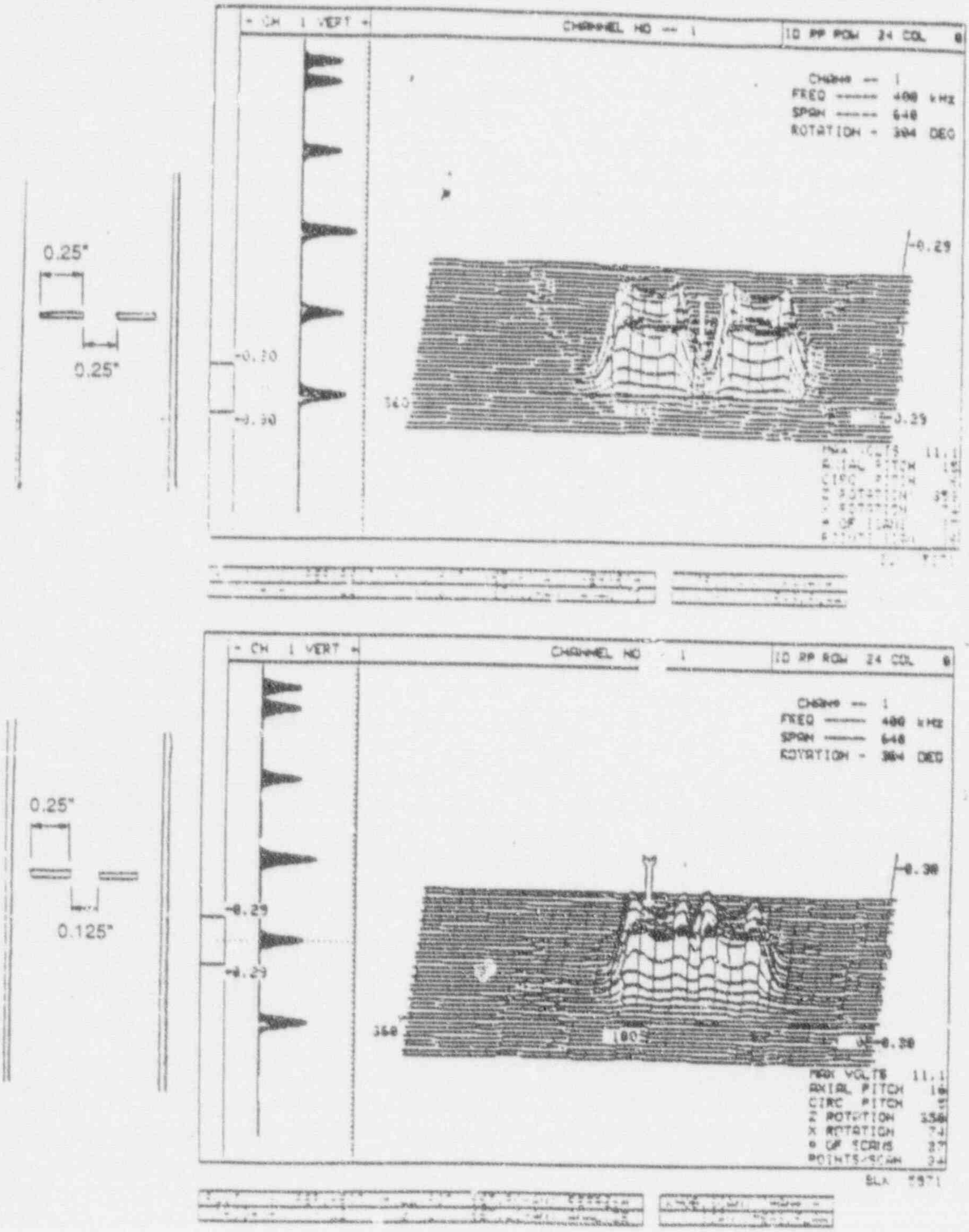


Figure 3-13



0.25"
0.25"
CH 1 VERT
CHANNEL NO -- 1
FREQ ------ 400 kHz
SPAN ----- 640
ROTATION - 304 DEG
0.25"
0.125"
CH 1 VERT
FREQ ------ 400 kHz
SPAN ------ 640
ROTATION - 304 DEG
MAX VOLTS
AXIAL PITCH
CIRC PITCH
Z ROTATION
X ROTATION
OF SCANS
POINTS/SCAN

Figure 3-14

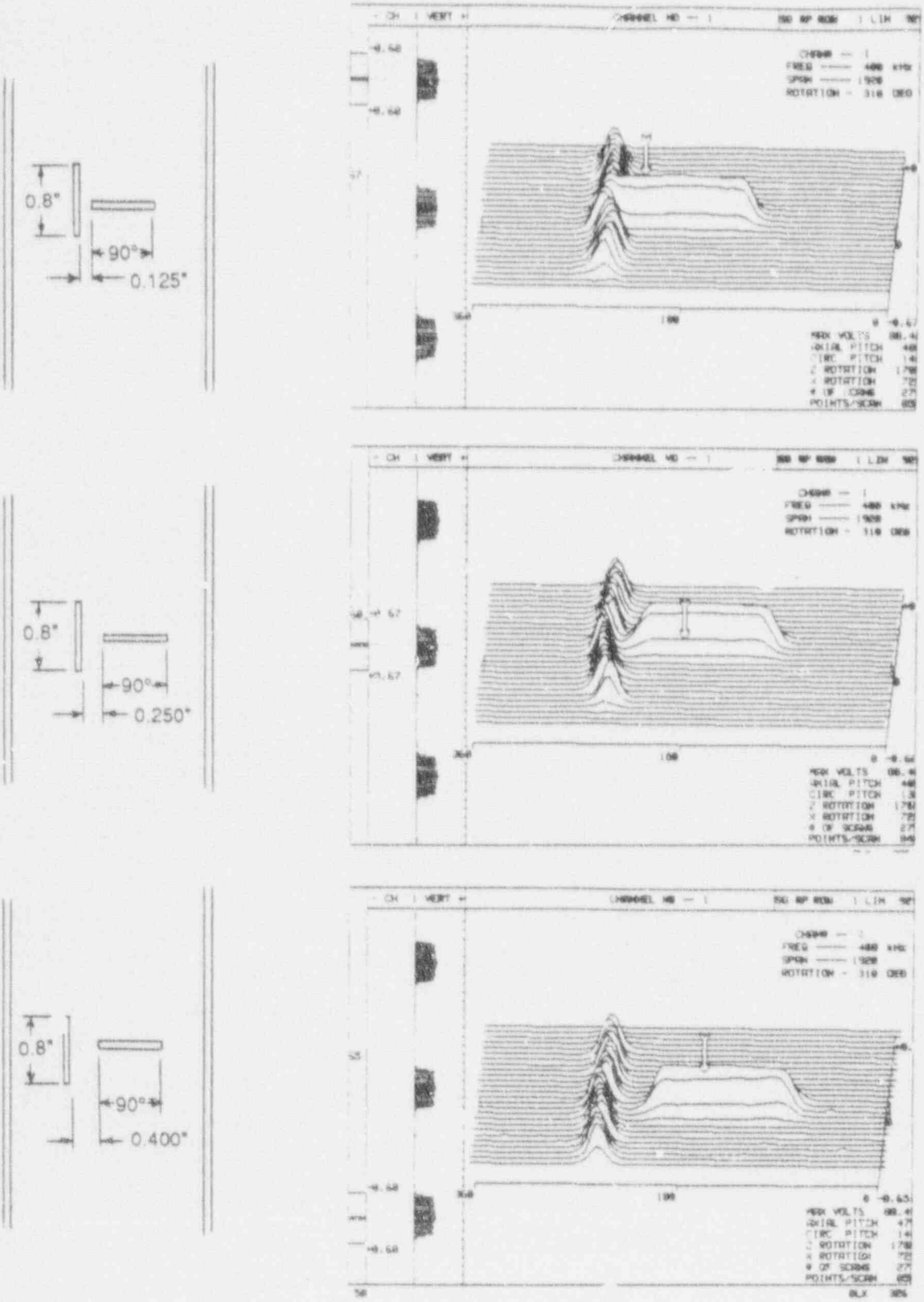

0.8"
90°
0.125"
0.8"
90°
0.250"
0.8"
90°
0.400"
CHANNEL NO — 1
FREQ — 400 kHz
SPAN — 1920
ROTATION — 310 DEG
MAX VOLTS
AXIAL PITCH
CIRC PITCH
Z ROTATION
X ROTATION
OF SCANS
POINTS/SCAN

Figure 3-15

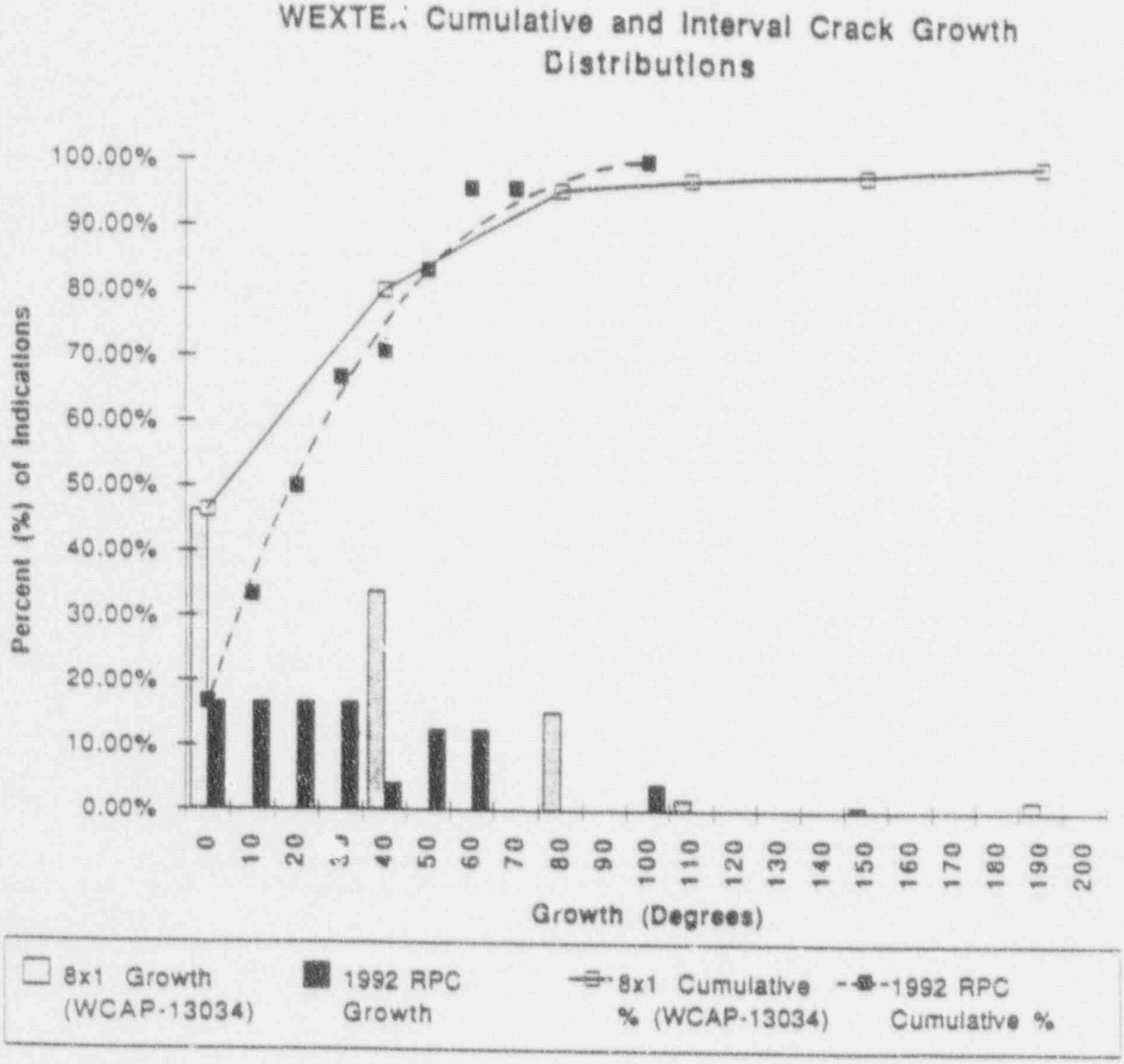
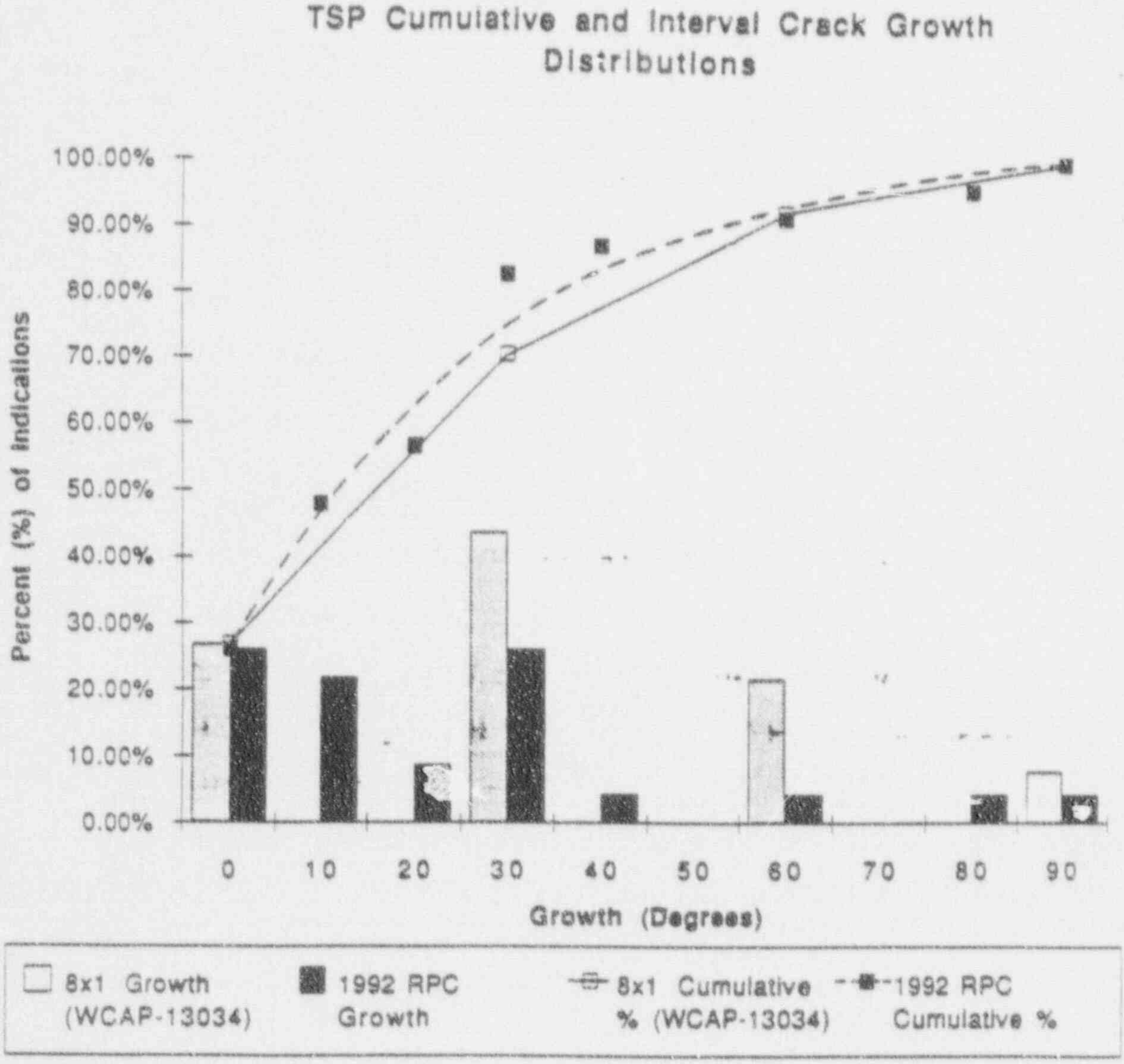


Chart WEXTEX Growth Rates 2/27/92

Figure 3-16



TSP Cumulative and Interval Crack Growth Distributions
100.00%
90.00%
80.00%
70.00%
60.00%
50.00%
40.00%
30.00%
20.00%
10.00%
0.00%
Percent (%) of Indications
0
10
20
30
40
50
60
70
80
90
Growth (Degrees)
8x1 Growth (WCAP-13034)
1992 RPC Growth
8x1 Cumulative % (WCAP-13034)
1992 RPC Cumulative %

4.0 OPERATING CYCLE CONSIDERATIONS

The North Anna Unit 1 steam generators will be operated at reduced load and primary coolant temperature conditions for the rest of the operating cycle. The reduced load and temperatures favor lower corrosion rates. The planned operating conditions, a comparison with prior values, and their impact on tube degradation are discussed below.

