APTECH IS APPLIED TECHNOLOGY ®

AES98033350-1-1
April, 1998
Revision 0

AN OPERATIONAL ASSESSMENT OF STEAM GENERATOR TUBE DEGRADATION AT CRYSTAL RIVER UNIT 3

Prepared by

J. A. Begley
M.G. Peck
T.F. Begley

Aptech Engineering Services, Inc.
Pittsburgh Office

Prepared for

Florida Power Corporation
Crystal River Energy Complex
1576 W. Power Line Street
Crystal River, FL 34428-6708

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Operational assessments of corrosion degradation of steam generator tubing at Crystal River Unit 3 are described in this report. Assessments of freespan axial ODSCC/IGA and axial PWSCC at roll expansion transitions in the upper tubesheet were conducted using a probabilistic approach and the probabilistic structural performance criteria of the draft NRC document DG-1074 on tube integrity. Volumetric intergranular attack, IGA, of a pit-like nature in the first span was evaluated according to the deterministic structural performance criteria of DG-1074. Projected leak rates at postulated steam line break conditions were considered as part of both the probabilistic and deterministic operational assessments.

Monte Carlo simulation models were used to project the progression of axial corrosion degradation at Crystal River Unit 3. Projected end of cycle numbers, depth and lengths of axial cracks allowable computation of the conditional probability of tube burst and upper bound leak rates at postulated steam line break (SLB) conditions. The probabilistic structural performance criteria of a maximum of 0.01 for the conditional probability of tube burst at SLB conditions for any one degradation mechanism and a total of less than 0.025 for all mechanisms is easily met for full cycle operation. Projected upper bound leak rates at postulated SLB conditions are minimal and do not challenge radiological dose limits.

With respect to volumetric IGA in the first tube span, worst case assumptions of initial depth and length, depth sizing error, tensile properties, growth rate, and a bounding burst pressure relationship show that deterministic structural performance criteria will be maintained and no contribution to leakage at postulated SLB conditions is expected.

SECTION 1

INTRODUCTION

Operational assessments of corrosion degradation of steam generator tubing at Crystal River Unit 3 are described in the following sections. Assessments of freespan axial ODSCC/IGA and axial PWSCC at roll expansion transitions in the upper tubesheet were conducted using a probabilistic approach and the probabilistic structural performance criteria of the draft NRC document DG – 1074 on tube integrity[1]. Volumetric intergranular attack, IGA, of a pit-like nature in the first span was evaluated according to the deterministic structural performance criteria of DG–1074. Projected leak rates at postulated steam line break conditions were considered as part of both the probabilistic and deterministic operational assessments.

At the last inspection, after 12.1 EFPY of operation, axial indications were found near roll expansion transitions in the upper tubesheet. These indications, interpreted as PWSCC, were found with the Plus Point eddy current probe. In the limiting steam generator, 51 indications were found in 49 tubes. This experience is consistent with that of other once through steam generator (OTSG) plants. Although the restraining presence of the tubesheet prevents an axial tube burst, both burst and leakage calculations ignored the effect of the tubesheet. This is grossly over conservative for burst but reasonable for leak rate calculations.

One freespan axial indication, interpreted as ODSCC/IGA, was found during the last bobbin probe inspection. The performance of other OTSG plants and the relative operating times indicate that onset of freespan axial corrosion degradation at Crystal River Unit 3 is a reasonable expectation[2]. A generic probabilistic analysis of this degradation mechanism was previously conducted for OTSG plants. The present analysis for freespan cracking represents an update and refinement of the generic analysis.

Volumetric IGA with a pit-like character has been present in the first span of Crystal River Unit 3 for a considerable period of time[3]. Growth of this degradation has been negligible for several cycles of operation. Depth sizing techniques have been developed and sizing uncertainties have been quantified. A 40% throughwall measured depth plugging criteria has been applied. A later section describes limiting dimensions required to maintain structural margins and leakage integrity. The results of a review of growth studies are presented. It is demonstrated that the 40% throughwall depth plugging criteria is conservative with respect to the deterministic structural performance criteria of maintaining a minimum burst pressure of at least 3 times the operating pressure differential.

The basic calculational technique employed for probabilistic analyses of freespan and roll transition axial cracking is one of simulating the processes of crack initiation, crack growth and detection via eddy current inspection using Monte Carlo methods4[4-8]. The Monte Carlo simulation model follows these processes over multiple cycles of operation. This allows benchmarking of the model by comparing calculated results for past inspections with actual observations. The simulation model tracks both detected and undetected populations of cracks and deals with actual crack sizes. When comparisons are made between calculated results and eddy current observations, an eddy current measurement error is applied to convert predicted real crack sizes to predicted eddy current observations.

