ENTERGY

ARKANSAS NUCLEAR ONE

UNIT TWO

STEAM GENERATOR
TUBE CIRCUMFERENTIAL CRACKING
REPAIR LIMIT EVALUATION

AUGUST 1995

Table of Contents

1.0 INTRODUCTION

The Arkansas Nuclear One, Unit 2 (ANO-2) steam generators (SGs) have experienced several forms of tubing degradation, most notably stress corrosion cracking (SCC) at the tube support plates (axially oriented) and at the expansion transition region (ETR) at the top of the hot leg tubesheet in the sludge pile region. The indications at the tubesheet have primarily been circumferentially oriented, but have also included axially oriented, as well as volumetric indications. This document addresses the repair criteria to be applied to circumferential cracks at the ETR in the future. It has been Entergy Operation's past practice to repair all tubes with circumferential indications regardless of size.

Recent improvements in nondestructive examination (NDE) technology have enhanced our ability to detect and accurately size circumferential flaws. Smaller and smaller cracks are being found, many of which result in no decrease in the burst strength of the tubing. Entergy Operations is committed to using the best inspection technology available, as has been demonstrated over the past several inspections by upgrading to new probes and coils, using alternate NDE, and taking steps to improve signal quality. This tradition will be continued in the upcoming outage, where the "plus-point" probe technology will be used. Additional steps are being taken in an attempt to optimize that probe design. However, continuing our practice of repairing all circumferential cracks could result in an unnecessary impact on operation of ANO-2. It is Entergy Operation's position, based upon the analysis presented in this report, that the existing ANO-2 Technical Specification (TS) repair limit of 40% is applicable for use with circumferential cracking, and provides the safety margins required by Regulatory Guide 1.121. This report provides the supporting technical information to utilize the TS repair limit by addressing its three major components: structural limit, NDE uncertainty, and flaw growth rate. Additionally, analyses will be conducted following the application of this approach, consistent with those performed in the past, to show that the probability of tube burst and quantity of leakage expected following design basis accidents are acceptable.

1.1 Background

The ANO-2 SGs are of the U-tube design manufactured by Combustion Engineering (model 2815). Each SG contains 8411 tubes constructed of high temperature mill annealed (HTMA) Inconel alloy 600 material with an outside diameter of 3/4 inches and a wall thickness of 0.048 inches. The tubes are explosively expanded to the full depth of the tube sheet. There are seven full eggcrate tube support plates (TSPs), two partial eggcrate TSPs, and two partial drilled TSPs. The reactor went into commercial operation in March 1980, and utilizes all volatile treatment (AVT) chemistry. Secondary side boric acid addition was initiated in 1983 to arrest denting at the partial drilled TSPs. The hot leg operating temperature was initially 607° F, but was reduced to ~600° F following the ninth refueling outage in the fall of 1992.

Circumferential cracking was first experienced at ANO-2 in March 1992. The cracking was discovered as a result of primary-to-secondary leakage from a crack in the "A" SG. The first inspection for circumferential cracking was performed during this forced outage. Since that time, four additional comprehensive examinations for circumferential cracking (during two refueling and two planned inspection outages) have been conducted. Because of their location and size, the circumferential cracks in the ANO-2 steam generators have

been difficult to detect. The cracks are located at the top of tubesheet, in the ETR of the tube, with sludge containing copper surrounding the tube. The damage consists of intermittent cracks on different axial planes in a narrow axial band with ligaments between the cracks. These ligaments contribute significantly to the strength of the tube.

Entergy Operations first employed rotating pancake coil (RPC) technology at ANO-2 in the March 1992 forced outage. Over the last year significant enhancements have been made in both probe design and analysis techniques. These enhancements have significantly improved the ability to detect and size small circumferential flaws. To better understand the damage mechanism and its implications and the ability of NDE to detect the flawed area, seven tubes with expansion transitions (five containing circumferential cracks and two "clean" transitions) have been removed from ANO-2. Extensive evaluations of circumferential cracking, including a program which produced forty-two laboratory cracks have been performed. Entergy Operations has also performed, as part of an integrated approach to SG management, a first of a kind probabilistic safety evaluation for circumferential cracking at ANO-2. This was presented to the NRC staff on July 14, 1994, with details submitted to the staff in February 1995(1). This evaluation is described in Appendix A and will be utilized in the future as necessary to ensure the conditional probability of tube burst remains at an acceptable level. This integrated approach to managing the circumferential cracking mechanism at ANO-2 has been very successful, i.e., no cracks have been found which would exceed NRC required design basis loading and no significant leakage has been detected.

1.2 Overview

Because of the advancements in inspection techniques and detailed analysis of multiple years of ANO-2 specific inspection data, it is believed that circumferentially cracked tubes with less than 40% degraded area, and no through-wall indications, can be safely left in service in accordance with technical specification requirements. In order to assess the appropriateness of the 40% degraded area repair limit for circumferential cracks, a comprehensive evaluation was performed to determine the structural integrity impact of leaving circumferential cracks in service in accordance with TS repair limits. The evaluation utilized the basic approach specified in the industry SG Degradation Specific Management Program (SGDSM)(2). New technology in the area of eddy current analysis, which can "profile" each crack and provide more refined data, has allowed for a more accurate and realistic picture of the cracking at ANO-2. The intent is to utilize the existing TS repair criteria if needed to avoid unnecessary repairs on a large number of structurally non-significant flaws which are now detectable due to increased technological improvements. If used, all cracks in excess of the TS criteria would be repaired.

Entergy Operations is proposing an integrated program to support leaving circumferential cracks less than the current TS limit in service, which would include a 100% inspection of the hot leg top of tubesheet region with the plus-point probe in refueling outage 2R11, pulling tubes, if needed, to confirm NDE accuracy, and performing a mid-cycle inspection.

The ANO-2 Technical Specifications require that defective tubes be removed from service by plugging or be repaired by sleeving, if the depths of the flaws exceed the repair limit of 40% through-wall or contain through-wall cracks. This repair limit ensures that tubes

accepted for continued service will retain adequate structural and leakage integrity during normal operating, transient, and postulated accident conditions, consistent with General Design Criteria (GDCs) 14, 15, 30, 31, and 32 of 10 CFR Part 50, Appendix A. Structural integrity refers to maintaining adequate margins against gross failure, rupture, and collapse of the steam generator tubing. Leakage integrity refers to limiting primary-to-secondary leakage to within acceptable limits.

The traditional strategy for achieving the objectives of the GDCs related to SG tube integrity has been to establish a minimum wall thickness requirement in accordance with the structural criteria of Regulatory Guide (RG) 1.121, "Bases for Plugging Degraded PWR Steam Generator Tubes." Development of minimum wall thickness requirements to satisfy RG 1.121 was governed by analyses for uniform thinning of the tube wall in the axial and circumferential directions. The assumption of uniform thinning results in a repair limit conservative for all flaw types occurring in the field[3]. The assumption of uniform thinning was originally made because the predominant damage type at that time was wastage, which is best simulated by uniform thinning. For circumferential cracking, uniform thinning, when limited to the expansion transition area, becomes a conservative representation of the damage type and thus the 40% repair limit is bounding for this damage mechanism. Further analysis and testing, referenced in this report, shows that circumferential cracks with 50% degraded area have burst pressures at or near that of unflawed tubes.

The original TS repair limit comprises a basic structural limit of 60%, minus 10% each for NDE uncertainty and flaw growth rate. At the time of implementation, these values were considered reasonable. The approach proposed for use at ANO-2 involves the use of the new technology and analysis techniques to determine the degraded area of circumferential cracks. The degraded area is determined by sizing depth at increments around the circumference (typically every 10°) and calculating the degraded area. This utilizes the desirable approach[3] to sizing flaws by using physical dimensions (length and depth) of defects as opposed to other parameters (e.g., voltage).

The basic overall approach involves the use of RG 1.121 safety factors, statistically valid material properties, NDE sizing data, growth rate data, and tube burst test data. Starting with a structural limit of 70% (95% lower bound adjusted for 95% lower bound material properties), subtracting an NDE uncertainty of 13% (95% lower bound), followed by an allowance for apparent growth of 28% (95%). With the numerous 95% values being used, the individual uncertainties were combined statistically such that the repair limit of 40% yields an operating interval of 420 EFPD of operation. This methodology demonstrates the validity and conservatism of the technical specification repair limit of 40% and confirms that safe operation is assured with cracks <40% degraded area left in service for the maximum 420 EFPD operating interval. The proposed mid-cycle inspection will be performed prior to reaching 420 EFPD, if the repair limit for circumferential cracks is utilized. Scatter in the apparent growth distribution contributes significantly to the overall uncertainties and associated reduction in the calculated repair limits. As more data becomes available, this scatter will likely diminish and full cycle operation may be justifiable. From a risk perspective, operation will be evaluated based on the cracks left in service to assure an acceptable conditional probability of burst and leakage considering

design basis accident conditions. In addition, all detected through-wall cracks will be repaired.

To better understand the circumferential cracking problem, comparisons between axial crack and circumferential crack burst and leakage performance have been made by Tractebel/Electrabel in Belgium[4]. Through-wall axial and circumferential notches of the same length were tested and demonstrated the comparative safety significance between the two. This testing showed that axial cracks burst at pressures significantly lower than their circumferential counterparts, and leak rates were about two orders of magnitude lower for circumferential cracks at the pressures of interest.

In summary, flaws that are at and even above the technical specification repair limit of 40% have virtually no decrease in the integrity of the tube over that of virgin tubes. Burst pressures are very high and demonstrate that significant margin exists even over RG 1.121 margins. This is primarily due to the discontinuous nature of circumferential cracks, where there are ligaments of sound material which generally are not detectable by conventional eddy current testing (ECT) analysis techniques. These ligaments, between crack segments, add significantly to the strength of the cracked section of tubing. In-situ pressure testing of the most severely degraded tubes with circumferential cracks in Combustion Engineering (CE) plants have demonstrated the tubes would meet RG 1.121 requirements with added margin. If the repair limit for circumferential cracks is utilized, the next cycle of operation for ANO-2 will be evaluated again following data collection from the September 1995 refueling outage (2R11). Growth rate, NDE uncertainty, structural and leakage integrity will be evaluated to ensure the acceptability of the proposed operating interval. Additional details of the evaluations performed to date are described in the remaining sections of this report.

2.0 STRUCTURAL INTEGRITY CONSIDERATIONS

2.1 Regulatory Guide 1.121 Evaluation

RG 1.121, "Bases for Plugging Degraded PWR Steam Generator Tubes" issued for comment in August of 1976, describes a method acceptable to the NRC staff for meeting GDCs 14, 15, 30, 31, and 32 by reducing the probability and consequences of steam generator tube rupture through determining the limiting safe conditions of degradation of steam generator tubing, beyond which tubes with unacceptable cracking, as established by inservice inspection, should be removed.

The RG 1.121 evaluations for ANO-2 have been submitted to the staff[5,6]. The structural limit previously utilized was 79%, which was based on a factor of safety of three for normal operating pressure. For this value, rupture occurs as a result of the axial load on the tube due to the differential pressure exerted on the U-bend (applicable for flaws with approximately 50-60% degraded area and larger). In addition, testing has shown that circumferential defects up to about 50% through-wall, 360 degree extent, or 100% through-wall for 90 degrees will fail with axial splitting due to circumferential stresses, at pressures equivalent to a virgin tube. This burst test data has been confirmed through tests conducted in France[7] and Belgium[8].

The observed top of tubesheet circumferential cracking at ANO-2 (based on pulled tubes) is comprised of a band of circumferential cracks. The sound material which resists axial pressure forces is composed of uncracked material from the leading edge of partial through-wall circumferential cracks at different axial locations. Machined circumferential flaws only simulate this first type of ligament. The ligaments of material between circumferential cracks at different axial locations in a band of circumferential cracks are not present in machined flaw geometries which have been tested to date[9], and thus burst testing performed to date represents conservative results when compared to field cracks.