4.1 Planned Operating Conditions for the Remainder of Current Cycle

The remaining half of the current fuel cycle of Unit 1 operation will extend 10 months from early March, 1992 to early Janutry, 1993. Unit 1 operation will be limited to a maximum load. Per this limit, the maximum load on the unit will not exceed 95% of the current rating. In addition to the 95% operating limit, the output will be further restrained by unit coast down, which is projected to start in September, 1992. The projected load profile is shown in Figure 4-1. Thus, operation at/near 95% load is expected for only a six month period.

The first half of the current Unit 1 fuel cycle was completed with 254 effective full power days (EFPD) of operation at 100% load. The remaining part of the Unit 1 fuel cycle will have 252 EFPD of operation. Of these EFPD, about 2/3 will be at/below 95% load and the remaining will in the coast down mode at even lower loads.

At the steam generator inlet, the primary coolant temperature (T_{hot}) corresponding to the 95% load operation will be 612.6°F. This is 3°F lower than the 615.6°F T_{hot} used during the recently completed, first half of the fuel cycle. The primary inlet and average temperatures are also displayed in Figure 4-1. Table 4-1 lists the projected steam generator primary and secondary side parameters at 95% load.

4.2 Comparison of Current and Prior Operating Parameters

Table 4-2 shows the full load operating conditions during the first half of the current fuel cycle. Comparing this with Table 4-1, it is observed that the projected primary inlet temperature has decreased by 3°F from the 1991 full load operating condition. Because of changes in the number of plugged tubes and adjustments to the turbine governor valve, the steam pressure is about the same as in the first half of the cycle.

4.3 Relative Corrosion Rate Modeling

Since the type of tubing corrosion found at North Anna Unit 1 has not been systematically studied in the laboratory, the most relevant means of determining the effect of operating conditions on the corrosion rate is to use the variation in the number of eddy current indications with tube support plate elevation. This variation is a function of the tubing temperature, the available superheat (as it affects the maximum chemical concentration in the crevices), and the applied stress (resulting from denting corrosion). The number of eddy current indications at a given tube support plate elevation follows:

HL TSP	Circumferential Cracks	Axial Cracks	Total
1	74	126	200
2	90	79	169
3	28	18	46
4	6	18	24
5	2	23	25
6	0	6	6
7	0	0	0
Total	200	270	470

The estimate does not include multiple crack indications. An equivalent Arrhenius activation energy can be calculated by estimating the tubing temperature in the crevices. Using laboratory test data for packed tube support plates, tubing temperatures of 585, 579, and 574°F were calculated for the first three tube support plate elevations, respectively. Applying these temperatures to the above data produces a very high activation energy, in the vicinity 160 kcal/mole.

As mentioned previously, this activation energy reflects possible contributions from temperature, chemical concentration, and stress on the variation in the number of indications. Since indications are only identified after the corrosion has progressed some distance through the tubing, the value also includes both initiation and propagation effects. Previous evaluations of the denting distribution indicate relatively little variation between the hot leg tube support plate elevations, with the average eddy current signal voltage at the bottom support plate being slightly lower than at the others; consequently, variations in stress are unlikely to be important.

4.4 Relative Corrosion Rates Between First and Second Half of Current Fuel Cycle

The operating characteristics of the previous and current operating periods are presented in Table 4-3. The current operating cycle reflects 6 months of operation at 95% power, followed by a 4-month coastdown to 45% power. This operating history is shown in Figure 4-1. The effect of this operating history on corrosion rates can be determined by comparing the time-at-temperature of the current and previous operating periods for various Arrhenius coefficients. This prediction assumes that the operating chemistries during the two periods are comparable, as is the extent of corrosion at the beginning of each period.

The predictions are presented in Table 4-3 for Arrhenius coefficients varying between 50 and 160 kcal/mole. The 160 kcal/mole value was derived from the variation in corrosion with tube support plate elevation, and includes both temperature and superheat effects. The 50 kcal/mole value is representative of laboratory test data collected under isothermal conditions. As should be expected, the relative corrosion during the second half of the operating cycle increases as the Arrhenius coefficient decreases.

The lower bound coefficient of 50 kcal/mole has been selected for conservatively estimating reductions in crack initiation and growth. Since the superheat for the first six months of the current operating period is only slightly below that in the first half of the cycle, the calculated coefficient of 160 kcal/mole may be too high. During the coastdown, the superheat decreases as the power decreases, so that a high coefficient is likely more appropriate. Consequently, the calculated normalized corrosion rate of 0.933 should exceed the actual rate.

Table 4-1

Projected Operating Conditions at 95% Load

Thermal load, Percent	95
Thermal load, MWt	920
Primary pressure, psia	2250
Primary inlet temperature (T_{hot}), °F	612.6
Primary outlet temperature (T_{cold}), °F	546
Steam pressure, psia	777
Steam temperature, °F	515
Circulation ratio	4.84

Table 4-2

Full Load Operating Conditions During 1991

Thermal load, Percent	100
Thermal load per steam generator, MWt	968
Primary pressure, psia	2250
Primary inlet temperature (T_{hot}), °F	616
Primary outlet temperature (T_{cold}), °F	546
Steam pressure, psia	783
Steam temperature, °F	516
Circulation ratio	4.58

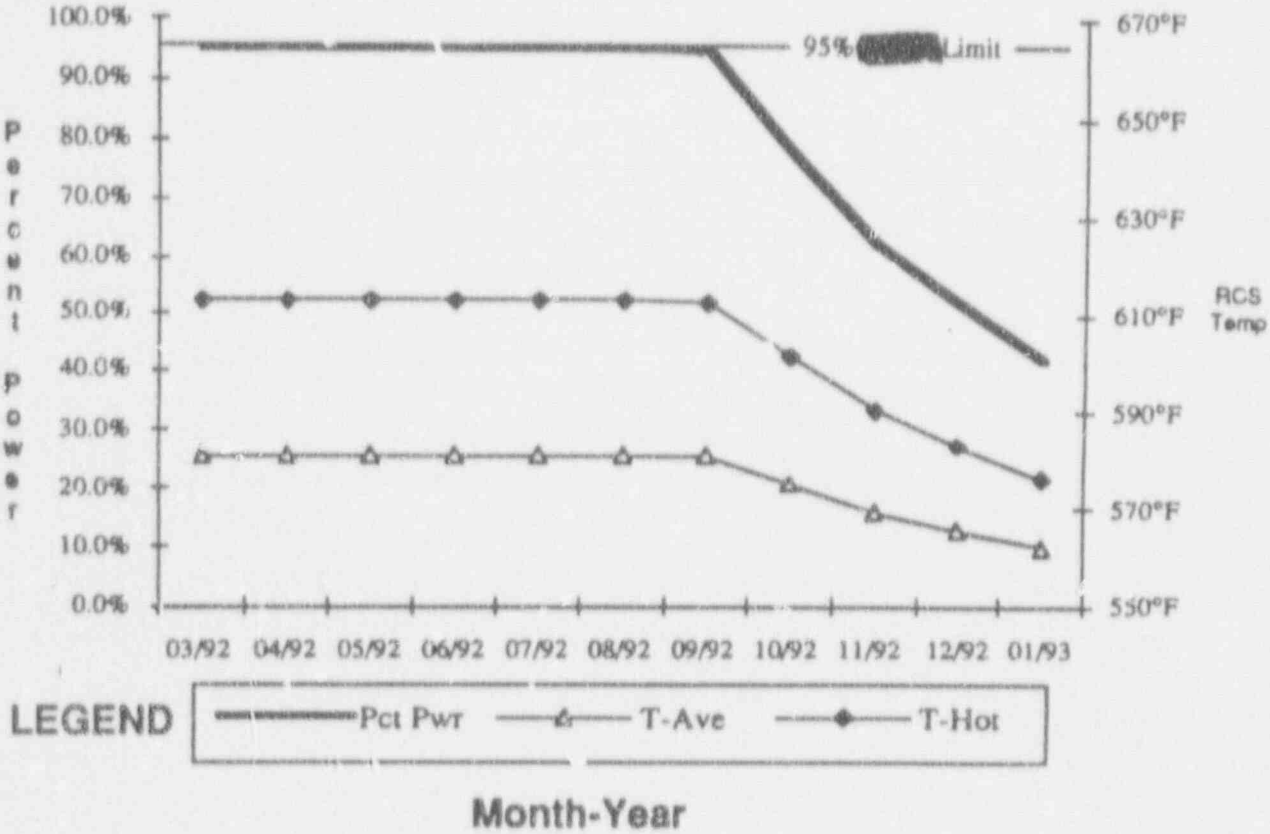
Table 4-3

Variation in Relative Corrosion with Activation Energy

Operating Cycle	Power (%)	Duration (days)	Hot Leg Temp (°F)	Tube Temp (°F)	Normalized Corrosion Activation Energy (kcal/mole) [illegible]	100	80	50
Previous	100	254	615.6	584.6	1.00E+00	1.00E+00	1.00E+00	1.00E+00
Current	95	182	612.6	582.2	5.20E-01	5.87E-01	6.11E-01	6.48E-01
Current	88	31	608.0	580.0	6.60E-02	8.31E-02	8.98E-02	1.01E-01
Current	70	30	595.0	572.7	2.38E-02	4.34E-02	5.31E-02	7.16E-02
Current	58	31	586.0	567.5	1.21E-02	2.88E-02	3.84E-02	5.93E-02
Current	45	30	580.0	565.7	9.13E-03	2.39E-02	3.28E-02	5.31E-02
Total for Current Cycle					0.631	0.766	0.825	0.933

Figure 4-1

Projected Unit Load Profile



5.0 SUMMARY OF CRACK SIZES SATISFYING REG. GUIDE 1.121

The tube integrity limits for single axial and circumferential cracks have been developed previously in Section 6.0 of WCAP-13034. The following sections summarize burst tests and crack propagation tests for multiple circumferential cracks. The acceptable crack conditions for multiple circumferential indications (MCIs), as well as for combined axial and circumferential (mixed mode) indications are presented. The acceptable single crack sizes which satisfy the tube burst requirements of Reg. Guide 1.121 are also summarized, from WCAP-13034, along with the acceptable single crack sizes which are expected to preclude vibration induced crack propagation.

5.1 Burst Tests for Multiple Circumferential Cracks

Room temperature tests of tubes with multiple coplanar circumferential EDM slits were conducted to verify the calculational methodology used to compute the pressure capability of tubes with multiple circumferential stress corrosion cracks (MCIs). At very large crack sizes, the burst pressure previously (WCAP-13034) was found to be proportional to the net remaining area. In this case a conservative burst pressure is obtained by setting the net section stress equal to the flow strength of the material. Figure 5-1 shows sketches of the large coplanar EDM slits and small ligament geometries of the present test series. Note that some ligaments are only partial wall thickness ligaments simulating a 50% deep crack in the remaining ligaments. The burst pressure test results for two repeats of each configuration are also shown in Figure 5-1.

When results are plotted in terms of the sum of all circumferential crack angles, the burst pressures for the sum of the multiple slits exceed those for the single circumferential slits. This is illustrated in Figure 5-2. Note that at large total crack angles, the lower bound burst pressure is simply the net area times the flow strength of the material. Ligament location and bending tendency (multiple ligaments reduce the bending tendency compared to a single slot) have only a second order effect on the burst pressure. This is logical given that the presence of the tube support plate restricts lateral motion and severely inhibits bending of the tube at the cracked section. Application of these test results to acceptable MCI configurations is addressed in Section 5.4.

5.2 Fatigue Crack Growth Rate Tests For Multiple Circumferential Cracks

Just as the burst pressure calculational methodology was benchmarked with test data for multiple coplanar circumferential cracks, the fatigue crack growth analysis procedure was benchmarked also. Figure 5-3 shows sketches of the EDM starter notches used in the fatigue crack growth rate tests. Under fatigue loading due to turbulence or fluidelastic vibration, the central issue is whether or not growth will occur. If the applied stress intensity range is above the threshold value, fatigue crack growth will occur and high vibration frequencies can lead to extensive growth in a relatively short period of time compared to the operational cycle. Rather than attempting time consuming fatigue crack growth threshold tests, the fatigue analysis was benchmarked by demonstrating that the fatigue crack growth rates measured on several ligament geometries correlated with results on a conventional geometry using stress intensity range as the correlating parameter; that is, the agreement of fatigue crack growth results of ligament and conventional geometries demonstrates the acceptability of stress intensity factor calculations for ligament geometries. For small ligaments, there are several limiting cases for stress intensity solutions for tension and bending. These were applied to the present case and worked well. For worst case service conditions, a minimum of three 35° ligaments are needed for fatigue stability and the largest crack angle between ligaments must not exceed the single circumferential crack limit for initiating crack propagation. Experimental work shows that the presence of the third ligament converts the behavior of the tube to essentially the single crack case and the minimum size for the third ligament is very conservative.

Figure 5-4 illustrates a plot of measured fatigue crack growth rates versus the computed stress intensity range obtained by applying the small ligament solutions. The good agreement of results for a variety of crack geometries supports the acceptability of the stress intensity range calculations and their comparison with fatigue crack growth threshold values.

5.3 Acceptable Single Crack Sizes for Tube Burst

The burst strengths of tubing with single circumferential cracks and single axial cracks have been evaluated previously in WCAP-13034. Sections 6.1 and 6.2 of WCAP-13034 summarize the burst tests performed for single circumferential and axial cracks. The burst test data are compared with analytical predictions, and the burst capabilities of tubes with axial or circumferential cracks are established in Section 6.4 of WCAP-13034.