Actual degradation conditions in terms of number of cracks, real crack depths, and lengths can be calculated for any selected time period. Hence, the conditional probability of burst at postulated steam line break conditions can be computed for the operating time of interest. The projected 95th percentile upper bound leak rate during such a postulated accident can be calculated from the simulated numbers and sizes of cracks for comparison with the site specific allowable value.

In the next section, a description of the methods of characterizing crack shapes and critical dimensions for axial cracking at both roll transition and freespan locations is presented. This is followed by explanations of burst pressure and leak rate calculations. Next, input to the Monte Carlo simulation program is defined, and the simulation steps are discussed. The conditional probability of burst and leak rate results for axial corrosion degradation at Crystal River Unit 3 is then presented. Finally a deterministic operational assessment for pit-like IGA in the first span is described and the contribution of this mechanism to leakage and conditional probability of tube burst is estimated.

SECTION 2

AXIAL CRACK STRUCTURAL INTEGRITY AND LEAK RATE MODELS

Burst strength and leak rate calculations for tubes exhibiting axial corrosion degradation are based upon idealized crack profiles. Axial degradation is modeled as planar cracking. The planar crack assumption is conservative for use in burst and leak rate calculations. The following paragraphs describe idealized morphologies for axial cracks and corresponding burst and leak rate equations.

2.1 Idealized Axial Crack Profiles

From the perspective of tube burst strength and leak rate calculations, each axial corrosion indication is idealized as a single planar crack. This is conservative in that the strengthening and leak limiting effects of ligaments between crack segments in physical crack arrays are neglected. In addition, the physical depth profile, which typically varies in a non-uniform fashion over the length of the crack, is modeled as a simplified ideal profile for burst and leak calculations.

Figure 2.1 illustrates the idealized crack profiles used for burst and leak calculations, compared to the corresponding physical depth profile as measured during a pulled-tube destructive examination. The idealized burst profile represents the portion of the physical profile that is structurally significant in computing burst pressure. The structurally significant dimensions are determined using the Structural Minimum Method[2-6], as follows. The physical profile is discretized over its length using a reasonable number of segments, typically between 20 and 50. For each contiguous portion of the crack (that is, for each potential structurally significant length segment), a corresponding depth is computed by equating the areas under the physical and ideal profiles. Each length and depth pair is then tested using the Framatome burst equation[9] (described below) to find the dimensions that minimize the computed burst pressure. The length and depth that minimize the burst pressure represent the structurally significant dimensions, and hence define the idealized burst profile. It is essential to note that historical measurements have shown that structurally significant length of a crack to be reasonably estimated by the portion of a physical crack length detected by a rotating pancake coil eddy current probe[4]. The axial length detected by the Plus Point eddy current probe is a conservative estimate of the actual structurally significant crack length.

The idealized leak profile length is identical to the structurally significant length computed for the burst profile. The tent-shaped leak profile is then determined by equating the maximum depth penetration for both physical and ideal profiles, and by again balancing the areas under the respective profiles over the structural length. The profile form factor, F, is defined to be the ratio of the maximum depth, d_{max}, to the structurally significant depth, d_{st}. The distribution characteristics of this form factor are based on pulled tube destruction examination data[2]. See Figure 2.2.

Crack growth over time is assumed to occur primarily in the depth direction. The structural length for both burst and leak profiles is considered to be constant in time. Compared to previous calculations, an element of conservatism has been added to the leak rate model. In contrast to the earlier leak model, the form factor is assumed to remain constant only until wall penetration occurs. Then, as the crack propagates througnwall, as shown in Figure 2.3, the inclined sides of the crack rotate outward until a limiting throughwall length equal to the structural length is reached. The incremental area of crack advance per unit time created by the rotating crack sides is equal to the specified average depth crack growth rate. The length of the throughwall segment, L_{leak}, is then defined by the geometry of the idealized profile to be:

$$L_{leak} = L_{st} \frac{d_{st} - \frac{t}{F}}{t - \frac{t}{F}}$$

2.2 Axial Crack Burst Pressure Calculation

Given the structurally significant length and depth dimensions, the burst pressure for an axially degraded tube is computed via the Framatome (Cochet et. al.) partial throughwall burst equation:

$$P = \frac{0.58St}{R_i}\left[1 - \frac{Ld\ /t}{L\ + 2t}\right],$$

where P is the estimated burst pressure, S the sum of the yield and ultimate tensile strength of the tube material, t the tube thickness, R_i the inner radius of the tube, L the characteristic degradation length, and d the characteristic degradation depth. The Framatome equation, when used with the structurally significant dimensions (L_{st} and d_{st}), produces consistently conservative burst pressure estimates compared to measured burst data, as shown in Figure 2.4. It is an excellent lower bound to an extensive set of pulled tube burst test data.