2.2 Flow Induced Vibration (FIV) Evaluation

A structural evaluation of the effects of FIV on circumferential flaws was performed for the ANO-2 steam generator tubing. Tube models simulating circumferential cracks at the secondary face of the tubesheet were analyzed for normal operating flow conditions. An allowable crack size was determined based on consideration of (a) fluid elastic instability and (b) fatigue crack growth. An allowable circumferential crack was also evaluated for flow loads during a main steam line break (MSLB) event.

Fluid /Elastic analysis indicated stable flow vibrations over the entire range of crack sizes. The analysis was performed for the worst case cross-flow conditions at the bundle periphery and is valid for all tubes in the bundle except in the tube lane region. The bounding case of a cracked section in excess of 95% degraded area resulted in an acceptable stability ratio.

Previous analysis of the tube lane region indicates a high local flow velocity and a more limiting stability ratio in the open flow lane. Defective tubes adjacent to the tube lane are

not considered in this evaluation. Tubes in the region adjacent to the tube lane and in the corner at the entrance to the tube lane are at risk of damage from flow induced vibration for even small through-wall cracks. It should be noted that no cracks have ever been detected in this region at ANO-2.

An allowable crack size was established on the basis of crack growth criteria for stable flow conditions. A through-wall crack extending 180° circumferentially was determined to be below the crack growth threshold for normal operating flows. The analysis was performed for the bounding cross flow velocity at the bundle periphery.

The MSLB flow load and concurrent pressure load were applied to a 79% through-wall (average) defective tube. The resulting stress was less than the stress for the MSLB peak pressure differential alone and does not invalidate previous MSLB calculations.

2.3 Tube Burst Test Data

Burst testing of tube flaws is performed to assess the structural limitations of a given set of flaw parameters (e.g., length, depth, amplitude, etc.). A relationship between burst pressure and a NDE parameter is typically used to establish a threshold to ensure that the structural requirements of RG 1.121 are satisfied during normal operating and postulated accident loading conditions.

Burst pressure determinations are usually performed considering a 95% probability/95% confidence lower tolerance limit on the flow stress (one-half of the sum of the yield stress and the ultimate stress) for a general population of tubes encompassing the heats of tubing used in the SGs for several plants. However, information relative to heats used in the fabrication of the ANO-2 SGs was available and thus site specific information was used at a 95%/95% limit.

Two U.S. utilities, Entergy and Northeast Utilities, have separately sponsored burst tests of steam generator tubes with circumferential flaws. A large number of specimens have been tested with various flaw depths and arc lengths intended to simulate the range of flaw sizes and geometries which potentially could occur in an operating SG. Test specimens were produced from tubes with circumferential cracks removed from operating steam generators and from tubes with laboratory generated flaws. The laboratory test specimens contain either electrical discharge machining (EDM) notches or laboratory generated stress corrosion cracks.

Symmetrical and asymmetrical circumferential flaw geometries were tested both with and without simulated eggcrate supports. The axial stress generated in a pressurized tube with a flaw is proportional to the degraded area of the flaw as measured in percent of the tube cross sectional area. Burst pressures of tubes with circumferential flaws correlate well with the corroded area for both tubes with uniform 360° flaws and tubes with asymmetric flaws supported by eggcrates. Figure 2-1, which is comprised of 32 laboratory cracks, 38 EDM notches, and two pulled tubes, shows that tubes with circumferential flaws less than 50% degraded area will burst at pressures near that of unflawed tubes. Specifically, three tubes without flaws were burst tested at an average pressure of 10,782 psi, while the

remaining 36 samples had average burst pressures of 10,271 psi. In fact, the majority of the samples burst at pressures above 10,000 psi. This demonstrates the strength of the circumferential cracks and shows that structural integrity is maintained on cracks <50% degraded area with significant margin.

This industry burst data was reviewed and screened to eliminate non-representative data. The largest set of non-representative data was determined to be those not achieving an actual burst condition (i.e., leakage and/or bladder extrusion resulted in the test being terminated before burst, thus the peak pressure obtained resulted in an abnormally low value). All data eliminated was based on the criteria for exclusion of burst data specified in the TSP outside diameter stress corrosion cracking alternate plugging criteria under the SGDSM program(2).

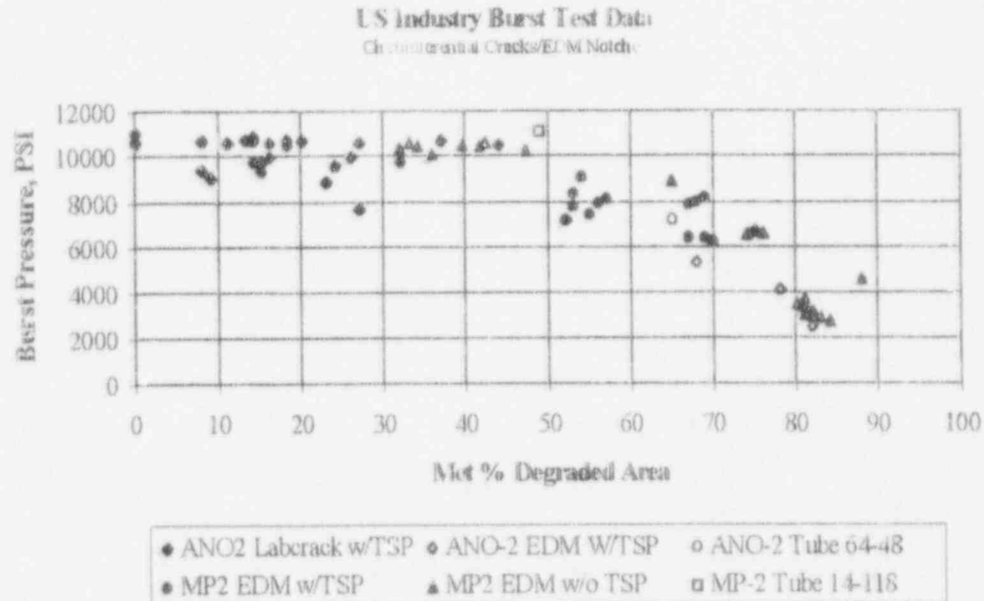

Figure 2-1
Comparison of Burst Tests to Reg Guide Limits

A regression analysis of the burst test data points was performed to determine the most appropriate value to evaluate against the data. The result, shown in Figure 2-2, yields a best estimate flaw size of approximately 79.452 average % through-wall (TW) for a $3\Delta P$ value of 4050 psi, and a lower bound (95%) value of 70.593%.

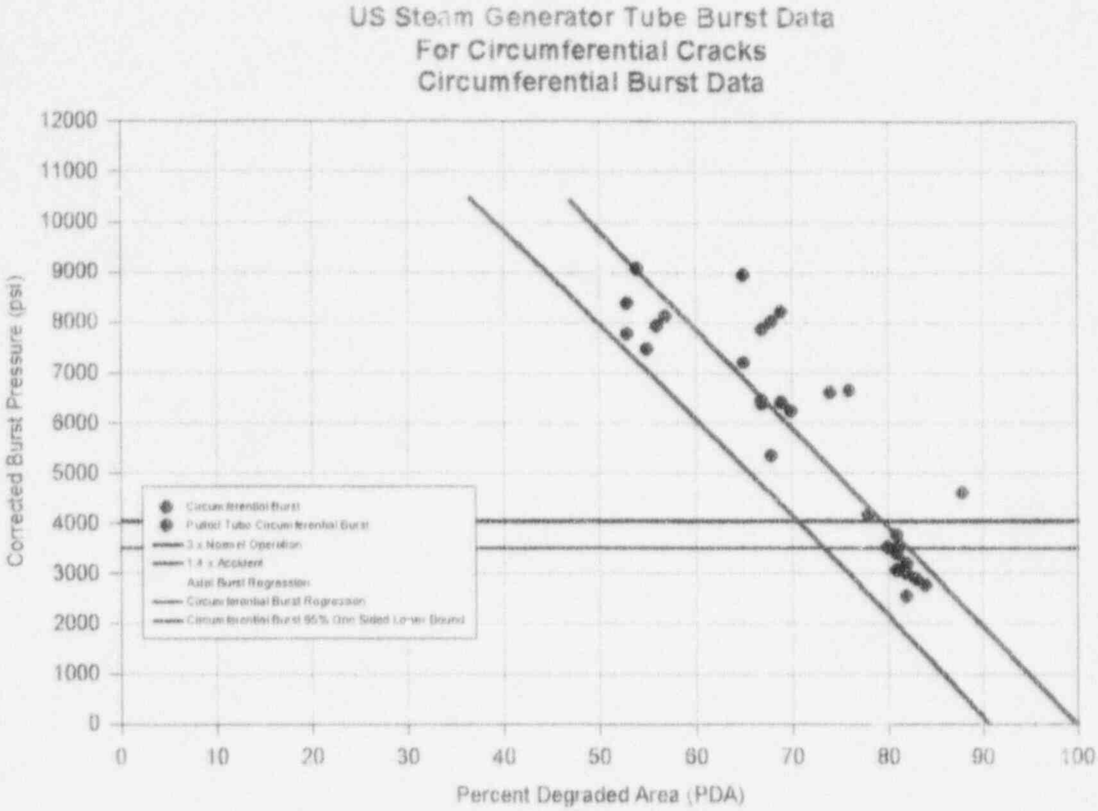

Figure 2-2
Burst Test Regression Analysis

For purposes of the evaluation of ANO-2 circumferential cracks, the lower bound number of 70% degraded area will be utilized. As described in Section 2.1, this results in additional margin because a planar flaw is assumed even though all known circumferential cracks at that size range have been comprised of a band of cracks, thus resulting in higher than predicted burst pressures.

To better understand the circumferential cracking problem, comparisons between axial cracks and circumferential crack burst performance have been made by Tractebel/Electrabel in Belgium[4]. Through-wall axial and circumferential notches of the same length were tested and demonstrated the comparative safety significance between the two. The comparison between burst pressures of the two is shown in Figure 2-3. The axial cracks burst at pressures significantly lower than their circumferential counterparts, especially around the 40% degraded area for circumferential cracks, which corresponds to a through-wall crack of approximately 25 mm (≈ one inch) in length.

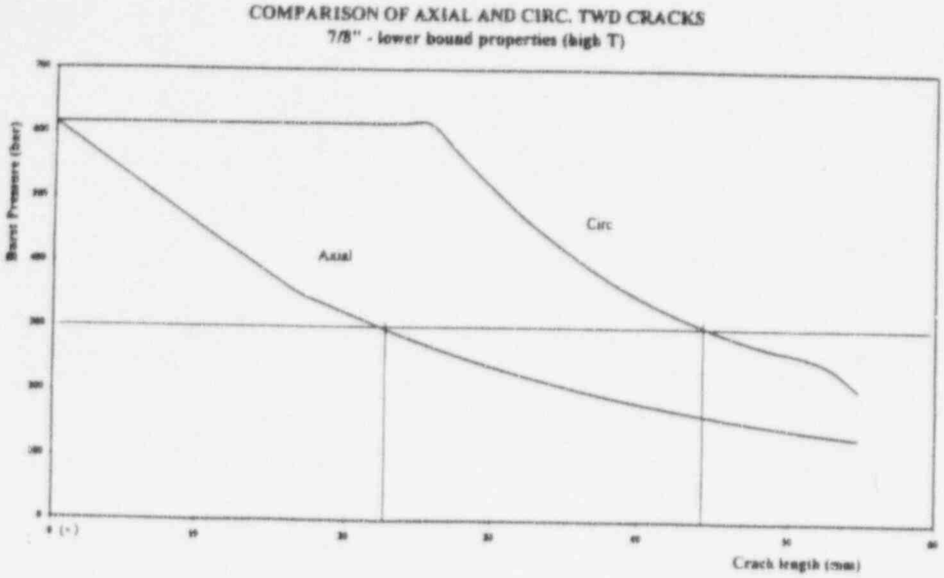

Figure 2-3
Belgium Axial/Circumferential Crack Burst Pressure Comparison

2.4 Finite Element Model

To augment the analytical RG evaluation, an approach to evaluate the response of certain flaws utilizing finite element techniques was developed. The technique was also utilized to allow evaluation of the strength imparted by the ligaments between microcracks. The axisymmetric finite element results support analyses that determined a 79% degraded area circumferential crack is the RG 1.121 3ΔP maximum crack size. 3-D finite element analysis results demonstrated the load carrying ability of the ligaments that may exist between cracks in an actual tube. The technique utilized NDE data from ultrasonic testing (UT) or RPC deconvolution analysis[10]. UT has been successfully utilized by others to evaluate the presence of ligaments for the purpose of performing structural evaluations[10]. RPC profiling and/or deconvolution type analysis will be used in the future with this model to provide additional structural integrity assessments.