Table 5-1 summarizes the acceptable crack sizes for single circumferential and axial cracks with either single throughwall crack or segmented crack morphologies. The limiting circumferential crack angle for a single crack is 226° for 3ΔP burst capability; a segmented crack satisfies 3ΔP for crack angles up to 297°. The maximum acceptable crack angles for ΔP_{SLB} are substantially higher; thus, the 3ΔP burst capability requirement provides the limiting circumferential crack angles for tube burst considerations. Single throughwall axial cracks of up to 0.435 inch in length will satisfy 3ΔP; for segmented crack morphologies, single axial cracks of up to 0.72" long are expected to meet 3ΔP. The acceptable single axial crack lengths for ΔP_{SLB} burst capability are substantially higher; hence, 3ΔP is also the limiting condition for single axial cracks.

5.4 Acceptable MCI Crack Conditions for Tube Burst

As developed in Section 3.8, the RPC inspection definition of an MCI requires the amplitude to return to the null point, and RPC resolution limitations imply a ligament size of the measured RPC ligament plus 30°. Thus, an MCI would have at least 35° ligaments, which were burst tested as described in Section 5.1. As shown in Figure 5-2, the burst pressure for two 35° full thickness ligaments exceeds that for a single 290° crack. Thus, the burst pressure for an MCI exceeds SLB pressure differentials which correspond to a 321° throughwall single crack with full wall thickness ligaments. Thus an MCI for WEXTEX indications, for which cracking in the remaining ligaments is not expected, would inherently exceed SLB burst capability. The burst test results of Figure 5-2 for 35° ligaments are equivalent to burst pressures for single throughwall cracks of less than the 226° crack angle for 3ΔP burst capability. However, not enough tests were performed to strongly support 3ΔP burst capability for 35° ligaments. For the present study, it is conservative and adequate to evaluate WEXTEX MCI burst capability as that for a single crack equal to the sum of the MCI crack angles after reduction of the RPC crack angles by 30° for coil lead-in and lead-out effects (see Section 3.8); that is, WEXTEX MCI RPC crack angles totalling about 286° (226°+30°+30°) or ligaments totalling 74° would meet 3ΔP burst capability. This analysis assumes that the cracks are very deep or throughwall, such that the RPC lead-in and lead-out reductions of RPC angles are applicable. If crack depths at the edges of the crack are less than about 50% depth, the actual crack angles can be equal to or greater than the RPC angle. In this case, the burst capability would also exceed that associated with the RPC angle so that it would be appropriate to reduce the RPC angle for comparisons with throughwall burst pressures. Thus, total RPC crack angles of 286° for MCI or [illegible]6° for an SCI would be expected to meet $3\Delta P$ burst capability.

For ODSCC circumferential cracks, for which a 50% deep crack is assumed in the remaining ligaments, the ligament sizes must be larger than the 35° for WEXTEX MCIs. The tests of Section 5.1 were performed for two 70° ligaments with 50% deep slots in the ligaments. The burst pressures for this case exceeded that of a 220° single throughwall crack which meets $3\Delta P$ burst capability. For the present report, it is conservative and adequate to require the RPC ligaments for TSP MCIs to total 80° (resolution adjusted ≈140°) or the RPC crack angles totalling <280° for $3\Delta P$ burst capability. More simply, if the minimum measured RPC ligament for TSP MCIs is 40° or larger, the indication would meet [illegible] burst capability.

5.5 Acceptable Combined Axial and Circumferential Crack Conditions

As noted in Section 3.7, no intersecting circumferential and axial indications have been found in the North Anna Unit 1 SGs at either WEXTEX or TSP locations. An RPC detectable ligament separating axial and circumferential indications has been identified for all mixed mode indications at the same edge of a TSP. No axial and circumferential indications have been found at the same elevation in the WEXTEX expansions, so that mixed mode cracking is not a concern for the North Anna Unit 1 WEXTEX expansions.

Based on the RPC resolution tests of Section 3.8 for mixed mode indications, the actual ligament size corresponds to the RPC measured ligament plus 30° (~0.2"). Scoping analyses indicate that a minimum ligament of about three wall thicknesses (0.15" or ~22°) is expected to be sufficient to provide burst capability comparable to the axial crack alone. This is supported by tests for small ligaments (EPRI NP-6368-1, Rev. 1) that show that ligaments approaching the tube wall thickness between throughwall circumferential and axial (L-shaped) cracks begin recovery of the mixed mode burst pressure loss compared to the axial crack alone. Thus, it is reasonable to expect that about a 22° ligament is adequate to obtain burst capability equivalent to the more limiting of the axial or circumferential crack.

Since the presence of an RPC measured ligament between deep axial and circumferential cracks implies a >30° ligament, the presence of an RPC ligament is sufficient to preclude significant reductions in burst pressures due to mixed mode cracking. Alternately stated, if a RPC ligament is found, the burst capability can be evaluated separately for the axial or circumferential crack and no mixed mode burst assessment is necessary.

Even if intersecting mixed mode cracking should occur, the burst capability is not affected unless the throughwall axial crack length exceeds 0.24 inch. Test results have shown that the average burst pressure of 270° throughwall circumferential cracks with intersecting 0.24 inch long axial cracks falls on the burst curve for single circumferential cracks. Since the circumferential cracks of interest occur near the surface of support plates, the axial crack length in the support plate crevice need not be considered due to denting within the TSPs. Only the axial crack length outside of the tube support plate will affect the burst pressure and this crack length must be greater than 0.24 inch before any significant degradation in burst pressure is observed.

With respect to fatigue crack growth under turbulence and fluidelastic vibration loadings, the limiting small ligament case is useful. As a circumferential crack approaches an axial crack, the stress intensity factor will increase. This effect can be bounded by considering the axial crack as another circumferential crack. Hence, from previous results, if the ligament between a circumferential crack and an axial crack is greater than 35°, the cracks can be considered non-interacting in terms of a fatigue crack growth threshold.

Based on the above, the presence of an RPC measured ligament implies a >30° ligament which permits the axial and circumferential cracks to be evaluated separately as non-interacting cracks for either tube burst or fatigue considerations. Thus, the RPC ligament precludes the need for more detailed mixed mode cracking evaluations.

5.6 Acceptable Single Crack Sizes for Tube Vibration

The analysis methods and models used for the tube vibration assessments for North Anna Unit 1 have been presented in Section 7 of WCAP-13034. This section presents the limiting circumferential crack sizes for the WEXTEX expansion transitions and the TSPs with respect to vibration induced crack propagation.

The tube vibration assessment given in WCAP-13034 was performed for each tube location in the SG. The analyses determined the uniformly throughwall crack angle at which a circumferential corrosion crack could potentially propagate by tube vibration. Minimum crack angles for propagation were developed for both turbulent and fluidelastic induced tube vibration. For TSP intersections, crack angles for propagation were obtained for a throughwall crack only (TW-only) and for a throughwall crack with a 50% deep crack in the remaining ligament (TW+50%). Table 5-2 summarizes the minimum crack angles for initiating propagation for conservative uniformly throughwall cracks and for the expected crack morphology. The expected crack morphology for WEXTEX PWSCC cracks is segmented cracks (short, deep cracks separated by uncorroded ligaments). For ODSCC at TSPs, it is expected that less than 60% of an RPC-measured crack angle would be throughwall. It can be seen from Table 5-2 that the potential for crack propagation is minimal for the expected crack morphology. WEXTEX segmented cracks at all tube locations and TSP ODSCC indications in central regions would not propagate even for 360° RPC crack angles. Only TSP circumferential cracks at the bottom of the first TSP at the periphery of the tube bundle would propagate for the expected morphology at RPC angles of [ ]b,c. It should be noted that the circumferential cracks at the upper edge of the top TSP were not evaluated, as circumferential indications have not been found above the fifth TSP, although all TSPs were 100% inspected.

The tube vibration assessment for tubes with circumferential cracks near the WEXTEX transition region can be summarized for sensitivity assessments by dividing the tubesheet region into zones with varying degrees of susceptibility to vibration-induced crack propagation. Figure 5-5 shows a tubesheet map with the various zones identified. The zones are described as follows:

Zone 1 - Tubes with potential for initiation of vibration-induced crack propagation for throughwall crack angles of [ ]b,c.

Zone 2 - Tubes with potential for initiation of vibration-induced crack propagation for throughwall crack angles of [ ]b,c.

Zone 3 - Tubes with potential for initiation of vibration-induced crack propagation for throughwall crack angles of [ ]b,c.

Zone 4 - Tubes for which initiation of vibration-induced crack propagation requires throughwall crack angles of [ ]b,c; Zone 4 corresponds to the low flow, sludge deposition area.

Zone 1 contains 620 tubes, Zone 2 contains 344 tubes, Zone 3 contains 940 tubes, and Zone 4 contains 1484 tubes. The minimum angles for crack propagation apply to only a few limiting tubes in each zone.

For the most limiting peripheral tube locations in Zone 1, for a crack at the WEXTEX transition, the initiation of turbulence driven propagation occurs for a throughwall crack angle of [ ]b,c; in this condition, the tube remains stable and turbulence driven propagation occurs until the crack angle reaches [ ]b,c, which is the crack angle associated with fluidelastic instability. The limiting total growth time during the turbulence propagation phase is [ ]b,c. Once the crack has reached [ ]b,c, the tube vibrates in a fluidelastic manner and fluidelastic crack propagation is initiated. The additional fluidelastic driven growth time to tube rupture is calculated to be [ ]b,c. The crack angle vs. time plot showing the turbulence and fluidelastic driven growth times is provided in Figure 5-6. For Zone 1 with crack angles <169°, all crack propagation would be initiated by turbulence induced vibration. Thus, Zone 1 defines all tubes which would initiate vibration below the crack angle for fluidelastic crack propagation.

For the limiting tube in Zone 2 with a crack at the WEXTEX transition, the initiation of turbulence driven propagation occurs for a throughwall crack angle of [ ]b,c; in this condition, the tube remains stable and turbulence driven propagation occurs until the crack angle reaches the critical angle for fluidelastic vibration, after which crack propagation is driven by fluidelastic instability. For the limiting tube in Zone 3 with a crack at the WEXTEX transition, the initiation of turbulence driven propagation occurs for a throughwall crack angle of [ ]b,c; in this condition, the tube remains stable and turbulence driven propagation occurs until the crack angle reaches the crack angle required for fluidelastic instability. For the limiting tube in the central sludge deposition area (Zone 4) with a crack at the WEXTEX transition, the initiation of turbulence driven propagation will not occur unless the throughwall crack angle exceeds [ ]b,c; however, a tube in Zone 4 vibrating in a fluidelastic manner would experience vibration induced crack propagation if the throughwall crack angle exceeds [ ]b,c. Zone 4 was found to include >90% of the WEXTEX indications observed during the 1992 mid-cycle inspections.

For circumferential cracks at the TSPs, only cracks at the bottom edge of the first TSP have significant potential for vibration induced propagation up to the largest angle of 244° throughwall that was evaluated. Above the first TSP, cross flow velocities and tube vibration amplitudes are sufficiently low as to be insufficient to cause tube vibration induced crack propagation. The TSP circumferential cracks have an ODSCC crack morphology. The RPC threshold for detecting ODSCC circumferential cracks is about 50% depth. For the tube vibration assessment of ODSCC cracks at the TSPs, the portion of the tube apparently free from degradation is conservatively assumed to have 50% throughwall degradation.

The tube vibration assessment for tubes with circumferential cracks at the TSPs utilizes the same zones with varying degrees of susceptibility to crack propagation as described for the WEXTEX region. Figure 5-5 shows the various zones used. Although the tubes within each zone are unchanged from the WEXTEX tube vibration assessment, the

limiting crack angles for the onset of vibration induced propagation are different than in the WEXTEX tube vibration assessment. The zones for the TSPs are defined as follows:

Zone 1 - Tubes with potential for initiation of vibration-induced crack propagation for throughwall crack angles ≥122°

Zone 2 - Tubes with potential for initiation of vibration-induced crack propagation for throughwall crack angles ≥170°

Zone 3 - Tubes with potential for initiation of vibration-induced crack propagation for throughwall crack angles ≥230°

Zone 4 - Tubes for which initiation of vibration-induced crack propagation requires throughwall crack angles of greater than the 244° minimum throughwall crack analyzed for crack propagation.

For the most limiting peripheral tube locations in Zone 1, for a circumferential crack at the bottom of the first TSP with 50% throughwall degradation assumed in the region apparently free from degradation (TW+50%), turbulence driven propagation initiates at a throughwall crack angle of [ ]b,c; in this condition, the tube remains stable and turbulence driven propagation occurs until the throughwall crack angle reaches the 244° crack angle associated with fluidelastic instability. Figure 5-7 shows the time history of crack propagation for the limiting peripheral tube. If the most limiting Zone 1 tube location is assumed to have a throughwall crack with no degradation in the remaining ligament, the limiting crack angle for the onset of vibration-induced crack propagation increases to [ ]b,c.

For the limiting tube in Zone 2 with a circumferential crack at the TSPs, the initiation of turbulence driven propagation occurs at [ ]b,c (TW+50%); in this condition, the tube remains stable and turbulence driven propagation occurs until the crack angle reaches the point of fluidelastic instability [ ]b,c. For the limiting tube in Zone 3 with a crack at the TSPs, the initiation of turbulence driven propagation occurs for a throughwall crack angle of [ ]b,c (TW+50%). For the limiting tube in the central sludge deposition area (Zone 4) with a circumferential crack at the TSPs, the initiation of vibration-induced crack propagation will not occur unless the throughwall crack angle exceeds the [ ]b,c maximum crack angle analyzed; this is true for both the TW-only and TW+50% conditions.

Table 5-1

Single Circumferential and Axial Crack Tube Burst Capability Summary

Crack Morphology	$3\Delta P_{N.O.}$	ΔP_{SLB}
	Circumferential Crack Angles	
Segmented Cracks	[	] b,c
Single Crack		
Single Crack with 50% Deep Crack		
	Axial Crack Lengths - inch	
Segmented Cracks	[	] b,c
Single Cracks		

Table 5-2

Acceptable RPC Crack Angles for Tube Vibration

	WEXTEX	PWSCC	TSP ODSCC(1) TW Only	TSP ODSCC(1) TW+ 50%(2)
Conservative TW Cracks				
o Peripheral Region	[			]b,c
- Turbulence				
- Fluidelastic				
o Central Region				
- Turbulence				
- Fluidelastic				]
Expected Crack Morphology				
o PWSCC Segmented Cracks	[ ]b,c			
- Turbulence				
- Fluidelastic				
o ODSCC Model				
- Peripheral:	[			]b,c
Turbulence				
Fluidelastic				
- Central:				
Turbulence				
Fluidelastic				]

Notes:

1. Limiting crack angles at TSPs applicable to bottom of 1st TSP only. Higher elevations to bottom of top TSP require TW crack angles [ ]b,c evaluated for crack propagation due to vibration.
2. Throughwall crack [ ]a,c
3. Most limiting peripheral tube locations
4. ODSCC Model assumes [ ]a,c

TAP2026:022692

Figure 5-1

Burst Test EDM Slit Geometries and Test Results for MCIs

(Cross-sectional views; shaded areas are remaining ligaments)

b,c

Figure 5-2

Burst Pressure vs. Total Circumferential Crack Angle,

Multiple Cracks Compared with Single Crack Case

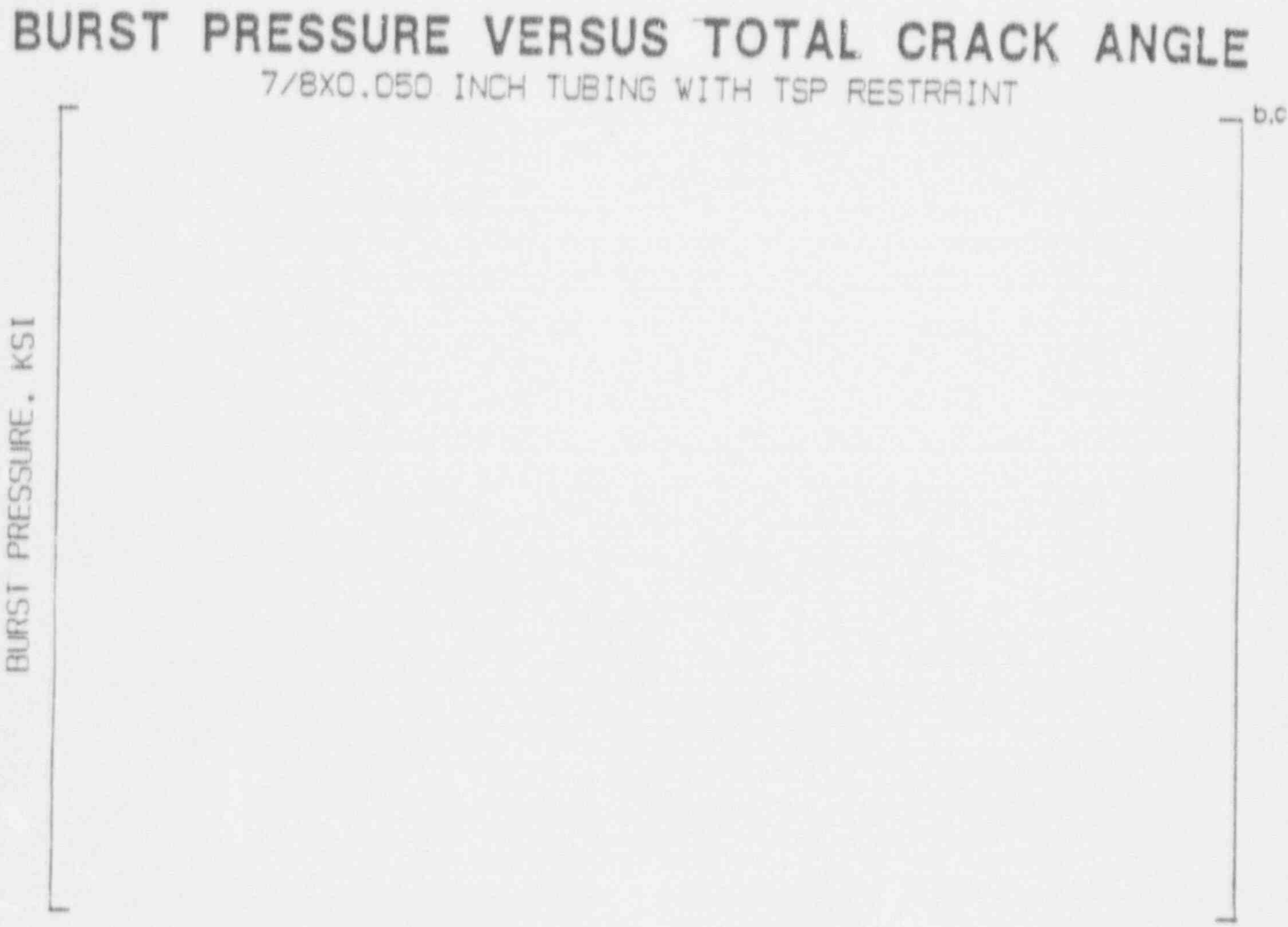
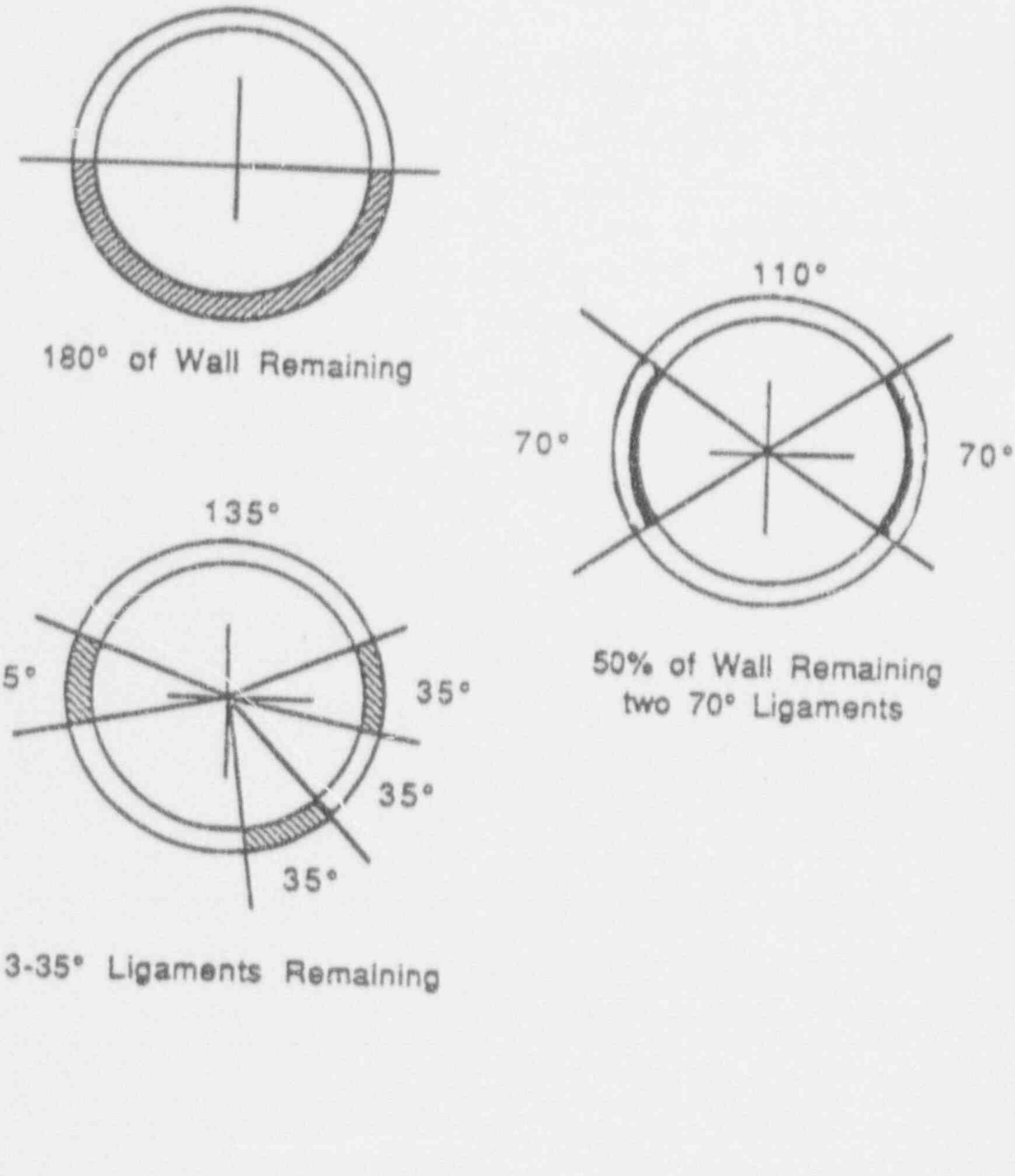


Figure 5-3

Fatigue Test EDM Slit Geometries

(Cross-sectional views; shaded areas are remaining ligaments)



180° of Wall Remaining

50% of Wall Remaining two 70° Ligaments

3-35° Ligaments Remaining

Figure 5-4

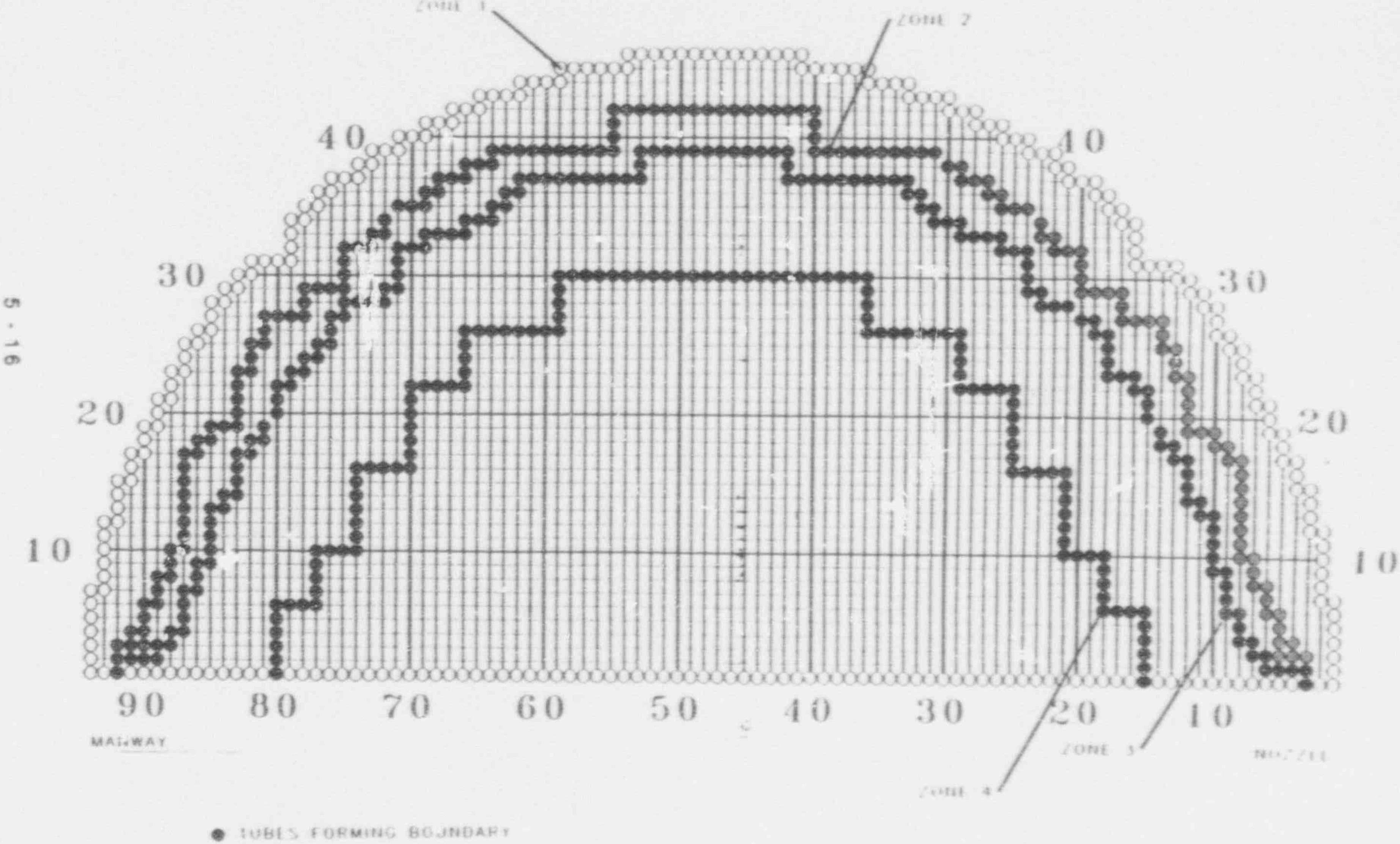
Measured Fatigue Crack Growth Rate Vs. Stress Intensity Range

Conventional and Ligament Geometries

[ ]b,c

Figure 5-5

Inspection Boundary Tubesheet Map



a,b,c

Figure 5-6

a,b,c

Figure 5-7

6.0 TUBE INTEGRITY ASSESSMENT

6.1 Crack Distributions for Second Half of Current Fuel Cycle

The second half of the current fuel cycle is planned for 252 EFPD compared to 254 EFPD for the first half of the cycle. Thus, if inspection methods and operating conditions (T_{hot}) were the same for both halves of the cycle, the last (mid-cycle, 2/92) inspection results on number and size of indications would be typical of that expected at the end of the current cycle. However, the operating interval for the second half of the fuel cycle (henceforth, current operating cycle) is expected to result in both fewer and smaller indications than found at the last inspection (Section 3.0). The following two considerations lead to the reduced crack severity anticipated for the current operating cycle:

- o As described in Section 4.0, the reduced power and end of cycle coastdown planned for the current operating interval lead to an approximately 7% reduction in the number of newly initiated cracks and in the growth rates of existing cracks undetected at the last inspection.

- o As described in Section 3.11, the "inspection transient" introduced by the first 100% RPC inspection at the TSP intersections would lead to a reduction in the number and size of indications at the end of the next operating interval.

Due to the relatively low growth rates found for circumferential cracks at both the TSPs and WEXTEX transitions, newly initiated indications are not a significant concern for tube integrity in the current operating cycle. More important are the indications already present, but undetected, and their growth over the operating cycle. Thus the influence of the reduced power conditions on crack growth is more important to the tube integrity assessment than their influence on crack initiation.

The 7% reduction in crack growth from the reduced power conditions would apply to both growth in depth and in crack angle. However, only crack angle is measured with confidence by the RPC inspection. Thus the growth reduction is applied only to the crack angle. The largest crack angle growth rates can be expected to result in the limiting crack angles. This is particularly relevant following an inspection transient, such as

...e first 100% RPC inspection at the TSPs in 1992, for which the large crack angles can be expected to have been detected. From Table 3-10, the largest crack growth rates found at TSPs were 39° and 45° for the last completed cycle. A 7% reduction in growth rate would reduce growth by about 3° and therefore lead to an expected reduction in the largest crack angle from 240° (Section 3.4) to about 237°. This correction is small and can be applied for all indications for the expected EOC crack distribution.

...nspection Transient", as discussed in Section 3.11, applies to the TSP indications ...d at North Anna-1 in that a 100% RPC inspection was performed for the first time. ...e first inspection with more sensitive probes or EC analysis guidelines tends to be ...owed by both fewer and smaller indications at the subsequent inspection. This ...plies for the expected end-of-cycle (EOC) indications at the TSPs being evaluated in this report. In Section 3.11 (Table 3-14), it is shown that the RPC inspection transient resulted in a reduction in the number of indications by a factor of 7 for the North Anna Unit 1 WEXTEX indications. From Tables 3-11, 3-12 and 3-14, the reductions for other tubesheet expansion indications were factors of 28, 6, and 2. No directly comparable data is available for ODSCC at TSPs. It is reasonable to expect that the number of TSP indications at the end of the current cycle will be at least a factor 1.5 lower than found at the last inspection. This conclusion is applied in Section 7 for the expected SLB leak rate at EOC conditions.