2.5 In-Situ Pressure Testing

Per the requirements of RG 1.121, the effects of defects on steam generator tube burst strength must be determined and found to be within the margins defined in the RG. Both analysis technique and NDE inaccuracies must be accommodated in assessing actual defects against the allowable defect size. Traditionally, to demonstrate this, defective tubes have been pulled from steam generators and burst testing is then performed in the laboratory. However, the removal of tubes for testing has many drawbacks, and thus an in-situ pressure test device has been developed to allow testing of a defective tube within the steam generator without the need to pull the tube, thereby avoiding the above drawbacks. The complete details of the in-situ pressure testing were provided in Reference 1.

For the deep penetration circumferential defects of interest, the main loading which is significant for burst testing is the axial load imposed by the tube internal/external pressure

differential times the tube cross sectional (nondefective inside diameter) area[8]. The in-situ device used at ANO-2 can impose that proper loading on the tube, and thus is an acceptable means of demonstrating structural integrity of defective tubes in accordance with the requirements of RG 1.121. When considering the advantages of the in-situ test over a tube pull as discussed above, the in-situ test becomes the preferred method.

In-situ pressure testing was first conducted in the industry by Westinghouse at the San Onofre Nuclear Generating Station in the early 1980s. The second known use was by Asea Brown Boveri (ABB)-CE at ANO-2 during the ninth refueling outage, where the entire tube was pressurized following plugging at both ends. That tube held a pressure of 4700 psi for ten minutes with no leakage. Entergy Operations has performed pressure tests on a total of seven tubes, demonstrating the ability of tubes with perceived large flaws to maintain integrity even at high pressures. Industry wide, CE plants have conducted 35 in-situ pressure tests since 1992. A graph of the test results compared to the RPC average depth is shown in Figure 2-4.

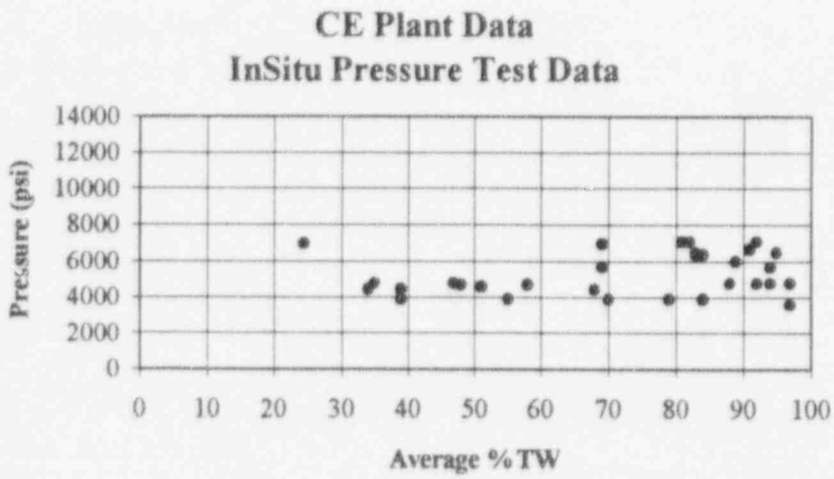

Figure 2-4
Industry In-situ Pressure Test Results
(Data reflects peak pressure obtained - none have resulted in a tube burst)

2.6 Summary of Structural Considerations

Numerous methods have been used to determine the structural limit of tubes with circumferential defects. Analytical work, finite element analysis, burst testing and in-situ pressure testing have demonstrated that circumferential cracks can be relatively large without compromising the structural integrity of tubes. This work has also demonstrated that NDE sizing has been conservative in the past, and more accurate analysis tools provide additional margin by projecting the cracks as a single planar flaw. Tubes with flaws of around 50% degraded area have demonstrated burst pressures at or near that of virgin tubes, thus showing the conservatism associated with a 40% repair limit. While 79% is a

sound analytical number for the structural limit, additional conservatism is provided by using the lower bound (95%) number of 70%, which supports the 40% TS repair limit, assuming NDE and growth rate information is reasonable. The burst information this is based on has been confirmed by worldwide burst testing and analysis.

3.0 NDE CONSIDERATIONS

Nondestructive examination is a critical element in assessing the structural significance of SG tubing flaws, and the inspection method must provide a reliable measurement of crack dimensions. Additionally, the inspection process will provide crack growth data which is required to establish allowable crack sizes and operating intervals for various conditions.

Previous techniques for using NDE data to assess structural compliance of given flaws utilized both ECT and ultrasonic data. One ECT technique used has been termed "average depth" and is defined as the maximum depth based on phase analysis multiplied by the detected arc length and divided by 360. This essentially takes the detected crack and turns it into an equivalent 360° crack. The UT technique determines a "crack area" of the detected flaw. Both the average depth and the crack area methods have shown reasonable agreement with the observations on pulled tubes. These results appear to provide conservative assessments of burst strength of circumferential cracks as demonstrated by the use of in-situ pressure tests at ANO-2 and other sites. This is generally attributable to the discontinuous nature of the circumferential cracks, where there are ligaments of sound material, not detectable by standard ECT analysis such as RPC or Plus Point, between crack segments, adding significantly to the strength of the cracked section of tubing. Assessments of the structural significance of circumferential cracks can be performed using arc length alone, as long as the length is short enough to support the necessary assumptions concerning threshold of detection. When the crack lengths are longer, some other parameter must be factored in, and thus the average depth concept was created. However, the success of the RPC to provide reliable depth estimates has been limited in the past. Recent improvements in the approaches to analysis of ECT data has resulted in the ability to develop a crack "profile," and thus determine the % degraded area, which can be directly compared to the destructive examination results from pulled tubes. The profiles are generated by measuring actual length and depth values and creating a circumferential planar profile of the cracked surface. Examples of these profiles are shown in Appendix B.

Figure 3-1 shows the results of the data for the plus point and 0.115" pancake coils.

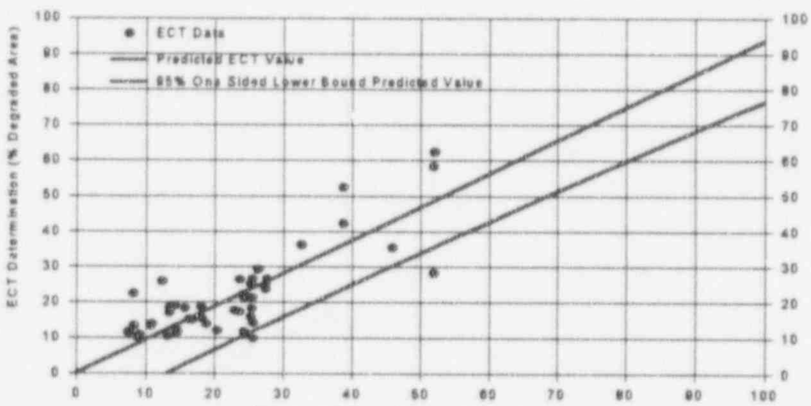

Figure 3-1
Resizing Data for Circumferential Crack Database
+ Point and 0.115" Pancake Data For Pulled Tubes and Laboratory Cracks

The specific data was reevaluated as follows:

Raw ECT data from pulled SG tubes (CE design) and laboratory cracks were analyzed using Eddynet95 (final Beta Version). This software enables depth sizing of EC signals, using the phase analysis technique, at several circumferential locations along the crack. The analyzed depth for each location was then entered into a data file along with similar information from the metallographic data for each tube. The data file was then used to provide a graphic comparison of the depth profiles. In addition, this file contained the necessary data to compute the average corroded area for the two data sets. The resulting corroded areas were then used to generate statistical information concerning the data sets.

The raw ECT data used in this study are classified as follows:

- 0.080" diameter pancake coil data from pulled tubes prior to 1992, and 30 laboratory grown cracks.
- 0.115" diameter pancake coil data from industry pulled tubes, and 30 laboratory grown cracks.
- Plus Point coil data from the industry pulled tubes (1995), and six (6) laboratory grown cracks.

All ECT data reevaluated in this study were performed in accordance with a guideline established prior to any analysis being undertaken. This practice ensured consistency in the analysis using the new software. The output of the ECT analysis was a graphic printout for each axial scan-line evaluated. This graphic printout consisted of the terrain map, depth sizing Lissajou showing the measurements and the circumferential Lissajou. Thus for each tube evaluated there were several graphic printouts. The measured depths were then entered into the data file as stated above.

The final results show the 0.080" diameter pancake coil consistently underpredicts the metallographic data. Since the 0.080" coil will not be used in the upcoming outage, the results are not being considered as part of this evaluation. Similar work for the 0.115" pancake coil shows a significantly better correlation with the metallographic data. The plus-point coil, however, provided the best overall results (shown in Figure 3-2) since its design permits better detectability and sizing. It should be noted that the data for this coil is limited to nine (9) data points. The study performed by Entergy Operations indicated that better sizing capabilities could be achieved with this coil design. This limited data set results in a larger uncertainty, and, as a result, Entergy Operations has undertaken the task of collecting and analyzing plus point data from additional samples in the Electric Power Research Institute (EPRI) Steam Generator Management Program. These samples were developed by the EPRI NDE center for the industry circumferential crack sizing program. The ECT data from these additional flaws has been collected and is in the process of being analyzed. Entergy Operations has also initiated an effort to produce an additional twelve laboratory crack samples to assess NDE capabilities. Expectations are that this work will provide information to reduce the uncertainties associated with the sizing. These efforts are scheduled to be completed in time to support the 2R11 outage.

Figure 3-2 demonstrates the ability of the Plus Point coil to provide accurate sizing. In fact, the data resulted in slight oversizing compared to the met data. As shown in the figure, a 95% one sided lower bound for a 40% repair limit yields a met value of 53%, and thus the defined uncertainty is 13% (53 - 40). This uncertainty is combined with the other individual uncertainties to yield a repair limit in accordance with the ANO-2 TS.

In order to develop a better understanding of the morphology of the cracks and their relationship to ECT data, Entergy Operations is undertaking a detailed metallographic evaluation of a few selected cracks from the six laboratory grown cracks. These cracks were evaluated using all three coil designs. A better understanding of the crack morphology and its correlation to the ECT signatures will provide a better basis to quantify the ECT sizing attributes.