The WEXTEX inspection transients also have been found to result in smaller crack angles at the subsequent inspection. For example, the maximum WEXTEX indication found at the first North Anna-1 RPC inspection was about 247° while the subsequent inspection found a maximum angle of 199° (R25C36, S/G B). The 199° followed a 9 month cycle. The growth of this indication over the 9 month cycle was 24°. Adding an additional 24° growth to the 199° indication yields an estimated 223° indication for an 18 month cycle. Thus the RPC inspection transient has resulted in a reduction of ~24° in the maximum WEXTEX indication. For Plant L and North Anna Unit 2, the reductions in maximum circumferential crack angles between the first and subsequent RPC inspections were 105° and 110°. Thus it is reasonable to expect that the 100% RPC inspection at the TSPs will result in a reduction of the maximum crack angle of at least 20° at the EOC compared to the last inspection. This corresponds to about an 8% reduction in crack angles such as for the 240° largest indication found at the TSPs.

Based on the above discussion, the expected EOC crack angles at TSP intersections are assumed to be reduced by 8% due to the RPC inspection transient and by about 3° due to the reduced power conditions. For example, the largest TSP crack angle of 240° at the last inspection would be expected to be (240° x 0.92) - 3° = 218° at the next EOC.

Table 6-1 summarizes the above influence of reduced temperatures and the TSP inspection transient on the expected number of indications and crack angles for the current North Anna-1 operating cycle. The expected maximum crack angles are used for the tube integrity assessment given in the following sections.

Prior to the last outage, axial indications outside the TSP were detected by bobbin coil inspection and confirmed by RPC. The 100% RPC inspection increased the number of detected axial indications from 126 to 286 or close to a factor of 2.2 increase. Thus it is reasonable to apply the factor of 1.5 reduction in number of indications for the TSP circumferential indications to the axial indications. The maximum crack length found in the 1992 inspection was shorter than found in the 1991 inspection, which was likely due to the shorter operating cycle. For conservatism in the tube integrity and SLB leak rate analysis, the effect of reduced temperatures and the RPC inspection transient are ignored for axial crack lengths. The axial lengths found in the 1992 inspection are applied for the end of the current cycle.

6.2 WEXTEX Tube Burst Assessment

The largest RPC circumferential, single crack angle found in the last outage was 199° (See Figure 6-1). From Table 6-1, the lower temperature conditions for the current cycle would be expected to reduce crack growth and result in a crack angle of about 196°. In either case, the largest RPC crack angle found in the last cycle or expected for the current cycle is less than the acceptable 226° through wall crack angle that meets 3ΔP tube burst capability.

The MCI burst test results given in Section 5.1 and evaluated in Section 5.5 show that MCIs separated by ligaments of 30-35° or more result in burst pressures exceeding that for an SCI having the same total crack angle. As noted in Section 3.6.1, the most limiting MCI found in the last inspection was tube R24C33 in S/G A (See Figure 6-2.) This indication had RPC crack angles of 149° and 85° separated by a measured 12°

ligament. After adjusting for RPC resolution (See Section 3.8), the minimum ligament would be 42°. Thus the smallest ligament exceeds the 35° minimum ligament to support acceptable MCI burst capability. The total RPC crack angle of 234° (174° adjusted for RPC resolution) is less than the 226° developed in Section 5.5 for 3ΔP burst capability. Thus the WEXTEX MCIs found in the last inspection exceed 3ΔP burst capability and represent an upper bound on indications expected in the current cycle.

6.3 TSP Circumferential Indication Tube Burst Assessment

Two TSP circumferential indications were identified in the last outage with RPC angles exceeding the 3ΔP burst capability of 226°. The associated RPC angles were 240° and 239° as shown in Figures 6-3 and 6-4. As discussed in Section 6-1, indications at the end of the current cycle would be less than the last cycle as a consequence of the 100% RPC inspection transient and the reduced temperature conditions of the current operating cycle. As developed in Table 6-1, the expected maximum TSP crack angle at the EOC would be 218° corresponding to a 240° crack in the prior cycle. Thus the limiting crack angle at the current EOC would be less than 226° and satisfy 3ΔP burst capability.

It can be noted that even the 240° indications found at the last outage would meet 3ΔP burst capability. The 226° angle for 3ΔP capability is based on a uniformly through wall crack. From Figures 6-3 and 6-4, it is seen that the high amplitude responses for the indications correspond to angles of about 134° and 96° for the two indications. The deepest part of the cracks correspond to the largest amplitudes. Thus, even if the indications had through wall penetration, the through wall angle would be <60% of the RPC crack angle. Thus these indications would meet 3ΔP tube burst capability.

The MCI burst test results (Sections 5.1 and 5.5) for through wall cracks plus a 50% deep crack in the remaining ligaments show that MCIs separated by ligaments of 70° meet 3ΔP tube burst capability. The maximum sum of crack angles in this case would be 220°, or less than the 226° for 3ΔP burst capability. From Table 3-6, the limiting TSP MCI was at TSP 3H in Tube R2C41 (See Figure 6-5). The RPC measured ligaments for this indication were 66° and 41° which, after the adjustment for RPC resolution developed in Sections 3.8 and 5.5, would exceed the 70° ligaments required for 3ΔP tube burst capability. In addition, the MCI crack angles would be reduced by about 30° for regions for all steam generators during the February 1992 inspections. Zone 4 contains 90% of the WEXTEX circumferential indications.

The throughwall crack angles required for the initiation of turbulence and fluidelastic driven crack propagation are given in Section 5.6. The WEXTEX region circumferential cracks at North Anna Unit 1 are comprised of PWSCC segmented cracks. Crack propagation due to turbulent or fluidelastic vibration does not occur for the expected segmented PWSCC crack morphology, even for crack network angles of 360°. Nevertheless, the crack angles observed during the 1992 mid-cycle inspection are compared to the acceptable crack angles from Section 5.6 below.

Only one WEXTEX circumferential indication was observed in Zone 1, in R25C8 of SG B, with an arc length of 142° measured in the field; laboratory reanalysis of the field data produced a measured arc length of 157°. The throughwall extent of this crack was less than the minimum [ ]b,c necessary for turbulence driven crack propagation in Zone 1; furthermore, the calculated throughwall angle necessary for turbulent crack propagation at the location of R25C8 is [ ]b,c. No circumferential indications were observed in Zone 2. Two WEXTEX circumferential indications were observed in Zone 3; both had RPC angles less than the [ ]b,c angle necessary for initiation of turbulence driven propagation (the maximum crack angle was 118° in R21C23 of SG A). The maximum crack angle in Zone 4 was 199°, in R25C35 of SG B. All WEXTEX region circumferential indications in Zone 4 had RPC crack angles less than the [ ]b,c minimum through wall angle required for crack propagation. Therefore, it is concluded that no WEXTEX indications are subject to crack propagation due to tube vibration.

6.7 TSP Tube Vibration Assessment

The tube vibration assessment for tubes with circumferential cracks at the TSPs is performed by dividing the tubesheet region into zones with varying degrees of susceptibility to crack propagation caused by tube vibration, as described in Section 5.6. Figure 5-5 shows a tubesheet map with various zones identified. The zones for the TSP tube vibration assessment are the same as the zones used for the WEXTEX assessment; however, the acceptable crack angles for TSP circumferential cracks are somewhat different, as summarized in Section 5.6. As described in Section 5.6, only the circumferential cracks at the bottom edge of the first TSP have significant potential for vibration-induced fatigue. Therefore, the following discussion addresses only the indications in the first TSP region.

Figure 6-7 shows the distribution of circumferential indications at the bottom edge of the first TSP in all SGs. Of the 31 circumferential indications observed at the bottom edge of the first TSP, 7 indications were within Zone 1. The longest, 167° in R45C50 of SG A, had well defined, deep crack angles of ~93°; this is less than the [ ]^{b,c} through wall angle required for vibration induced crack propagation for the most limiting Zone 1 tube location and the [ ]^{b,c} required angle for the R45C50 tube location. The remaining six circumferential indications, all had crack angles of 104° or less. All three of the circumferential indications in Zone 2 were less than the [ ]^{b,c} minimum throughwall crack angle necessary for vibration induced propagation. All six of the circumferential indications in Zone 3 were less than the [ ]^{b,c} minimum throughwall crack angle necessary for vibration induced propagation. All fifteen of the circumferential indications in Zone 4 were less than the 244° maximum throughwall crack angle analyzed for vibration induced propagation. Only the 31 indications at the bottom edge of the first TSP were potentially susceptible to vibration induced propagation. Therefore, none of the circumferential indications at the TSPs are expected to experience tube vibration-induced crack propagation.

6.8 MCI and Mixed Mode Tube Vibration Assessment

All of the MCIs in the WEXTEX region were observed in Zone 4, where the minimum throughwall crack angle necessary for vibration induced crack propagation was 275°. Accounting for the segmented crack morphology in this region, the circumferential cracks would be required to reach 360° for crack propagation. None of the MCIs observed in the February 1992 inspections were sufficiently long to reach these limiting crack angles. In addition, there were no occurrences of mixed mode cracking observed in the WEXTEX region.

As described previously, only cirumferential cracks at the bottom edge of the first TSP were found to have the potential for vibration induced propagation during the TSP tube vibration assessment. There were no occurrences of MCIs or mixed mode cracking at the bottom edge of the first TSP.

the current cycle due to the RPC inspection transient and reduced temperature conditions.

In summary, the current EOC indications can be expected to meet 3ΔP tube burst capability. Indications found in the last inspection meet 3ΔP capability and the effects of the RPC inspection transient and reduced temperatures would further increase the tube burst margins.

6.4 TSP Axial Indication Tube Burst Assessment

Only the axial crack lengths above and below the edges of the TSPs are considered for the tube burst and leakage evaluations; the extensive denting at the TSPs is considered to prevent axial cracks within the confines of the TSPs from opening. The axial crack lengths were measured by RPC, rather than by bobbin as in previous outages; EPRI document NP-6368-L demonstrates that there is good agreement of RPC-measured crack lengths with pulled tube data. The axial crack lengths measured by RPC during the 1992 inspections were shorter than crack lengths measured in previous bobbin inspections, likely due to the reduced operating cycle time and to reduced lead-in and lead-out effects for RPC compared to the bobbin coil. During the 1992 mid-cycle inspection program, the longest axial crack length outside the TSPs was 0.49 inch; this was less than the axial crack lengths of up to ~0.9" observed in prior outages.

As described in Section 5.3, the exposed axial crack length resulting in burst at 3ΔP is [ ]b,c and the length for burst at ΔP_{SLB} is [ ]b,c based on the Belgian burst equation. However, examination of pulled tubes at North Anna Unit 1 has shown the presence of small ligaments in the axial crack networks (WCAP-12349). Accounting for the segmented crack burst capability as described in Section 5.3, the longest macrocrack with elastic ligaments to meet 3ΔP is [ ]b,c and macrocracks up to [ ]b,c in length meet ΔP_{SLB}.

As described in Section 6.1, the effect of reduced temperatures and the RPC inspection transient are ignored for axial crack lengths, and the axial lengths found in the 1992 inspection are applied for the end of the current cycle for conservatism. For exposed lengths of axial cracks above or below the TSP edges, the maximum expected length is 0.49 inch. On a segmented crack basis, this is well below both the [ ]b,c length for $3\Delta P$ burst capability and the [ ]^{b,c} length required for ΔP_{SLB} burst capability. Therefore, the current EOC axial indications can be expected to meet both the $3\Delta P$ and ΔP_{SLB} burst requirements.

6.5 Potential TSP Mixed Mode Assessment

Of the 469 tubes plugged for axial and circumferential indications at TSPs, there were 14 occurrences of circumferential and axial indications at the same TSP. Table 3-8 summarizes the locations, circumferential crack angles and ligament angles of all potential mixed mode indications. Seven of these occurrences involved axial cracks either inside the TSP or on the opposite edge from the circumferential cracks; these occurrences are not a concern for mixed mode considerations. The other seven occurrences involved axial indications at the same edge of the TSPs as the circumferential indications.

From Table 3-8, all TSP indications with axial and circumferential indications at the same edge of the TSP have measured RPC ligaments. Tube R30C67 has the smallest RPC-measured ligament of 5°, which implies (Sections 3.8 and 5.5) a minimum ligament of >35° when adjusted for RPC resolution of deep crack indications. This ligament size is also obtained using the derived ligament angle of Table 3-8.

As developed in Section 5.5, the presence of an RPC ligament permits both tube burst and fatigue evaluations to be performed based on separate, non-interacting cracks. Thus, none of the TSP indications of Table 3-8 require a more detailed mixed mode evaluation. The axial and circumferential indications given in Table 3-8 meet $3\Delta P$ burst capability when evaluated as non-interacting indications.

6.6 WEXTEX Tube Vibration Assessment

The tube vibration assessment for tubes with circumferential cracks near the WEXTEX transition region is performed by dividing the tubesheet region into zones with varying degrees of susceptibility to crack propagation caused by tube vibration, as described in Section 5.6. Figure 5-5 shows a tubesheet map with various zones identified. Figure 6-6 shows the locations of all 31 circumferential indications found in the WEXTEX

Table 6-1

Expected Reductions in Circumferential Crack Angles for Current Cycle

Causative Factor	TSP Circ.Indications		WEXTEX Circ. Indications	
	No.Ind.	Crack Angles	No.Ind.	Crack Angles
Reduced Temp. & Power Conditions	Ignored	-3°	Ignored	-3°
RPC Inspection Transient	56%*	8%	Not Applicable	
Influence on Current Operating Cycle				
Max. Crack Angle Last Cycle	---	240°	---	199°
Resulting Expected Maximum Crack Angle in Current Cycle	---	218°	---	196°
No. Indications Last Cycle	212	---	31	---
Expected No. Ind. in Current Cycle	140	---	31	---

* Also applied for TSP axial indications.

Figure 6-1

Largest WEXTEX Circumferential Indication: R25C36, SG B

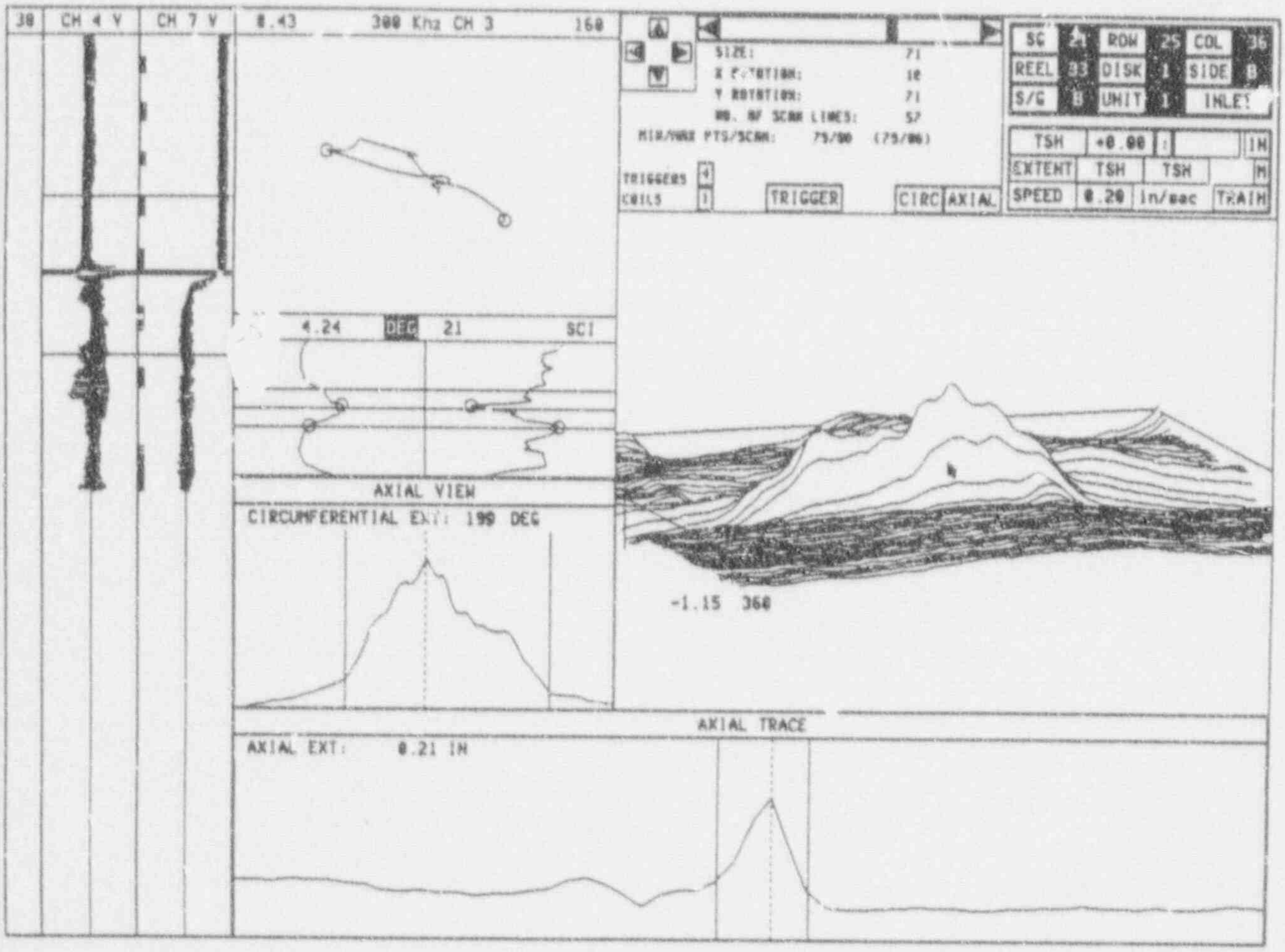


Figure 6-4

239° TSP Circumferential Indication: R18C39, SG A

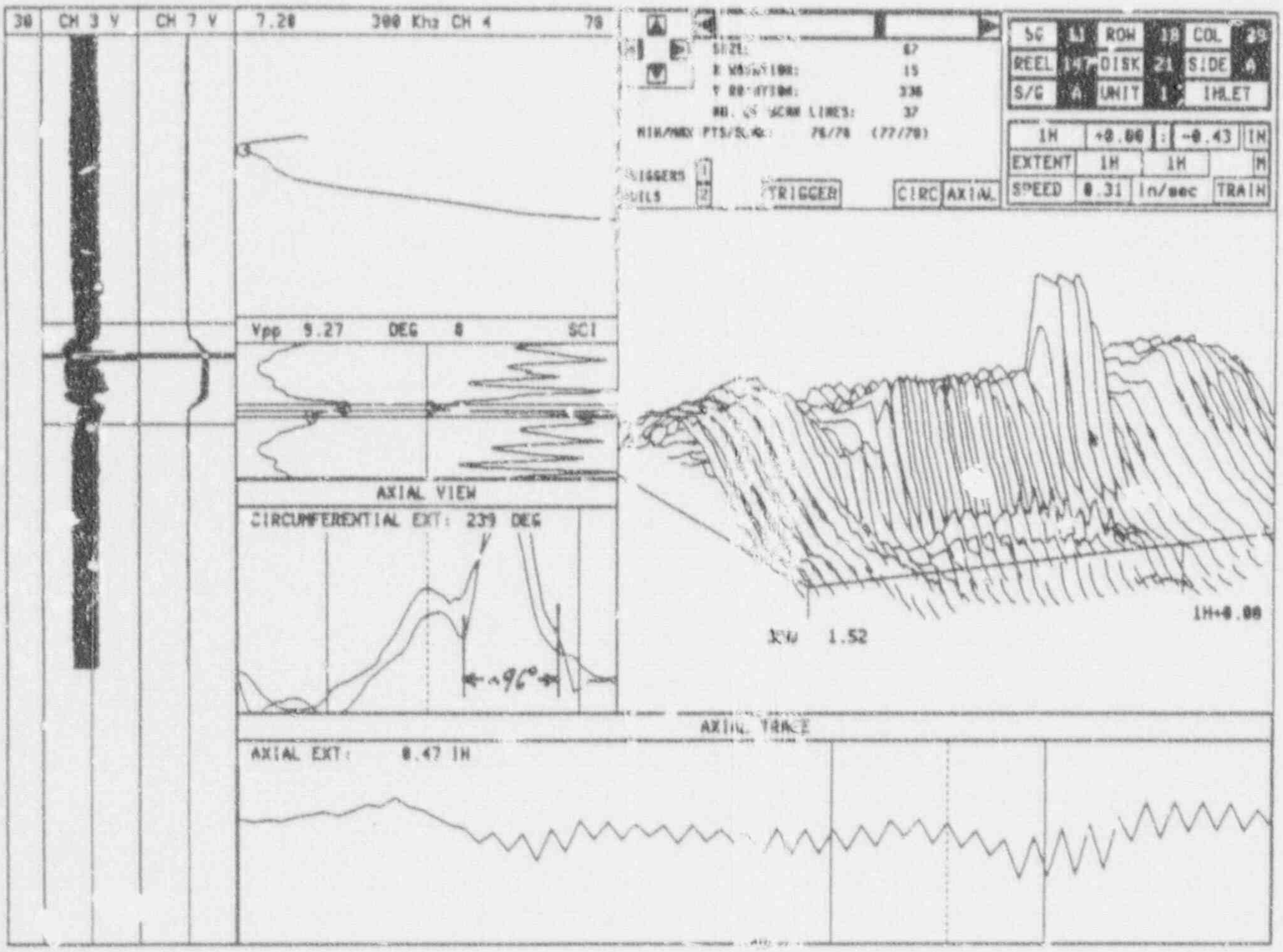


Figure 6-5

Limiting TSP MCI: R2C41, SG B

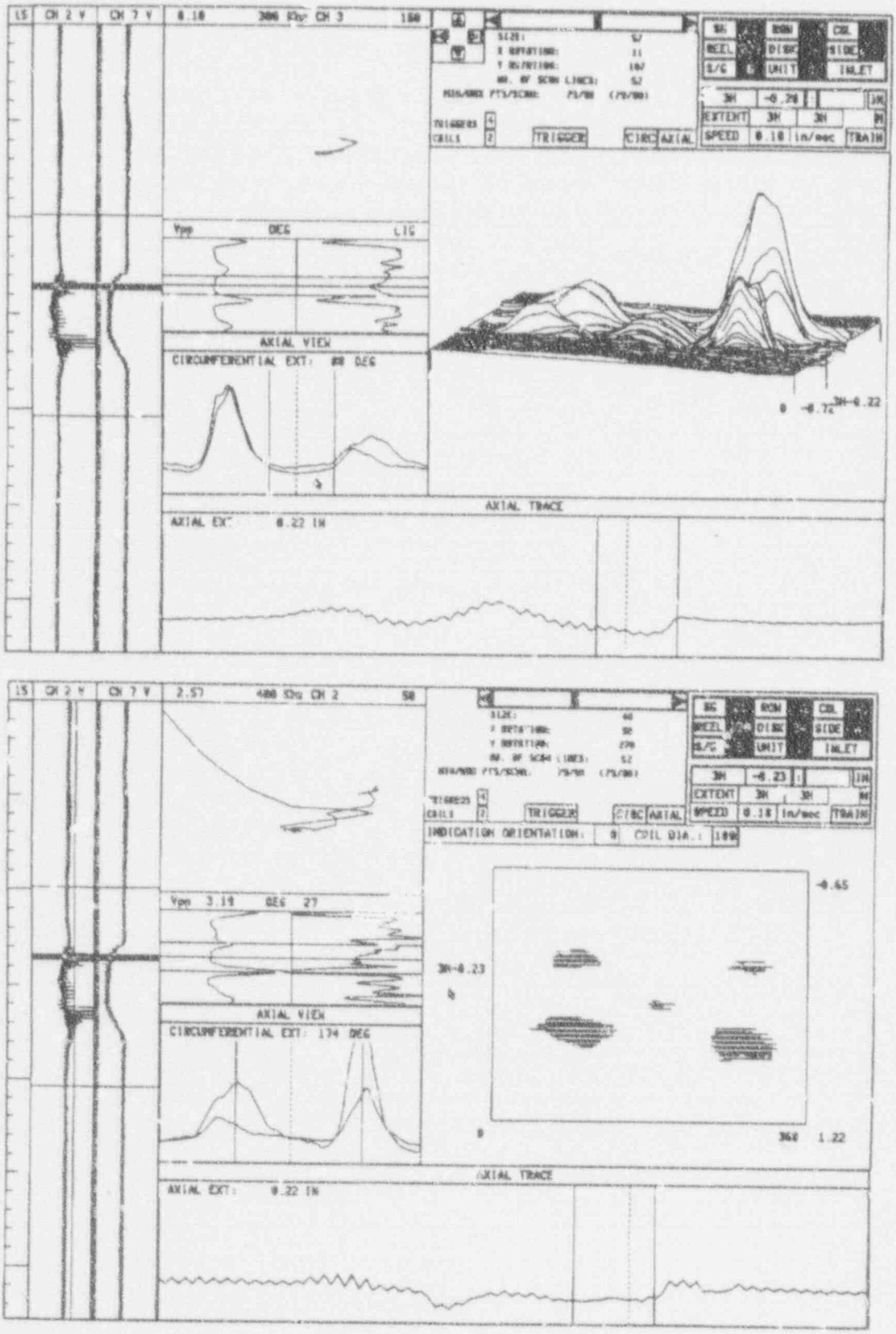


Figure 6-2

Limiting WEXTEX MCI: R24C33, SG A

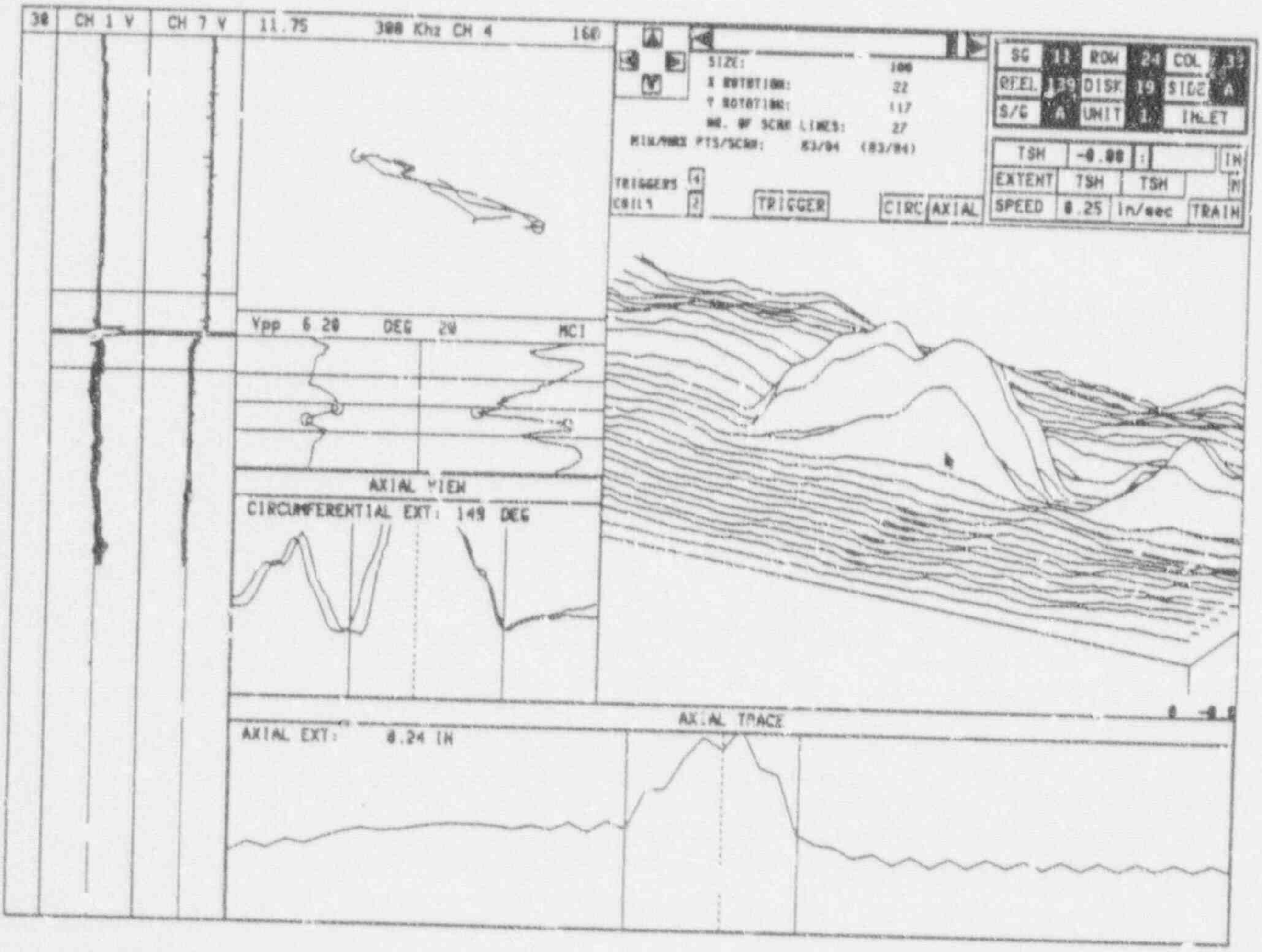


Figure 6-3

Largest TSP Circumferential Indication: R34C42, SG A

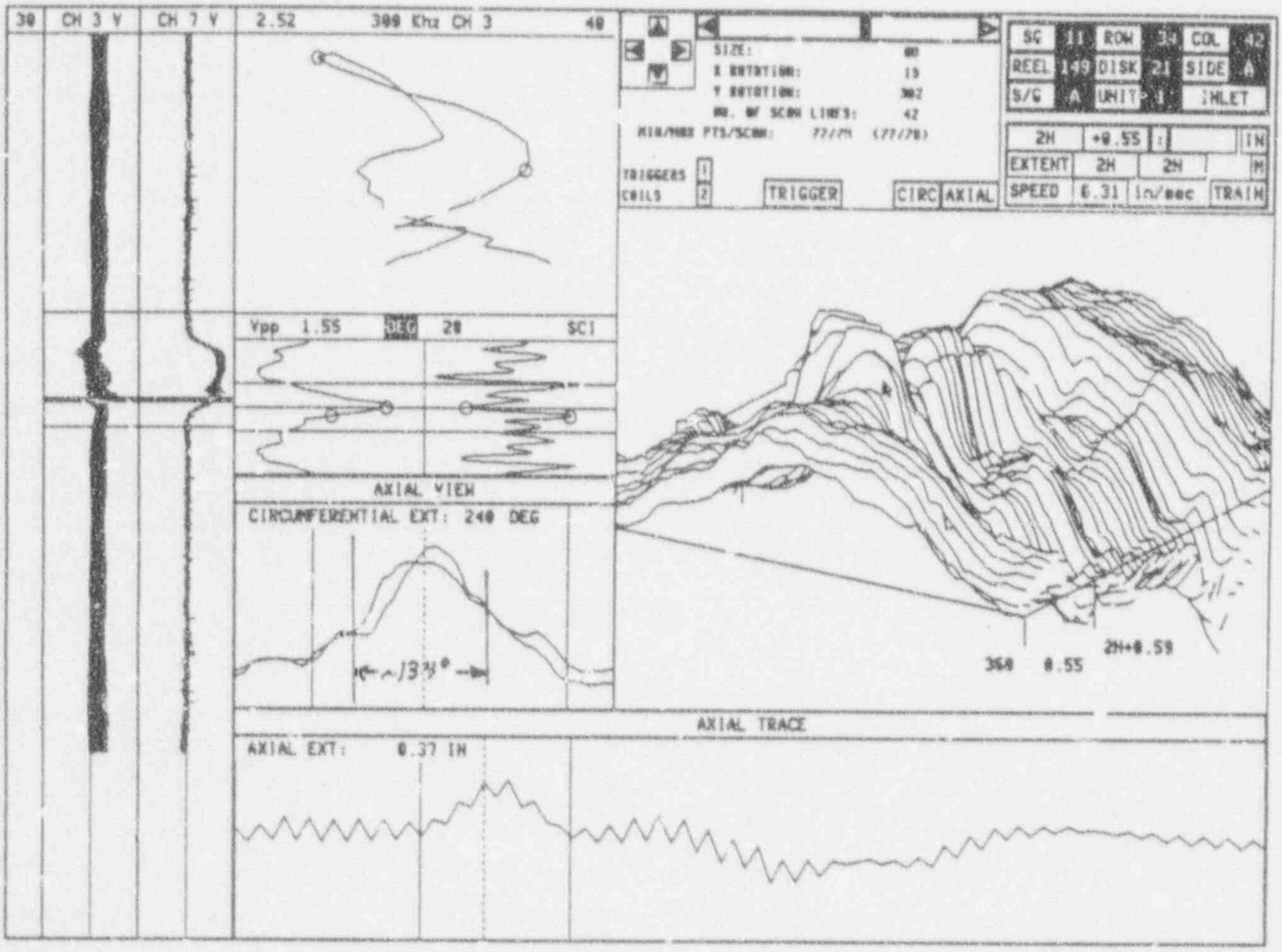


Figure 6-6

North Anna Unit 1 WEXTEX Circumferential Indications - All SGs

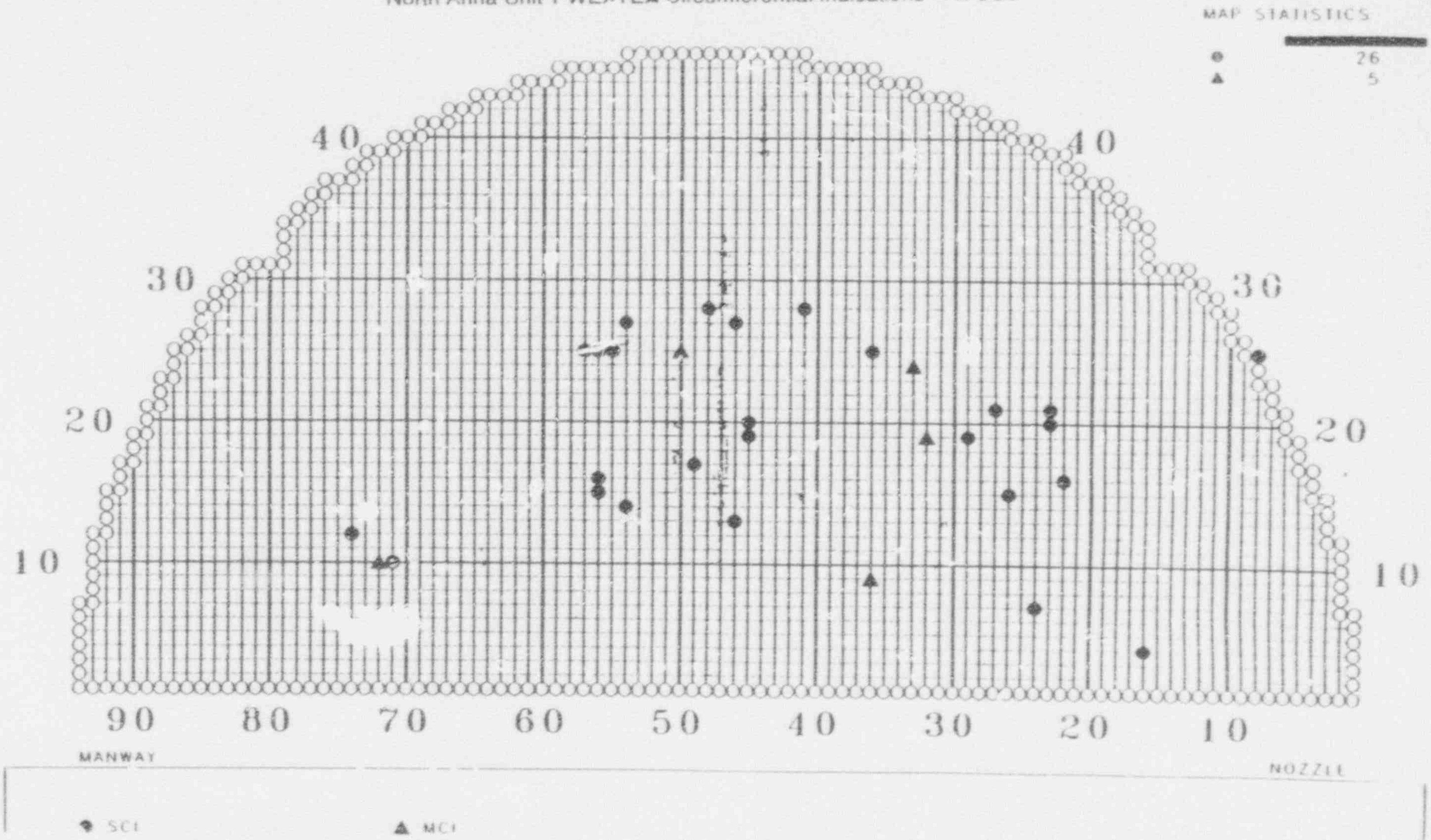
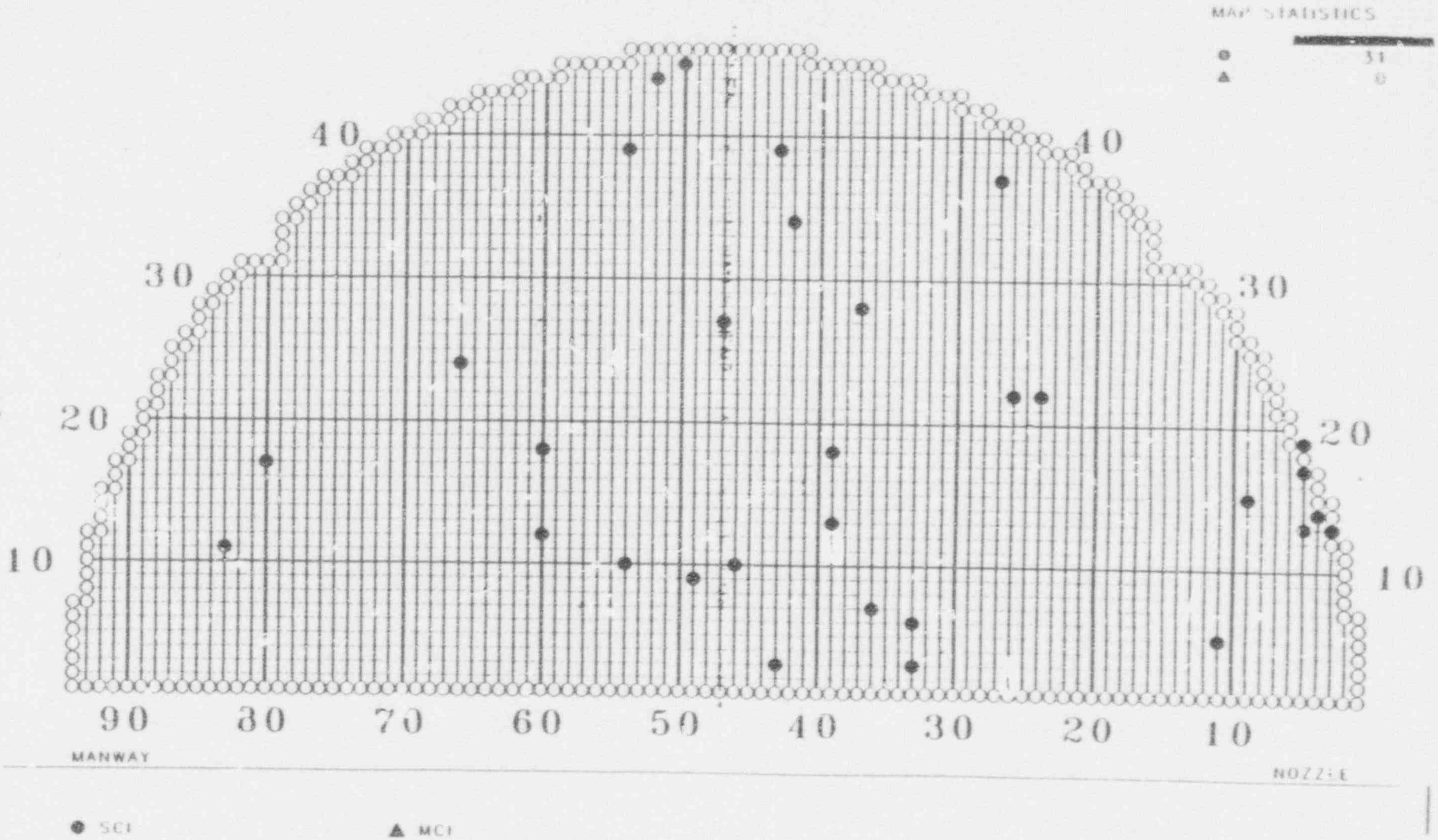


Figure 6-7

North Anna Unit 1 Circumferential Indications at Bottom Edge of TSP 1 - All SGs



distributions for the hot leg WEXTEX and TSP regions are conservatively projected to be the same as those found during the 100% RPC inspections of those regions performed in January - February 1992. This assumption is based on similar lengths of operation (254 EFPD for the first half of the current cycle vs. 252 EFPD for the second half of the cycle). Changes in operating conditions (Section 4.0) and inspection transient considerations (Section 3.11) dictate that the number and size of indications at the end of the current fuel cycle are expected to be less than those found at the end of the first half of the fuel cycle. Therefore, use of the crack distributions shown in Tables 7-4 and 7-5 for the limiting SG is judged to provide a conservative, bounding leak rate.

7.2 Leak Rate Analysis Methods

7.2.1 Leakage Model for Axial Cracks

An analytical model has been developed for predicting primary-to-secondary leak rates through cracked steam generator tubes. The model is based on [

]a,c. The model predictions are shown to exhibit acceptable agreement with laboratory and pulled tube test data. The leakage model for axial cracks has been described in detail in Section 6.3 of WCAP-13034. A comparison of the crack model results with experimental results is provided below.

The crack data base consists of field (pulled tubes) and Westinghouse laboratory formed stress corrosion cracks. Crack model results are compared with the test data in Figures 7-1 and 7-2 for normal plant operation and steam-line break conditions, respectively. The crack model results are also compared to other experimental data (labeled crack data base in the figures). As indicated in the figures, good agreement between prediction and measurement is shown. Data scatter is attributed to crack geometry parameters which are difficult to define with any degree of precision. Crack geometry parameters which affect flow are [ ]a,c.

An error analysis of the measurements versus predictions was performed to obtain the standard deviation for uncertainty analysis. The standard deviation of the prediction is

[ ]b,c for normal operation and [ ]b,c for steam line break for the log-log comparisons of Figures 7-1 and 7-2. For an uncertainty factor, t , the predicted leak rate would be factored by [ ]b,c for normal operation and by [ ]b,c for steam line break.

7.2.2 Leakage Relationship for Circumferential Cracks

The semi-empirical relationship for leakage through circumferential cracks is given by

[ ]b,c