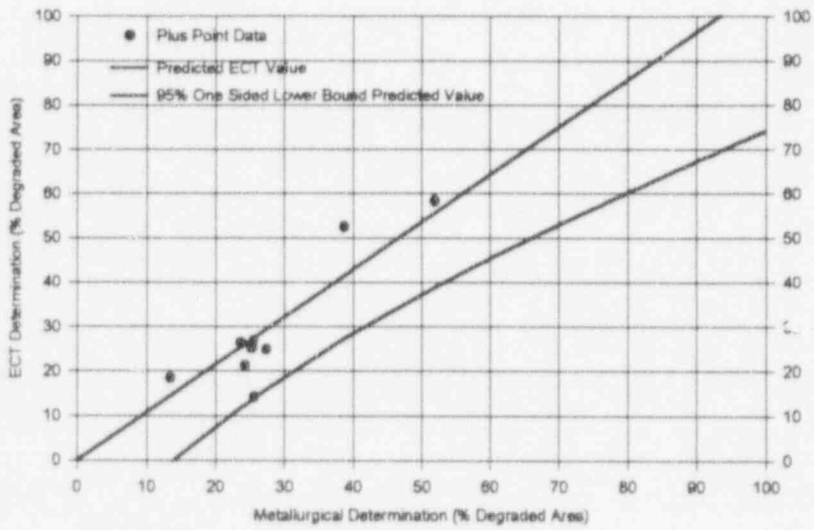

Figure 3-2
Resizing Data for Circumferential Crack Database
+ Point Data From Pulled Tubes and Laboratory Cracks

4.0 CRACK GROWTH RATE

The growth rate of circumferential cracks at ANO-2 has been perceived to be high based on the performance of previous ECT capabilities, where relatively large flaws were "missed" or weren't present, therefore resulting in a large apparent growth. Recent improvements allow for a review of that data and subsequent realistic representation of the results. It should be noted that regardless of the sizes discovered, all flaws have met RG 1.121 requirements as demonstrated by in-situ pressure tests.

Using the new analysis techniques, thirty-six (36) data points from previous ANO-2 outages were evaluated to assess growth rates. Specifically, all circumferential cracks exhibiting an apparent growth of >1 mil/month (≈25%/EFPY) were chosen for evaluation with the new analysis technique. The result was a significant decrease in the measured growth rate, which was more consistent with what would be expected. The average growth rate was 4.1% degraded area per EFPY, with a standard deviation of 12.8%. This yields a 95% upper bound growth rate of 28% per EFPY. This is the number that is used to determine the operating interval until the complete data set is analyzed and a new number established. The remainder of the tubes (≈250) are being reanalyzed as of this writing. Since the number of points used is small relative to the total sample, the growth rate is expected to decrease upon completion of the analysis currently being performed. As such, the current values reflect the population of cracks believed to have demonstrated the largest growth, which provides conservative results relative to the growth rate of the total sample.

A limited scope literature review of intergranular stress corrosion cracking (IGSCC) crack growth rate (CGR) in an environment representative of the secondary side of the steam generators provided two references. Pertinent results from these papers are summarized below:

From Reference 11:

1) The stress intensity (K) at the IGSCC crack tip decreases as the number of cracks increase.

2) The growth rate for IGSCC cracks, with secondary side faulted water chemistry (10 ppm NaOH), was in the range from 0.06 mils/month to 0.3 mils/month, (7.9×10^{-8} in/hr - 3.94×10^{-7} in/hr).

3) Very high CGR was attained in very highly contaminated secondary side water (20 wt% NaOH + 4 wt% Na_2CO_3). In this case the CGR was 10.8 mils/month (1.5×10^{-5} in/hr). This highly faulted condition is far from the normal operating regime, (20 wt% ≈ 2×10^5 ppm).

From Reference 12:

1) Tests conducted with Double Cantilever Beam (DCB) specimens in water chemistry controlled by hydrazine and boric acid (5-10 ppm) showed CGR range from 0.31 to 0.5 mils/month (4.3×10^{-7} in/hr to 7.09×10^{-7} in/hr).

2) In tests conducted with hydrazine but without boric acid, low boron intensity at the crack tip, showed a CGR of 0.87 mils/month (1.14×10^{-6} in/hr).

The observed circumferential cracks at ANO-2 are found to be intermittent cracks with ligaments and are located on different axial-circumferential planes in a narrow axial band. This cracking morphology would tend to produce lower stress intensity at the individual crack tip[11], than that for a single equivalent circumferential crack. The CGR to stress intensity relationship, in the lower K regime, being a power law, would result in lower growth rates for the multiple crack morphology.

The estimated growth rates for ANO-2, based on the ECT results obtained from previous outages, are supported by the experimental findings summarized above. However, it must be recognized that the present estimate for growth rate is based on the ECT results obtained using conventional RPC techniques with analysis software designed for detectability and minimal sizing capability. The experience and knowledge gained from the Entergy Operations circumferential crack sizing study, described earlier, will provide a more consistent and accurate measure for average corroded area starting with the upcoming refueling outage. The continued effort to improve the ECT practice will enhance the sizing accuracy and will therefore enable the estimation of more realistic growth rates.

With continued controls on water chemistry and a long history of boric acid addition, it is reasonable to expect that the actual CGR would be considerably lower than 1.0 mil/month. The improvement in the ECT practice would provide a vehicle to demonstrate the validity of lower CGR.

5.0 LEAK RATE CONSIDERATIONS

The ANO-2 circumferential cracks are of varying circumferential extent, sometimes occurring as a crack network in multiple axial planes, separated by remaining structural ligaments and may contain arc segments which extend through-wall. Under postulated faulted load conditions these cracks may leak, with the amount of leakage (leak rate) dependent primarily on the effective differential pressure and the total crack opening area.

Leak rates for individual cracks were previously determined using a basic calculation technique, described in Reference 9, for leak rates through axial cracks caused by primary water stress corrosion cracking (PWSCC) in expansion transitions. The leak rate from a circumferential crack, expressed in gallons per minute at the primary fluid temperature, is given by the same formula as for an axial crack, and is proportional to the crack opening area, a flow discharge coefficient and the square root of the effective differential pressure. This technique has been updated and modified in accordance with Reference 13.

This methodology was utilized to compare the difference between the leak rates from axial and circumferential cracks of the same length. A single length of 28.3 mm (180°) was used and the calculation performed for the full range of pressures up to burst. The results are shown in Figures 5-1 and 5-2 (linear scale and log scale, respectively). The leak rates are about two orders of magnitude lower for circumferential cracks. When the burst pressure value was reached, a jump was assumed to limit the leak rate to correspond with an orifice with a section equal to the tube internal cross sectional area.

This basic leakage model will be utilized in conjunction with the statistical model to provide an assessment of potential end of cycle (EOC) leakage expected under MSLB loads. The distribution curve of arc lengths for cracks left in service for the interval following 2R11 will be used to estimate the leakage under the peak accident pressure after applying the applicable growth rate. For each crack an assumption of the 100% TW extent will be made and used at a 95% limit. At EOC, the total summed leakage from all cracks under MSLB loads (2500 psid at operating temperature) will be made. This will lead to an offsite dose value to be compared against the applicable 10CFR100 and control room dose limits. If the applicable limits are exceeded, the appropriate steps will be taken in accordance with Reference 3 to reduce the dose to within acceptable limits.

The ANO-2 leak rate shutdown limit is administratively set at 0.1 GPM. This is further described in Section 7.

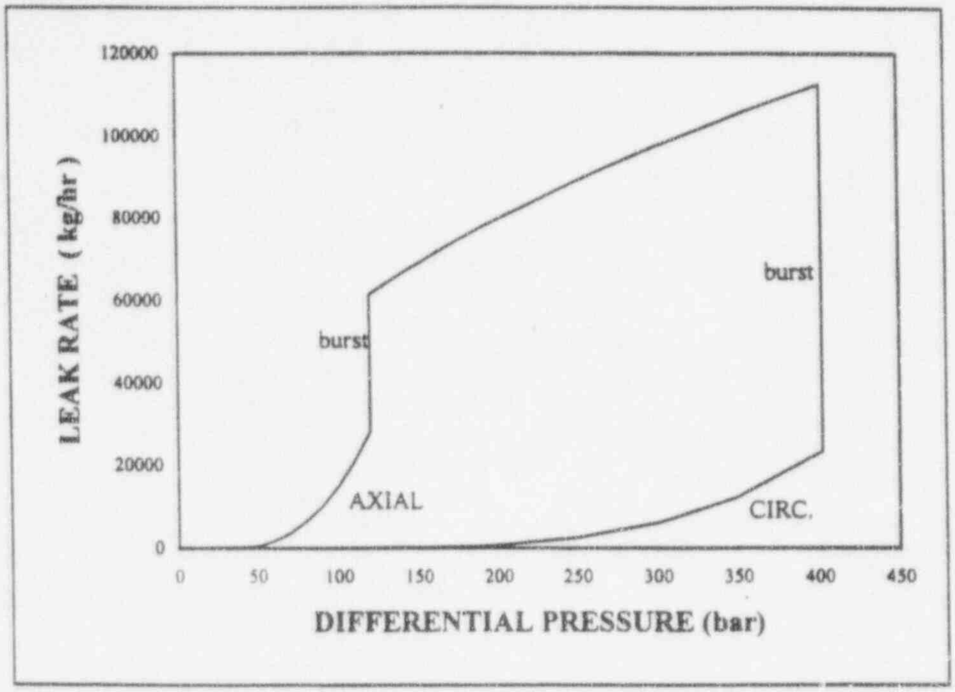

Figure 5-1
Comparison of Leak Rates for Axial and Circumferential Cracks of Equal Length

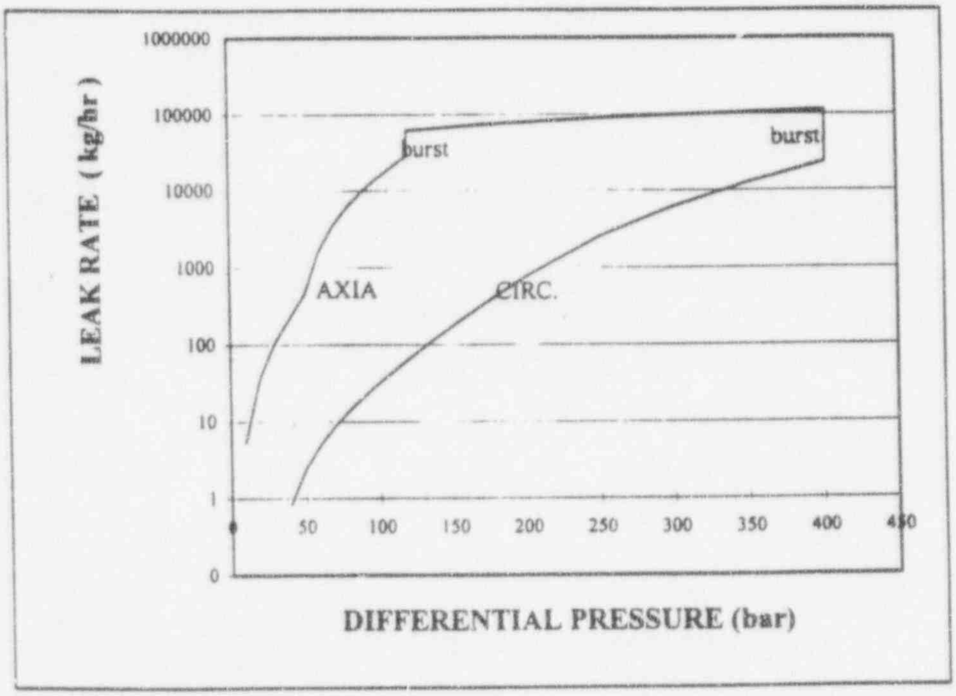

Figure 5-2
Comparison of Leak Rates for Axial and Circumferential Cracks of Equal Length (Log Scale)

6.0 SAFETY ASSESSMENT

The avoidance of a severe accident leading to core damage is an important part of assuring adequate protection of the public health. Such severe accidents are important because, although extremely unlikely, they have the potential of releasing large quantities of fission products to the environment. A probabilistic safety analysis (PSA) was performed for the operating interval from Refueling Outage 2R10 (March, 1994) to Refueling Outage 2R11 (September 1995), including SG Inspection Outage 2P95. This was performed in order to assess the impact of the SG tube degradation mechanism on the probability of such a severe accident at ANO-2[1]. The objective of this PSA was to identify the optimum ANO-2 SG inspection interval: one which assures adequate protection to the public, yet minimizes ANO-2 operational costs and radiation worker exposure. The results showed that the conditional probability of tube failure for a primary-to-secondary differential pressure (PSdP) of 2500 psid based on the expected number of tube defects at 2R11 obtained by this convolution technique was approximately 2.2E-03 which is less than the 1.0E-02 threshold value provided in the Generic Letter for Voltage-Based Repair Criteria[3].

Extension of the ANO-2 SG inspection interval from one half cycle (MOC11) to a full cycle (EOC11) interval was shown to have a negligible increase on the average ANO-2 core damage frequency (CDF) due to a steam generator tube rupture (SGTR). Specifically, using the 95% confidence level (CL) CDF, the increase in ANO-2 CDF due to spontaneous and induced SGTRs is only 0.59E-07/rx-yr or about 0.2% of the ANO-2 CDF due to internal events reported in the ANO-2 individual plant examination (IPE)/PSA. This increase in CDF is small and is well within the NO ACTION recommendation category per SECY 91-270. In addition, it is below the NO ACTION recommendation per NUMARC 91-04 and within the NON-RISK SIGNIFICANT classification per the draft PSA Applications Guide. Since the increase in the ANO-2 SGTR CDF over a half cycle is small, the greater than expected SG defect population found during 2P95 at the middle of Cycle 11 (MOC) indicated that the continued operation of ANO-2 for the remainder of Cycle 11 is not risk significant.

This first of a kind analysis for circumferential cracks was presented to the staff on July 14, 1994, and specific details were provided in Reference 1. As added assurance of safe operation with circumferential cracks remaining in service, this probabilistic approach will be applied to evaluate the probability of burst and the change in core damage frequency associated with operation in the next interval. The probability of burst will be maintained below 1.0E-02 for the proposed operating interval in accordance with Reference 3. The evaluation for the current interval is included as Appendix A.

7.0 OPERATIONAL RESPONSE

An operational leak rate limit is established to provide reasonable assurance that flaws either missed during inspection or growing more rapidly than expected will not render the tube vulnerable to tube rupture in the event of a MSLB. The ANO-2 Technical Specification limit is 0.5 GPM per SG, but an administrative procedural limit of 0.1 GPM (144 GPD) exists to provide for added margin against burst. In addition, rate of change limits exist to ensure rapidly propagating cracks or damage will be addressed at the earliest possible stages.

Upon any control room alarm indicating primary-to-secondary leakage, the Operations and Chemistry Departments enter abnormal operating procedures. If the leak rate is ≥0.1 GPM, a plant shutdown is procedurally required. In addition, a plant shutdown is procedurally required if the leak rate is projected to be ≥0.1 GPM in one hour. Stable leak rates of >0.01 GPM procedurally require management awareness for continued plant operations.

The Operations Department trends the steam, condenser off-gas, and steam generator sample systems in determining indication of steam generator tube leak. Steam lines are monitored via radiation monitors and nitrogen sixteen (N-16) gamma detectors, which provide the chemists and operators with the capability of quantifying leakage. Procedures are utilized when the monitors or trend recorders for the aforementioned systems exhibit increasing trends. The Operations Department enters these procedures to place the plant in a stable condition and to mitigate the consequences of a steam generator tube leak.

Extensive training for operators is performed and places emphasis on changes in plant parameters and develops an aggressive strategy to identify and mitigate early signs of a steam generator tube rupture event. During a NRC Region IV inspection in June 1994[14], inspectors noted that the operators "...exhibited excellent capability and used diverse methods for detection of primary-to-secondary leakage..." In addition, an ANO-2 requalification scenario involving a SGTR event was witnessed by an inspector, who observed that the communication was "excellent."

The Chemistry Department routinely samples both the primary water and secondary water systems to identify primary-to-secondary leakage and trends the sample results to identify possible primary to secondary occurrences.

8.0 CONCLUSIONS

Entergy Operations has performed an extensive investigation into the circumferential cracking occurring at ANO-2. The investigation includes comprehensive inspections, application of appropriate safety factors, use of statistically valid (95/95) material properties, NDE data, growth rate, and tube burst test data. First of a kind probabilistic evaluations were previously performed to assess the safe operation for previous and current intervals. A similar probabilistic evaluation will be performed for the upcoming interval following the outage using the new data. Entergy Operations has performed extensive studies into circumferential cracking, and has sponsored several initiatives in this area. These include the most pulled tubes containing circumferential cracks in the U.S., the generation of 42 laboratory circumferential cracks for NDE and structural studies, and a first of a kind probabilistic safety assessment of circumferential cracking.

From a structural standpoint, circumferential cracks on the order of 50% degraded area and smaller exhibited burst pressures equal to or near that of unflawed tubes. This has been demonstrated by programs in both the U.S. and other countries for burst testing of SG tubes with circumferential flaws. These programs exhibited the inherent strength of tubes containing stress corrosion circumferential cracks. This strength is generally attributed to the discontinuous nature of circumferential cracks, where there are ligaments of sound material which generally are not detectable by conventional ECT analysis techniques. These ligaments, between crack segments, add significantly to the strength of the cracked section of tubing. In-situ pressure testing of the most severely degraded tubes in CE plants have demonstrated the tubes would meet RG 1.121 requirements with added margin.

For NDE, the use of the Plus Point probe significantly enhances the ability to detect and accurately size the cracks. This technology, combined with new software for analysis of data, provides the necessary information to implement a TS repair limit of 40%. The new software has also allowed for a re-evaluation of flaw sizes by providing more accuracy. Growth rates of circumferential cracks have been shown through this enhanced analysis to be lower than that reported based on earlier analysis. The technological advances in NDE have resulted in the ability to detect smaller flaws, many of which would have not been detected previously. These small flaws constitute little if any challenge to the structural integrity of tubing, and have been shown to be acceptable for remaining in service as a result of the previous higher detection thresholds. The inspection program planned for ANO-2 in 2R11 will provide additional assurance of safe operation of the unit following the outage.

Additional areas provide added margin above that required by RG 1.121. Throughout the assessments, planar depth is assumed, thus not accounting for the ligaments previously mentioned. In addition, lower bound (95%) values were used for material properties, NDE uncertainty, and the structural limit, as well as an upper bound (95%) value for growth rate. These conservative numbers still yield an acceptable repair limit of 40% degraded area, which complies with the ANO-2 Technical Specifications.

Should this approach be utilized, Entergy Operations will remove tube sections if needed to validate the NDE sizing accuracy and evaluate structural compliance. In addition, the operating interval following 2R11 will be limited to ≤ 420 EFPD assuming the NDE accuracy, growth rate numbers, and burst probability allow operation for that time.

Entergy Operations has utilized a comprehensive integrated approach to managing steam generator tube integrity at ANO-2. Using mid-cycle outages, the likelihood of tube rupture and/or leakage has been minimized. An excellent primary-to-secondary leakage program exists at ANO-2 with excellent operator communication and training programs to ensure early detection and a rapid response should leakage occur. Additional projects are currently ongoing, including the production of additional crack samples, reanalysis of the ANO-2 database using advanced analysis techniques, and development of a state of the art leak rate model. Utilization of the technical specification repair limit of 40% degraded area would be combined with that same integrated philosophy, by removing additional tubes if needed for evaluation and conducting a mid-cycle outage to validate the assumptions. Entergy Operations is committed to operating ANO-2 safely, and believes this proposal ensures the continued safe operation of the unit.

9.0 REFERENCES

1) 2CAN029505, "2P95-1 Steam Generator Inspection Results and Circumferential Cracking Evaluation," February 17, 1995.

2) EPRI TR-103017, Steam Generator Degradation Specific Management.

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

4) "Belgian Experience with Circumferential Cracking," by Paul Hernalsteen of Tractebel/Electrabel, Presented at the EPRI Circumferential Cracking Workshop, June 1995.

5) ANO/NRC Meeting Concerning Eddy Current Methodologies, July 15, 1993.

6) 2CAN089302, "Information to Support Upcoming Steam Generator Meeting," August 17, 1993.

7) EPRI NP-6865-L, Steam Generator Tube Integrity, Volumes 1 & 2 (Framatome Data).

8) EPRI NP-6626, Belgian Approach to Steam Generator Tube Plugging for PWSCC.

9) "Some NDE, Leak Rate and Burst Pressure Considerations in Support of the Analysis of Circumferential Cracking Incidents at ANO Unit 2," by S.D. Brown and J.A. Begley, Packer Engineering Report No. B51677-R1, Revision 0, September 1994.

10) Westinghouse Owners Group/NRC SG Circumferential Cracking Issue Meeting, September 26, 1994.

11) "Intergranular Attack and Stress Corrosion Cracking Propagation Behavior of Inconel Alloy 600 in High Temperature Water," Hirotaka Kawamura et al, Proceedings of the Sixth International Symposium on Environmental Degradation of Materials in Nuclear Power Systems - Water Reactors, Editors: R.E. Gold and E.P. Simonen, TMS Publication, 1993.

12) "IGA/SCC Crack Propagation Rate Measurements on Alloy 600 Steam Generator Tubing Using a Side Stream Model Boiler," H. Takamatsu et al, ibid.

13) Tetra Engineering Report TR-95-023, Leak Rate Model for ANO-2 Circumferential Cracks.

14) 0CNA079416, "NRC Inspection Report 50-313/94-17; 50-368/94-17," July 13, 1994.

APPENDIX A

SAFETY ASSESSMENT

1.0 Safety Analysis

An important aspect of any safety analysis is the demonstration that calculated offsite doses are within the NRC staff criteria given in the Standard Review Plan (SRP), NUREG-0800. Steam generator tube leakage is especially significant since it has the potential to lead to a containment bypass.

For ANO-2, the analysis utilized guidance from Reference 1, SRP assumptions, realistic assumptions for reactor coolant system (RCS) activity, and a best estimate methodology (ANO-2 specific CEPAC Model), examining both pre-existing and event-generated iodine spike (PIS and GIS) consequences.

Using best estimate methodologies, the following were evaluated:

- Valid emergency operating procedure (EOP) guidance
- Acceptable offsite dose consequences
- Adequate refueling water tank (RWT) inventory

The evaluation was performed for the following events:

- SGTR - single tube
- SGTR - multiple tubes
- MSLB induced tube leak(s) or rupture(s)*

  * The MSLB induced single and multiple tube rupture event is limiting.

The general methodology was to use the ANO-2 simulator and operating crews to determine the best estimate operator response times for representative MSLB/SGTR scenarios. These results were then incorporated into the ANO-2 specific CEPAC evaluations of various MSLB/SGTR scenarios. The CEPAC results were then compared to "hand" calculations.

The safety analysis performed for ANO-2 yielded the following results:

- EOP guidance was valid for event induced tube ruptures; therefore, no significant changes or improvements to the existing EOPs were needed.
- The offsite dose limits of 10CFR100 and the control room dose limits of GDC 19 can be satisfied using realistic assumptions.

- Based on generic system calculations and demonstration in the ANO-2 simulator, there is sufficient RWT inventory to shut down and depressurize the plant before depleting the RWT and sustaining core damage.

Details of this analysis were presented to the NRC staff on August 30, 1993.

2.0 Probabilistic Safety Analysis

The avoidance of a severe accident leading to core damage is an important part of assuring adequate protection of the public health. Such severe accidents are important because, although extremely unlikely, they have the potential of releasing large quantities of fission products to the environment. A probabilistic safety analysis (PSA) was performed in order to assess the impact of the SG tube degradation mechanism on the probability of such a severe accident at ANO-2[2]. The objective of this PSA was to identify the optimum ANO-2 SG inspection interval: one which assures adequate protection to the public, yet minimizes ANO-2 operational costs and radiation worker exposure.