where Q is the leak rate in gallons per day (gpd), ΔP is the differential pressure in psi and the crack length is the total crack length in inches. This relationship is benchmarked by selected data points on measured leak rates and the fact that for small cracks, [

]b,c.

7.3 Leak Before Break (LBB) Capability

The leak-before-break rationale is to limit the maximum allowable primary to secondary leak rate during normal operation such that the associated crack length is less than the critical crack length corresponding to tube burst during a postulated steam line break event. Thus, on the basis of leakage monitoring during normal operation, it is assumed that unstable crack growth leading to tube burst would not occur in the unlikely

7.0 SLB LEAK RATE ANALYSES

The SLB leak rate analyses are performed for two sets of crack distributions. Expected leak rates are calculated based on expected reductions in the number and size of indications at the end of the current fuel cycle as compared to those found at the end of the first half of the current cycle in February 1992. Bounding leak rates are calculated based on the actual number and size of indications from the February 1992 inspection program; since both halves of the current fuel cycle are expected to have approximately the same duration in effective full power days, the 1992 crack distributions are judged to produce conservative leak rates based on inspection transient considerations.

7.1 Crack Distributions for SLB Leak Rates

For the SLB leak rate analyses, the number and size of indications are required for the WEXTEX and TSP circumferential indications as well as the TSP axial cracks. Tables 7-1 through 7-3 summarize the crack distributions found in February 1992 at the end of the first half of the current fuel cycle. Table 7-1 presents the 1992 WEXTEX crack distributions for all three SGs. (Although shown in Table 7-1, axial cracks in or above the WEXTEX region are not considered in the SLB leak rate analyses, since all axial cracks exeeding 40% through wall dep[illegible]e plugged before returning to power and throughwall cracks are not expected in one cycle of operation). The TSP circumferential and axial crack distributions for all three SGs are summarized in Tables 7-2 and 7-3, respectively.

The SLB leak rates are calculated based on the crack distributions for the most limiting steam generator. Although SG C has the fewest number of tubes with WEXTEX circumferential cracks (9 in SG C vs. 12 in SG A and 10 in SG B), SG C has the most tubes with circumferential and axial cracks at the TSP elevations. The calculated leak rates for the TSP circumferential cracks are substantially larger than for the same crack sizes in the WEXTEX region due to the occurrence of segmented PWSCC cracks in the WEXTEX region. Based on the number of tubes with TSP circumferential and axial cracks in each SG, SG C is therefore selected as the most limiting SG for the SLB leak rate analyses. The numbers and sizes of WEXTEX and TSP circumferential cracks for SG C are shown in Table7-4. The number and sizes of TSP axial cracks for SG C are shown in Table 7-5. The values shown in Table 7-5 are for crack lengths outside of the

TSPs; since the North Anna 1 TSP intersections are dented, only the cracks extending outside of the TSPs are considered to leak during SLB.