The severe accident safety impact was evaluated by estimating the change in the ANO-2 CDF as a function of the time between SG inspections since the beginning of Cycle 11 (BOC11) steam generator inspection. Several proposed inspection interval lengths were considered: (1) a half-cycle interval at the middle of Cycle 11 (MOC11), (2) a full cycle interval at the end of Cycle 11 (EOC11), and (3) strictly for comparison purposes, a two cycle interval at the end of Cycle 12 (EOC12). The formal analysis was based upon steam generator inspection results through 2R10 (BOC11). The results of these analyses were qualitatively extended to include the 2P95-1 SG tube inspection findings in order to assess the risk of operating for the remainder of Cycle 11.

The CDF estimates were developed via the use of a modified version of the ANO-2 PSA plant model. The ANO-2 SG inspection interval risk analysis was performed via the development and quantification of event tree and fault tree models in a manner similar to that done in the ANO-2 IPE/PSA analysis[3]. The subject ANO-2 SG inspection interval safety analysis differed from the ANO-2 IPE/PSA analysis in that the subject analysis was limited to accidents involving SGTRs, since its intent was to estimate the change in ANO-2 CDF for several inspection interval options. In addition, the subject analysis accounted for the risk contributions due to both spontaneous SGTR initiators (R) and SGTRs induced by other initiators. The ANO-2 IPE/PSA did not account for SGTRs induced by other initiators.

The ANO-2 SGTR CDF analysis included the following steps:

1. Review and identification of events which could lead to spontaneous or induced SGTRs (either initiators or subsequent events),

2. Assessment of the SGTR conditional probability (CP) given an initiator or subsequent event which could cause a SGTR,

3. Identification of the safety functions important to assuring adequate core cooling,

4. Development of event tree logic which accounts for combinations of safety function failures which lead to core damage (i.e., core damage accident sequence),

5. Development of system fault tree logic to account for component failures which contribute to safety function failures, and

6. Quantification of the above event and fault trees to estimate the frequency of core damage involving SGTRs.

The frequency of spontaneous SGTRs (i.e., those occurring during power operation which are not due to significant changes in the primary-to-secondary pressure differential) was estimated to be 9.77E-3/rx-yr per the ANO-2 IPE/PSA[3]. The frequency of induced SGTRs (i.e., those occurring during power operation which are a result of a significant change in the primary-to-secondary pressure differential) required the review of the transient and loss of coolant accidents (LOCAs) described in the ANO-2 Safety Analysis Report (SAR)[4], NUREG-0844, and other sources of information. The potential for a SGTR event in each of these accidents was assessed by estimating the maximum primary-to-secondary differential pressure (PSdP) occurring in each and estimating the probability that one or more SG tubes will fail as a result of this differential pressure. An accident was considered a candidate for inducing a SGTR only if its maximum PSdP exceeded the nominal operating PSdP of 1350 psid (2250 psia - 900 psia).

Based on a review of the ANO-2 SAR and other sources, three accident initiators were identified to produce PSdPs significantly greater than the nominal 1350 psid PSdP: the steam line break (SLB), the feed line break (FLB), and the anticipated transient without scram (ATWS). Other initiators, including LOCAs, were not considered significant SGTR initiators. Due to differences in the plant response, the FLB/SLB accidents are assessed together followed by the ATWS-induced SGTR accidents.

2.1 FLB/SLB Analysis

In order to account for the ANO-2 plant response dependencies on the SLB location and to distinguish the FLB from the SLB, the ANO-2 IPE/PSA combined SLB/FLB initiator (T5) was split into four parts and given a unique initiating event designator:

1. Steam line piping outside of the main steam isolation valves (MSIVs) (T5-1),

2. Steam line piping inside of MSIVs and outside of the containment (CNMT) on both SGs (T5-2),

3. Steam line inside of the CNMT on both SGs (T5-3), and

4. Feedwater line inside of the feedwater check valves on both SGs (T5-4).

The frequency of each initiation was taken as the fraction of the total lengths of the steam line (SL) and feedwater line (FL) that each section represents times the total ANO-2 IPE/PSA SLB/FLB frequency. A summary of these calculated SGTR frequencies is provided in Table 2-1 below.

Table 2-1
Summary of SGTR Initiating Event Frequencies

Initiating Event	ANO-2 IPE/PSA Frequency (/rx-yr)	Fraction of Total SL/FL Length	SGTR Analysis Frequency (/rx-yr)
R	9.77E-3	not appl.	9.77E-3
T5-1	1.1E-3	0.699	7.690E-4
T5-2	1.1E-3	0.107	1.182E-4
T5-3	1.1E-3	0.114	1.258E-4
T5-4	1.1E-3	0.079	8.710E-5

The probability of a tube rupturing in a given accident was assessed by developing an estimate of the probability of a tube wall failure as a function of average tube wall defect depth (i.e., %TW) at selected ANO-2 burnups and comparing each of these "fragility curves" with the expected population of ANO-2 SG tube defects at each of these burnups.

The expected population of ANO-2 SG tube defects, i.e., the number of tube defects as a function of defect size (%TW), was estimated using SG tube inspection data collected in past ANO-2 SG inspection campaigns through 2R10. It has been shown that the Weibull function can be used to predict the total number of defective tubes as a function of operating time. Furthermore, the data collected at ANO-2 through 2R10 and including the recent 2P95-1 inspection indicates that the sizes of the defects (avg %TW) can be described by a Gamma probability distribution function[2]. Using these two relationships, estimates of the defect population after a half-cycle, a full-cycle, and two-cycles of operation were developed. The results of these analyses were qualitatively extended to include the 2P95-1 SG tube inspection findings in order to assess the risk of operating for the remainder of Cycle 11.

The SG tube "fragility curves" were based on experimental SG tube burst pressure test data. These burst tests were performed for a wide range of tube wall defect sizes based upon metallurgical examination of the tubes after failure. For use in this study, these test results were corrected for temperature and to an average RPC %TW indication. The resulting data was used to estimate the probability a tube will, as a function of its defect average depth, fail for a given PSdP. The likely number of SG tube failures resulting from an accident is the combination (i.e., convolution) of the SG tube defect population and the SG tube fragility distribution for a given burnup and PSdP and is depicted graphically in Figure 2-1.

The conditional probability of tube failure for a PSdP of 2500 psid based on the expected number of tube defects at 2R11 obtained by this convolution technique was approximately 2.2E-03 which is less than the 1.0E-02 threshold value provided in the draft Generic Letter for Voltage-Based Repair Criteria[1]. This value is the sum of the EOC11 SG "A" and SG "B" conditional probabilities at the 95% confidence level (0.87846 for SG "A" plus 0.14689 for SG "B" per Table 2-2, below) divided by the sum of the expected number of tube defects at 2R11 (276 for SG "A" plus 200 for SG "B"). In order to assure conservative results, the EOC11 SG "A" and SG "B" tube rupture probabilities (the

numerator) assume that a single defective tube randomly distributed between 60%TW and 100%TW was not detected during the BOC11 tube inspection campaign. **This single defective tube assumption dominates the SGTR conditional failure probability estimate.** For SLB- and FLB-induced SGTRs, the PSdP was assumed to be 2500 psid. This is the maximum credible differential pressure between the primary and secondary systems and represents the primary pressure at approximately the primary code safety relief valve setpoint with the secondary pressure at atmospheric conditions. For these conditions, if the number of tubes susceptible to rupture for a given accident was estimated to be less than one tube, this value was conservatively interpreted as the conditional probability of a single tube rupture in the PSA analysis of CDF. A summary of these SGTR conditional probabilities are provided in Table 2-2 below.

Table 2-2

SGTR Conditional Probabilities for Accidents Involving a SLB or FLB Event

SG Inspection	SGTR Conditional Probability Used (+1 tube @ 95% CL)	
	SG "A"	SG "B"
BOC11	0.3688	0
MOC11	0.61434	0.06532
EOC11	0.87846	0.14689
EOC12	1.0	0.41861

These SGTR conditional probabilities were applied directly to the SLB and FLB initiating event frequencies provided in Table 2-1 to obtain the frequency of SGTR in a given SG following a SLB or FLB at the specified time after the BOC11 SG inspection.

Consistent with that performed in the ANO-2 IPE/PSA, the spontaneous SGTR, the SLB-induced SGTR, and the FLB-induced SGTR CDF analyses were performed via use of event trees and fault trees. Event trees specific to the SGTR accident were developed in order to provide a more detailed account of the accident progression than that in the ANO-2 IPE/PSA. The safety functions listed in Table 2-3 below were identified to be important for the SGTR accidents involving spontaneous, SLB-induced, and FLB-induced SGTRs.

Table 2-3

Spontaneous and SLB/FLB-Induced SGTR Safety Functions

Safety Function	Descriptor	Description
Reactivity control	K	Insert sufficient negative reactivity to stop nuclear reaction and maintain reactor subcritical
SGTR isolable with RCS intact	I_{RCS}	Ruptured SG can be isolated from environment and Containment
SGTR isolable within containment	I_{CNMT}	Ruptured SG can be isolated from environment
Feedwater (FW) available to intact SG	B_{1I}	Main feedwater (MFW), emergency feedwater (EFW), or auxiliary feedwater (AFW) provides feed to intact SG
FW available to intact or ruptured SG	B_{1N}	MFW, EFW, or AFW provides feed to either intact or ruptured SG
Secondary system pressure control via intact SG	B_{2I}	Operation of atmospheric dump valves (ADVs) and/or turbine bypass valves (TBVs) on intact SG
Secondary system pressure control via intact or ruptured SG	B_{2N}	Operation of ADVs and/or TBVs on either intact or ruptured SG
RCS inventory control	U	High pressure safety injection (HPSI) or, if sufficient, charging
Once through cooling	F	RCS depressurization via emergency core cooling system vent valve or low temperature overpressure protection vent valves
Long-term cooling	X	Shutdown cooling (SDC) or HPSI recirculation

These safety functions were used to develop a spontaneous and SLB/FLB-induced SGTR event tree. This event tree identifies the combinations of initiating events and functional failures expected to lead to core damage resulting in fifty-two (52) accident sequences of importance. Using these event trees and Boolean algebra, the ANO-2 CDF due to spontaneous and SLB/FLB-induced SGTR was quantified at BOC11, MOC11, EOC11, and EOC12. These CDF values are "point estimates," i.e., they correspond to their respective burnup conditions. These CDF values were averaged over the intervals between BOC11, MOC11, EOC11, and EOC12 in order to determine the average ANO-2 CDF due to spontaneous and SLB/FLB-induced SGTRs in each interval. These CDF values are reported in Section 2.3.

2.2 ATWS Analysis

Due to its severe thermohydraulic challenge to the plant, the ATWS-induced SGTR safety analysis was performed separately from that of other initiators. As in the ANO-2 IPE/PSA, the dominant ATWS-induced core damage risk was assumed to be associated with only three transient groups: turbine trips (T1), loss of MFW (T2), and loss of off-site power (T3) initiators. The safety functions listed in Table 2-4 below were identified to be important in the ATWS-induced SGTR core damage accidents. Note that these functions were selected to be relatively independent of each other in order to ensure that the ATWS-induced SGTR CDF is conservatively quantified.

Table 2-4

ATWS-Induced SGTR Safety Functions

Safety Function	Descriptor	Description
Reactivity control	K	Control rods insert sufficient negative reactivity to stop nuclear reaction and maintain reactor subcritical
Emergency AC power	AC	Emergency AC power
Turbine trip (TT) successful	TT	Turbine Trip successful
MFW available	MFW	MFW available
EFW available	E	EFW available
Moderator temperature coefficient	MTC	Moderator temperature coefficient for TT/MFW/E and burnup condition produces RCS-SG pressure differential less than 3700 psid
SG integrity	SGI	SG tube integrity remains intact following ATWS pressure excursion
Primary relief secured	W	Primary relief following ATWS pressure excursion secured
Borated water	BW	Borated water injection inserts sufficient negative reactivity to stop nuclear reaction and maintain reactor subcritical
Long-term cooling	LTC	SDC successful

These safety functions were used to develop three ATWS-induced SGTR event trees which identify forty-two (42) accident sequences of importance. Using these event trees, the ANO-2 CDF due to ATWS-induced SGTR was arithmetically quantified for the intervals between BOC11, MOC11, EOC11, and EOC12. The arithmetic quantification of the ATWS-induced SGTR CDF is consistent with that performed in the ANO-2 IPE/PSA and with the screening nature of the ATWS analysis. The ATWS-induced SGTR CDF values are averaged over the intervals between BOC11, MOC11, EOC11, and EOC12 (the averaging is accounted in the ATWS event trees). These CDF values are included in the combined CDF values reported in Section 2.3.

2.3 PSA Analysis Results

The results of the ANO-2 SG inspection interval safety analyses are listed in Table 2-5 below and are graphically depicted in Figure 2-2. These results include the combined core damage contributions of the spontaneous SGTR, the SLB- and FLB-induced SGTR, and the ATWS-induced SGTR accidents.

Table 2-5
ANO-2 Spontaneous, SLB/FLB-Induced, and ATWS-Induced SGTR
CDF Results Averaged @ MOC11, and EOC11 and EOC12
w/95% +1 Confidence Level

Case	BOC11 to MOC11	BOC11 to EOC11	BOC11 to EOC12
Spontaneous and Induced SGTR CDF w/ SG Insp @ BOC11 only	3.79E-07	3.98E-07	5.25E-07
Spontaneous and Induced SGTR CDF w/ SG Insp @ Mid-Cycles	3.79E-07	3.39E-07	3.39E-07
CDF Increase	0	5.92E-8	1.86E-7

These results, slightly revised from those presented to the NRC staff on July 14, 1994, show that the extension of the ANO-2 SG inspection interval from one half cycle (MOC11) to a full cycle (EOC11) interval has a negligible increase on the average ANO-2 CDF due to a SGTR. Specifically, using the 95% confidence level CDF, the increase in ANO-2 CDF due to spontaneous and induced SGTRs is only 0.59E-07/rx-yr or about 0.2% of the ANO-2 CDF due to internal events reported in the ANO-2 IPE/PSA[3]. This increase in CDF is small and is well within the NO ACTION recommendation category per SECY 91-270[5]. In addition, it is below the NO ACTION recommendation per NUMARC 91-04[6] and within the NON-RISK SIGNIFICANT classification per the draft PSA Applications Guide. Since the increase in the ANO-2 SGTR CDF over a half cycle is small, the greater than expected SG defect population found during 2P95-1 at MOC11 indicates that the continued operation of ANO-2 for the remainder of Cycle 11 is not risk significant.

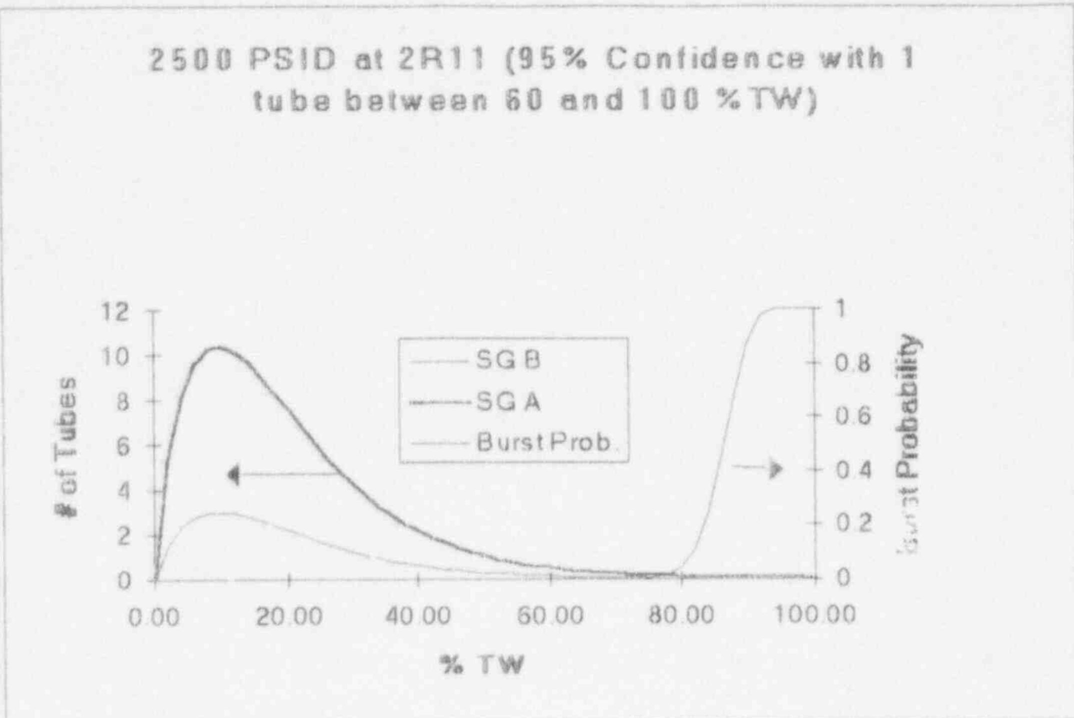

Figure 2-1

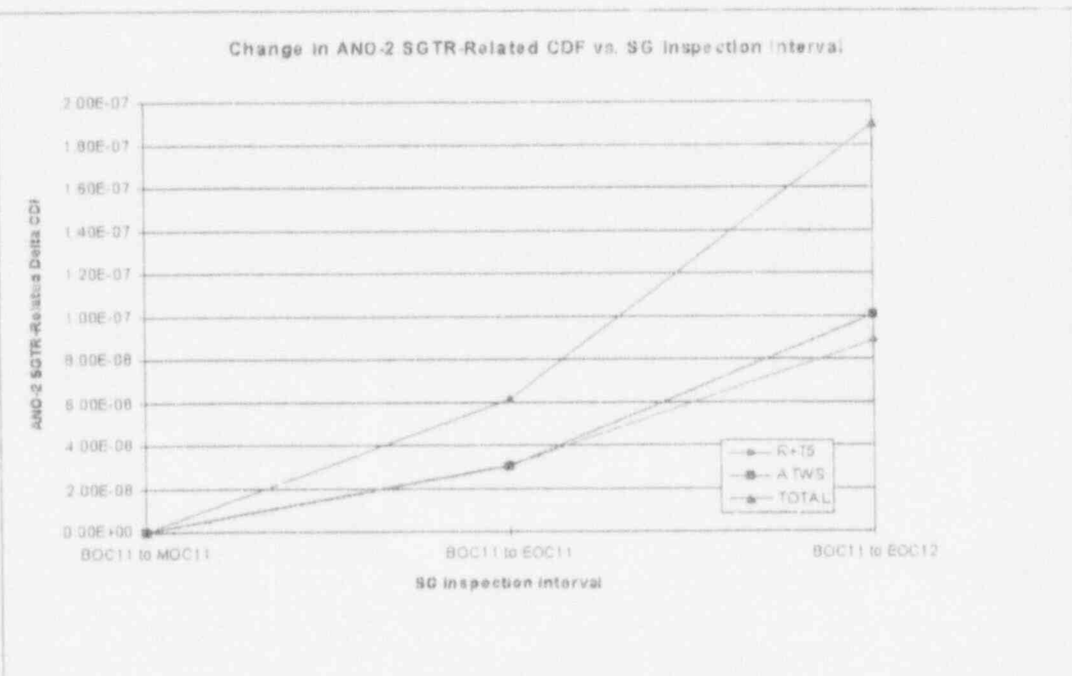

Figure 2-2

References for Appendix A

1) "Voltage-Based Interim Plugging Criteria for Steam Generator Tubes - Task Group Report," Draft NUREG-1477, June 1, 1993.

2) "ANO-2 SG Inspection Interval Risk Analysis Based on Inspection Data through 2R10," Calc. 93-E-0079-05, Rev 0.

3) "ANO-2 Probabilistic Risk Assessment (PRA), Individual Plant Examination (IPE) Submittal," Report 94-R-2005-01, Revision 0.

4) ANO-2 Safety Analysis Report, Amendment 12.

5) "Interim Guidance on Staff Implementation of the Commission's Safety Goal Policy," Letter form J.M. Taylor (NRC) to the Commissioners, SECY 91-270, August 27, 1991.

6) "Severe Accident Issue Closure Guidelines," NUMARC 91-04, January 1992.

APPENDIX B

NDE PROFILE EXAMPLES

Raw ECT data from pulled SG tubes (CE Design) and Laboratory cracks were analyzed using the Eddynet95 (final Beta Version). This software enables depth sizing of EC signals, using the Phase Analysis technique, at several circumferential locations along the crack.

All ECT data reevaluated in this study were performed in accordance with a guideline established prior to any analysis being undertaken. This practice ensured consistency in the analysis using the new software. The output of the ECT analysis was a graphic printout for each axial scan-line evaluated. This graphic printout consisted of the terrain map, depth sizing Lissajou showing the measurements and the circumferential Lissajou. Thus for each tube evaluated there were several graphic printouts.

Examples of the data from six laboratory cracks and one pulled tube are shown in Figures B-1 through B-7.