7.1.1 Crack Distributions for Expected SLB Leak Rates

The expected reductions in the number and size of indications at the end of the current fuel cycle, compared to those found in February 1992 after the first half of the current cycle, were developed in Section 6.1. For the SLB leak rate analyses, the number and size of indications are required for the WEXTEX and TSP circumferential indications as well as the TSP axial cracks.

From the evaluations given in Section 6.1, the current EOC indications can be obtained by the following adjustments to the inspection results of February 1992:

WEXTEX Circumferential Indications

- reduction in crack angles by 3°
- no change in the number of indications

TSP Circumferential Indications

- reduction in crack angles by both 3° and 8% of the last inspection results
- reduction in the number of indications by a factor of 0.67

TSP Axial Indications

- no change in crack length
- reduction in the number of indications by a factor of 0.67.

The above adjustments are applied to the crack distributions from the February 1992 inspection program to obtain the expected EOC SLB leak rate for the second half of the current fuel cycle. Tables 7-6 and 7-7 show the crack distributions used to obtain the expected SLB leak rate for the most limiting SG.

7.1.2 Crack Distributions for Bounding SLB Leak Rates

A bounding SLB leak rate is also calculated based on the actual crack distributions found at the end of the first half of the current fuel cycle. The enveloping EOC crack event of a limiting accident. Leak before break provides protection against a coupled steam line break and tube rupture event which is outside of the design basis of the plant. The administrative leak rate limit for normal operation is 50 gpd per steam generator.

The leak-before-break rationale for a single through wall crack, growing in an orderly fashion is straightforward. However, typical cracking patterns are more complex. Crack networks rather than single isolated cracks appear most often. Pulled tube examination results and laboratory cracked samples provide examples of crack networks. As discussed above, ligaments of material between through wall cracks in a crack network increase tube strength relative to that of a single through wall crack of the same total length. While ligaments increase strength, they also decrease the leak rate relative to the same length for a single through wall crack.

7.3.1 Tubes with Axial Cracks

The leakage model for tubes with axial cracks, described in Section 7.2.1, was applied using North Anna 1 SG conditions to obtain the following predicted leak rates for normal operation and SLB as a function of crack length:

Crack Length (inch)	Leak Rates N.O. (gpm)	N.O. (gpd)	SLB (gpm)

[ ]b,c

Consideration has been given to the error of the predictions of leak rate compared to measured leak rates. In Section 7.2.1.3, the error is given as [

]a,c

[

]a,c

During normal operation, the leak rate limit is 50 gpd for North Anna Unit 1. Referring to the tabulations above and the mean curve of Figure 7-3 of leak rate versus axial crack length, the allowable leak rate of 50 gpd will limit the through wall axial crack length to [ ]b,c. Since the through wall 3ΔP crack length (Section 5.3) is [ ]b,c, LBB is assured on a mean leak rate basis. Considering the prediction error for ≈95% certainty, the axial crack length will be no longer than [ ]b,c. At this length, ΔP_{SLB} is satisfied with margin since [ ]b,c is acceptable.

For segmented cracks, the conservative assumption is that the ligaments are elastic at normal operation ΔP and the leak is therefore a minimum equal to the sum of the leakage of the individual cracks. The macrocrack length is therefore maximized and strength minimized on this basis. The leak rates for segmented cracks are plotted in Figure 7-4 with the points for the typical 5/1 aspect ratio crack shown as the 0.25" segments line. For this typical aspect ratio, on a mean predicted leak rate basis the 50 gpd limit corresponds to a macrocrack containing [ ]b,c. From Section 5.3, the macrocrack length needed for 3ΔP burst capability is less than or equal to [ ]b,c, which is less than the leak limit permitted, [ ]b,c. However, LBB is assured for segmented cracks for ΔP_{SLB} since a [ ]b,c macrocrack would have ΔP_{SLB} burst capability.

7.3.2 Tubes with Circumferential Cracks

The leak rate model of Section 7.2.2 for tubes with circumferential cracking results in the following predictions of leak rate for North Anna 1 SG normal operating and SLB conditions as a function of arc length:

Arc Length (degrees)	Leak Rates N.O. (gpd)	SLB (gpd)	SLB (gpm)

[ ]^{b,c}

With the 50 gpd leak rate limit, the corresponding arc length of a single circumferential crack is slightly less than [ ]^{b,c}. Considerable margin is available versus the single crack that lowers tube burst capability to $3\Delta P$, [ ]^{b,c}, and to ΔP_{SLB}, [ ]^{b,c} (Section 5.3).

For WEXTEX circumferential indications, the expected crack morphology is segmented cracks. Segmented cracks are also present for ODSCC in the initial stages of crack formation, although the limited pulled tube data indicates that the ODSCC ligaments may be lost by corrosion for throughwall cracks. Figure 7-5 shows the leak rates for segmented circumferential cracks. For aspect ratios of 5/1 and 4/1, the 50 gpd leak limit corresponds to 110° and 180°, respectively. Since these angles are less than the 297° segmented angle for $3\Delta P$ burst, LBB capability is obtained for segmented, circumferential cracks.

Establishing the operating leak limit of 50 gpd based on segmented crack morphologies, for which axial PWSCC cracks are most limiting for LBB considerations, recognizes the expected crack morphology and provides substantially greater LBB margin than obtained assuming uniformly throughwall cracks. North Anna Unit 1 has had small operating leak rates although measured RPC crack angles are significant. This reflects the presence of ligaments (segmented and remaining wall thickness) that reduce leakage and increase tube burst capability.

7.4 Limiting Crack SLB Leak Rate

This section develops estimated leak rates under SLB conditions based on maximum leakage from the limiting crack leaking at 50 gpd under normal operation. Leak rates for the EOC crack distributions are developed in Section 7.5. Use of the EOC crack distributions is highly conservative in that the EOC distribution would be expected to leak at well in excess of 50 gpd under normal operation based on application of the leak rate and crack models used in this report.

The potential for leakage from a single crack during SLB is limited by the 50 gpd normal operation leak rate limit. Assuming operation at the 50 gpd limit, it is 95% certain that a single through wall axial crack (a conservative assumption) is shorter than [ ]^{b,c} (Figure 7-3). It is also a 95% certainty that a [ ]^{b,c} axial crack would leak less than [ ]^{b,c} based on nominal SLB leakage of [ ]^{b,c} for 95% certainty (Section 7.3.1). The assumption of -95% uncertainty on normal operating leakage resulting in +95% uncertainty at SLB leakage is extremely conservative. This process leads to an SLB to normal operating leak rate ratio of 275 compared to the nominal ratio of about 10. Extensive testing of leak rates on corrosion cracks in WCAP-13187 has resulted in SLB/N.O. leak rate ratios of 1 to about 80 with 95% of the 33 specimens tested having a ratio of <20. For a ratio of 20, the 50 gpd normal operating leak rate would correspond to a SLB leak rate of about [ ]^{b,c}.

Applying the same rationale to the limiting circumferential crack of a [ ]^{b,c} (see Table 6.1), assumed to be uniformly through wall, leads to an expected leak rate of about [ ]^{b,c}. If it is more realistically assumed that 60% of the 218° crack angle is through wall, the SLB leak rate reduces to about [ ]^{b,c}.

Overall, the ratio of 20 for SLB to N.O. leak rate rates is more representative of measured leak rates and the limiting crack causing plant shutdown at 50 gpd would result in an SLB leak rate of about [ ]^{b,c}.

7.5 SLB Leak Rates for Crack Distributions

7.5.1 Expected SLB Leak Rates

In the very unlikely event that all indications have through wall or near through wall cracks that do not leak during normal operating conditions but open up to leak during a postulated SLB, the expected SLB leakage under this assumption can be obtained based on calculated leakage for the EOC crack distributions described in Section 7.1.1. This calculation utilizes nominal leak rates for the entire distribution on the basis that an average leak rate would result for the large number of indications in service. The EOC distributions utilized are the EOC axial crack distribution of Table 7-7 and the circumferential crack distributions of Table 7-6. The segmented crack model is applied for the projected TSP PWSCC axial cracks and WEXTEX PWSCC circumferential crack distributions. For ODSCC circumferential cracks at the TSPs, it is assumed that the through wall crack length is [ ]^{b,c} of the RPC crack angles of Table 7-6 based on the pulled tube examination results for North Anna Unit 1, R11C14 (see WCAP-13034). The resulting total SLB leak rate is estimated at about [ ]^{b,c} including contributions of about [ ]^{b,c} from WEXTEX cracks, [ ]^{b,c} from circumferential cracks at TSPs and about [ ]^{b,c} from axial cracks at the TSPs.

7.5.2 Bounding SLB Leak Rates

In order to bound potential leakage in the unlikely event that through wall or near through wall cracks that do not leak during normal operating conditions but may leak during a postulated SLB exist, a SLB leak rate can be obtained based on calculated leakage for the February 1992 crack distributions, as discussed in Section 7.1.2. This calculation utilizes nominal leak rates for the entire distribution. The EOC distributions utilized are the 1992 axial crack distribution of Table 7-5 and the 1992 circumferential crack distributions of Table 7-4. The segmented crack model is applied for the projected TSP PWSCC axial cracks and WEXTEX circumferential crack distributions. For ODSCC circumferential cracks at the TSPs, it is assumed that the through wall crack length is [ ]^{b,c} of the RPC crack angles of Table 7-4. The resulting total SLB leak rate is estimated at about [ ]^{b,c} including contributions of about [ ]^{b,c} from WEXTEX cracks, [ ]^{b,c} from circumferential cracks at TSPs and about [ ]^{b,c} from axial cracks at the TSPs.

7.6 Conclusions

The test and analysis basis for burst capability and leakage of tubes with axial or circumferential cracking provides a justification of structural integrity and LBB per Reg. Guide 1.121. Margin is demonstrated for burst capability during accident pressure loadings (ΔP_{SLB}) as single and segmented cracks are limited by the normal operation leak rate limit of 50 gpd. The 50 gpd leak limit provides confidence that a 3ΔP burst capability is obtained in all cases for tubes with circumferential cracking and for single axial cracks. Segmented cracks up to [ ]^{b,c} in length provide 3ΔP burst capability but segmented cracks limited only by the 50 gpd normal operation leak rate limit may be longer. The strength of segmented cracks has conservatively been minimized consistent with a minimum leakage model (elastic ligaments).

The potential SLB leak rate is expected to be limited by the 50 gpd operating leak limit to about 0.7 gpm based on SLB leak rates of about a factor of 20 (at ~95% cumulative probability) higher than normal operating leak rates. Very conservatively, the potential SLB leak rate would be bounded by approximately [ ]^{b,c} for a single through wall axial crack. In the very unlikely event that all indications have through wall or near through wall non-leaking cracks during normal operating conditions and that these cracks all open up for SLB leakage, the SLB leak rate can be conservatively estimated for the distribution of RPC crack angles and lengths at EOC conditions. For the February 1992 mid-cycle inspection crack distributions, the bounding leak rate would be approximately [ ]^{b,c} The expected SLB leak rate calculated from the projected EOC crack distributions which account for expected reductions in the number and size of indications at the end of the current fuel cycle as compared to those from the mid-cycle inspection would be approximatley [ ]^{b,c}.

Table 7-1

North Anna Unit 1 February 1992 WEXTEX Inspection Results

Type of Indication	Number of Tubes SGA	SGB	SGC
Single Axial (SAI)	3	0	2
Multiple Axial (MAI)	0	0	0
Single Circumferential (SCI)	10	9	7
Multiple Circumferential (MCI)	2	1	2

Note: There were no tubes with mixed mode degradation identified in the WEXTEX transitions.

Table 7-2

North Anna Unit 1 Tubes With TSP Circumferential Cracks - February 1992

Elevation	SGA SCI/MCI	SGB SCI/MCI	SGC SCI/MCI
1H	25/3	22/0	27/0
2H	15/0	33/3	42/3
3H	2/0	7/2	19/2
4H	3/0	0/0	1/0
5H	1/0	0/0	1/0
6H	0/0	0/0	0/0
7H	0/0	0/0	0/0
Total	46/3	62/5	92/5

SCI = Single Circumferential Indications

MCI = Multiple Circumferential Indications

Table 7-3

North Anna Unit 1 Tubes With TSP Axial Cracks - February 1992

Elevation	SGA SAI/MAI	SGB SAI/MAI	SGC SAI/MAI
1H	36/0	53/4	37/5
2H	24/2	14/3	41/1
3H	7/0	6/0	5/1
4H	5/0	5/0	8/0
5H	21/0	1/0	1/0
6H	3/0	1/0	2/0
7H	0/0	0/0	0/0
Total	95/2	80/7	94/7

SAI = Single Axial Indications

MAI = Multiple Axial Indications

Table 7-4

Steam Generator C WEXTEX and TSP Circumfererıtial Cracks - February 1992

Crack* Angle (deg.)	Number of Observations WEXTEX	TSPs
45	0	0
55	1	4
65	1	12
75	4	28
85	2	27
95	1	32
105	0	23
115	0	6
125	0	10
135	0	2
145	0	4
155	1	2
165	1	3
175	0	1
185	0	1
195	0	0
205	0	1
215	0	0
225	0	0
235	0	1
245	0	0
Total	11	157

* Mid-point of crack angle range; for example, 55° is mid-point of 51°-60° range.

Table 7-5

Steam Generator C TSP Axial Cracks - February 1992

Crack* Length (inch)	Number of Observations
0.05	25
0.15	25
0.25	20
0.35	9
0.45	6
0.55	0
0.65	0
0.75	0
0.85	0
0.95	0
Total	85

* Mid-point of crack length range; for example, 0.15 is mid-point of 0.11-0.20 range.

Table 7-6

Steam Generator C WEXTEX and TSP Circumferential Cracks - Expected Distribution at EOC

Crack* Angle (deg.)	Number of Observations WEXTEX	TSPs
45	1	6
55	1	14
65	4	26
75	2	22
85	1	17
95	0	6
105	0	4
115	0	3
125	0	3
135	0	2
145	1	1
155	1	1
165	0	0
175	0	1
185	0	0
195	0	0
205	0	1
215	0	0
225	0	0
235	0	0
245	0	0
Total	11	107

* Mid-point of crack angle range; for example, 55° is mid-point of 51°-60° range.

Table 7-7

Steam Generator C TSP Axial Cracks - Expected Distribution at EOC

Crack* Length (inch)	Number of Observations
0.05	17
0.15	17
0.25	14
0.35	6
0.45	4
0.55	0
0.65	0
0.75	0
0.85	0
0.95	0
Total	58

* Mid-point of crack length range; for example, 0.15 is mid-point of 0.11-0.20 range.

Figure 7-1

Measured vs. Predicted Leak Rate (Normal Plant Operation)

b,c

Figure 7-2

Measured vs. Predicted Leak Rate (Steam Line Break Conditions)

b,c

[ ]

Figure 7-3

Leak Rate Versus Axial Crack Length

[ ] b,c

Figure 7-4

Leak Rate Versus Axial Crack Length
(Leak Rate With Elastic Ligaments)

b,c

Figure 7-5

Leak Rate Versus Circumferential Crack Angle

[ ]b,c