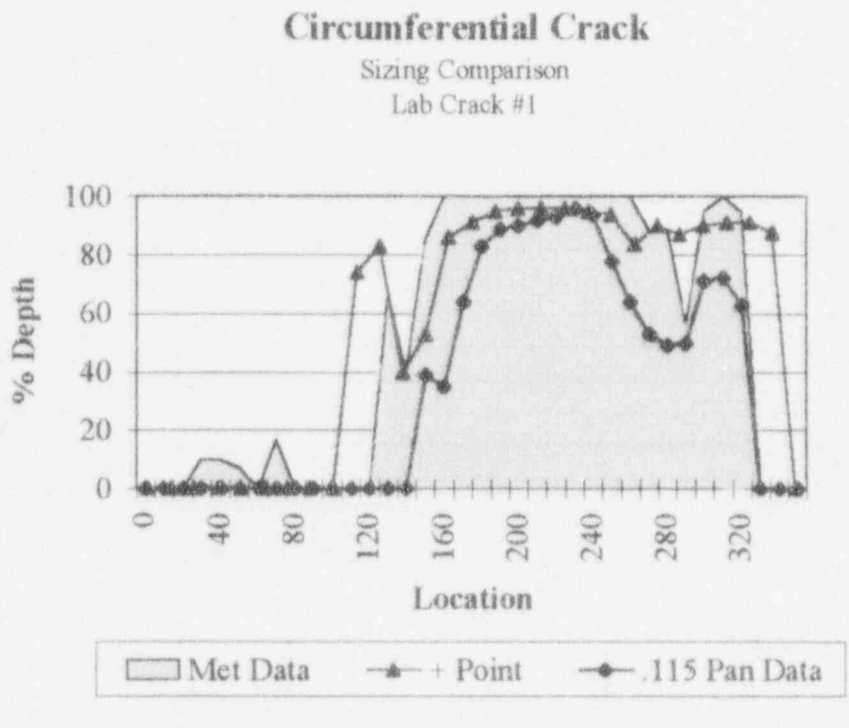

Figure B-1
Lab Crack #1 - Comparison of Met, + point, and 0.115 Pancake Data

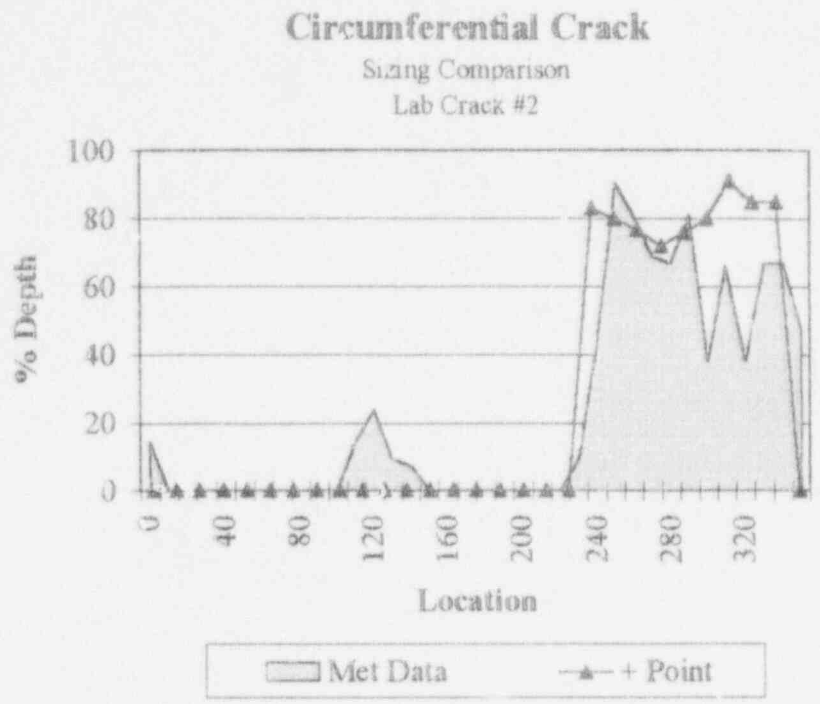

Figure B-2
Lab Crack #2 - Comparison of Met and + Point Data

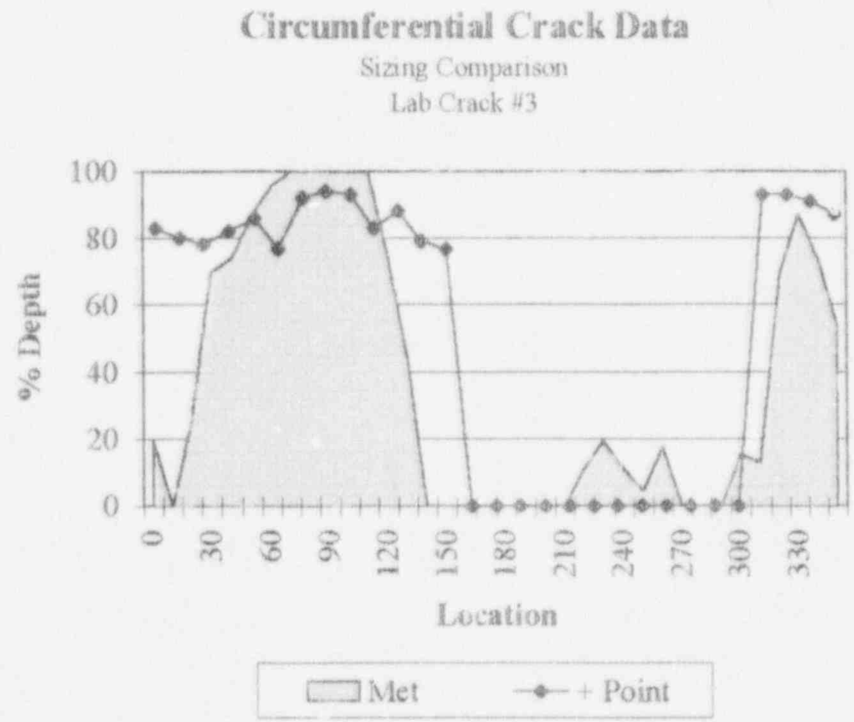

Figure B-3
Lab Crack #3 - Comparison of Met and + Point Data

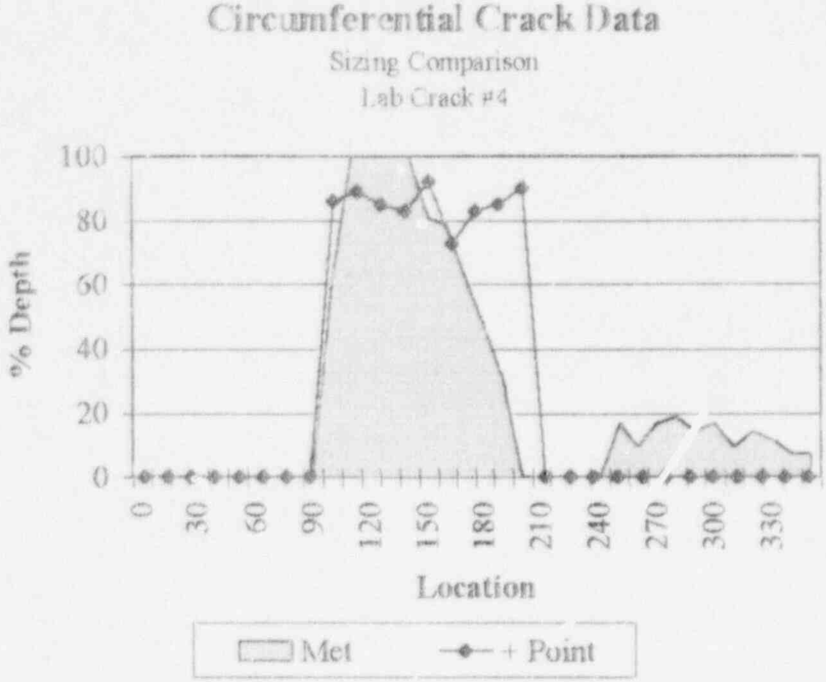

Figure B-4
Lab Crack #4 - Comparison of Met and + Point Data

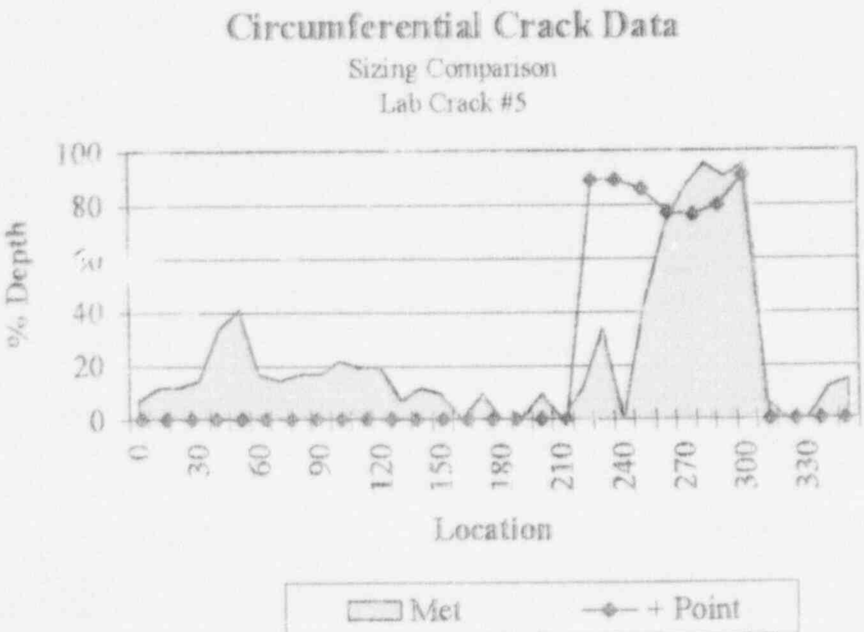

Figure B-5
Lab Crack #5 - Comparison of Met and + Point Data

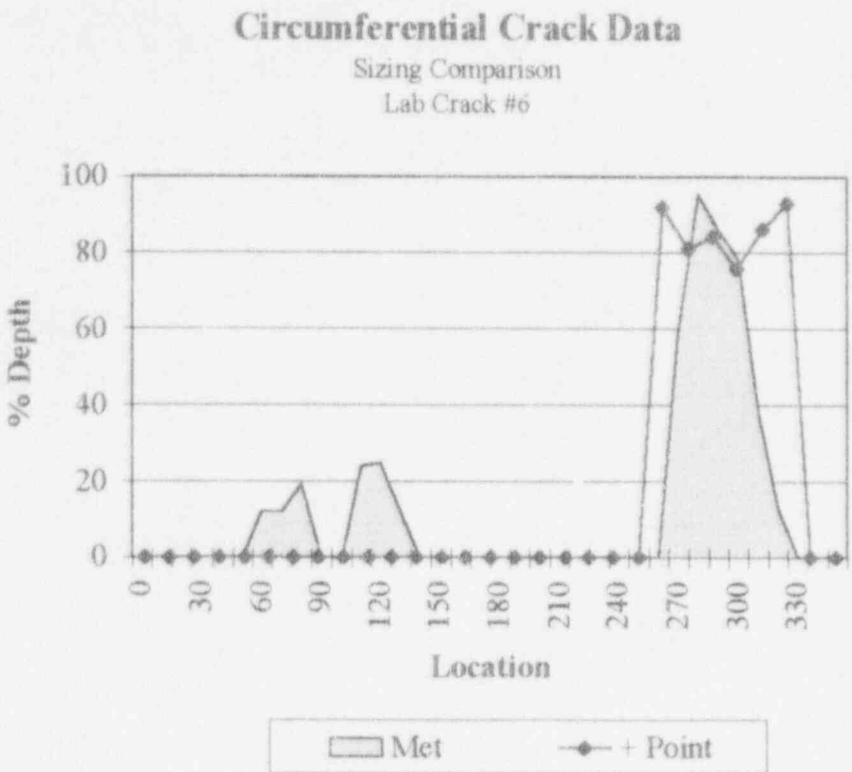

Figure B-6
Lab Crack #6 - Comparison of Met and + Point Data

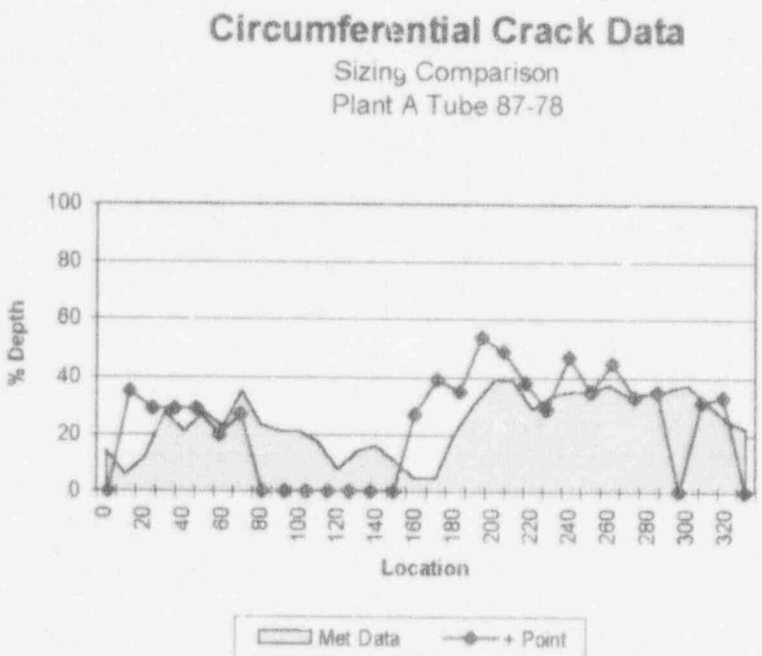

Figure B-7
Plant A Pulled Tube 87-78 - Comparison of Met and + Point Data