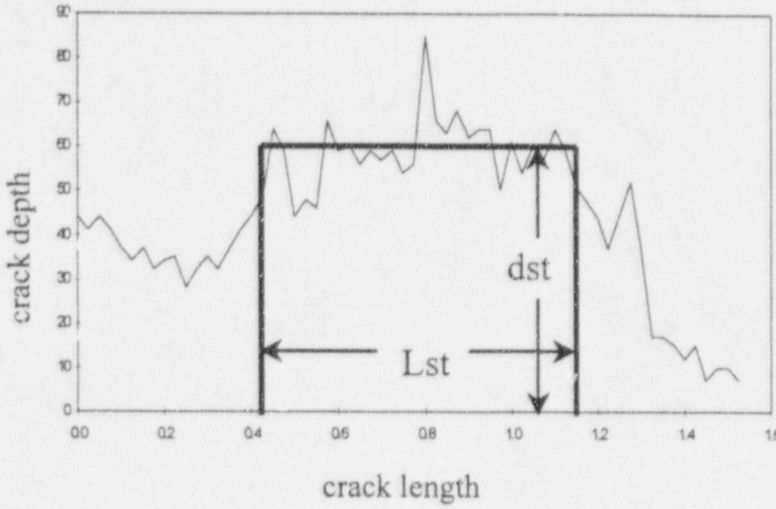
2.3 Axial Crack Leak Rate Calculation

As described in Reference 10, Version 3.0 of the PICEP two-phase flow algorithm was used to compute flow rates through cracks as a function of pressure differential (p), temperature (T), crack opening area (A), and total throughwall crack length (L). Friction effects and crack surface roughness were included in the model. Steam line break, room temperature, and normal operating condition leak rates calculated by PICEP were fitted to regression equations. The PICEP-based leak rate regression equation for steam line break conditions is given as:

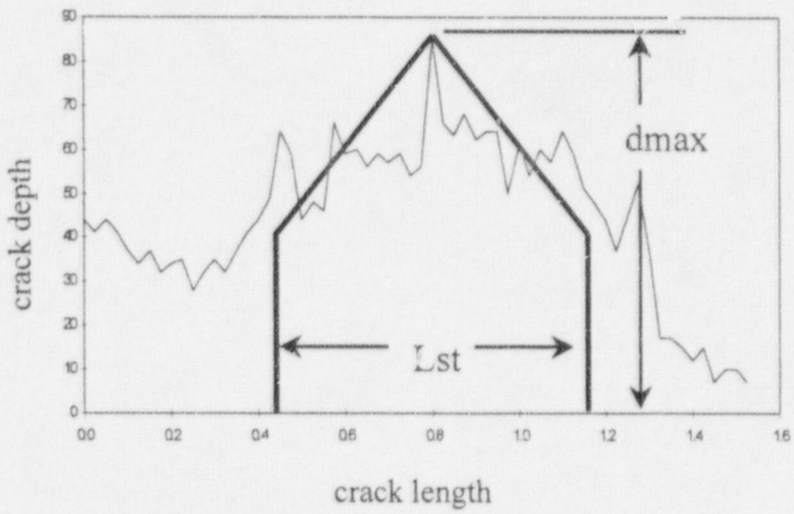
$$Q = \{a + b \exp [c (A/L)^{0.451} + d (A/L)] \} A p^{1.333},$$

where *a-d* are regression coefficients as determined by an analysis of PICEP results. The leak rate Q is expressed in terms of gallons per minute at room temperature (70°F). To convert to gallons per minute at any other temperature, the calculated Q is multiplied by the ratio of the specific volume of water at temperature (T) to the specific volume of water at 70°F. The pressure, p, is in units of psi, A is in inches^2 and L (equivalently L_{leak} as defined above) is in inches. The crack opening area is calculated using a twice-iterative plastic zone correction to adjust the linear elastic solution for plasticity effects. Further details of the PICEP regression equations and the crack opening area derivation can be found in References 11 and 12.

A check of the validity of the leak rate equations is provided by a comparison of calculated leak rates versus measured leak rates listed in Reference 12. Measured leak rates at typical normal operating steam generator conditions are available for axial fatigue cracks in steam generator tubing and axial stress corrosion cracks in steam generator tubing. Leak rates through stress corrosion cracks are less than those through fatigue cracks of the same length because of the more torturous cracking in stress corrosion samples. A good conservative leak rate calculation methodology is considered to be one which is a closer match to leak rate results from fatigue cracks rather than stress corrosion cracks. Figure 2.5 shows that this criteria is met by the chosen methodology. Calculated leak rates, illustrated by the dotted lines, serve as a good bound to data from stress corrosion cracked samples of the same tubing dimensions. The calculated leak rates are just below the measured data for fatigue cracked samples.



(a)



(b)

Figure 2.1 Idealized Crack Profiles for (a) Burst and (b) Leakage.

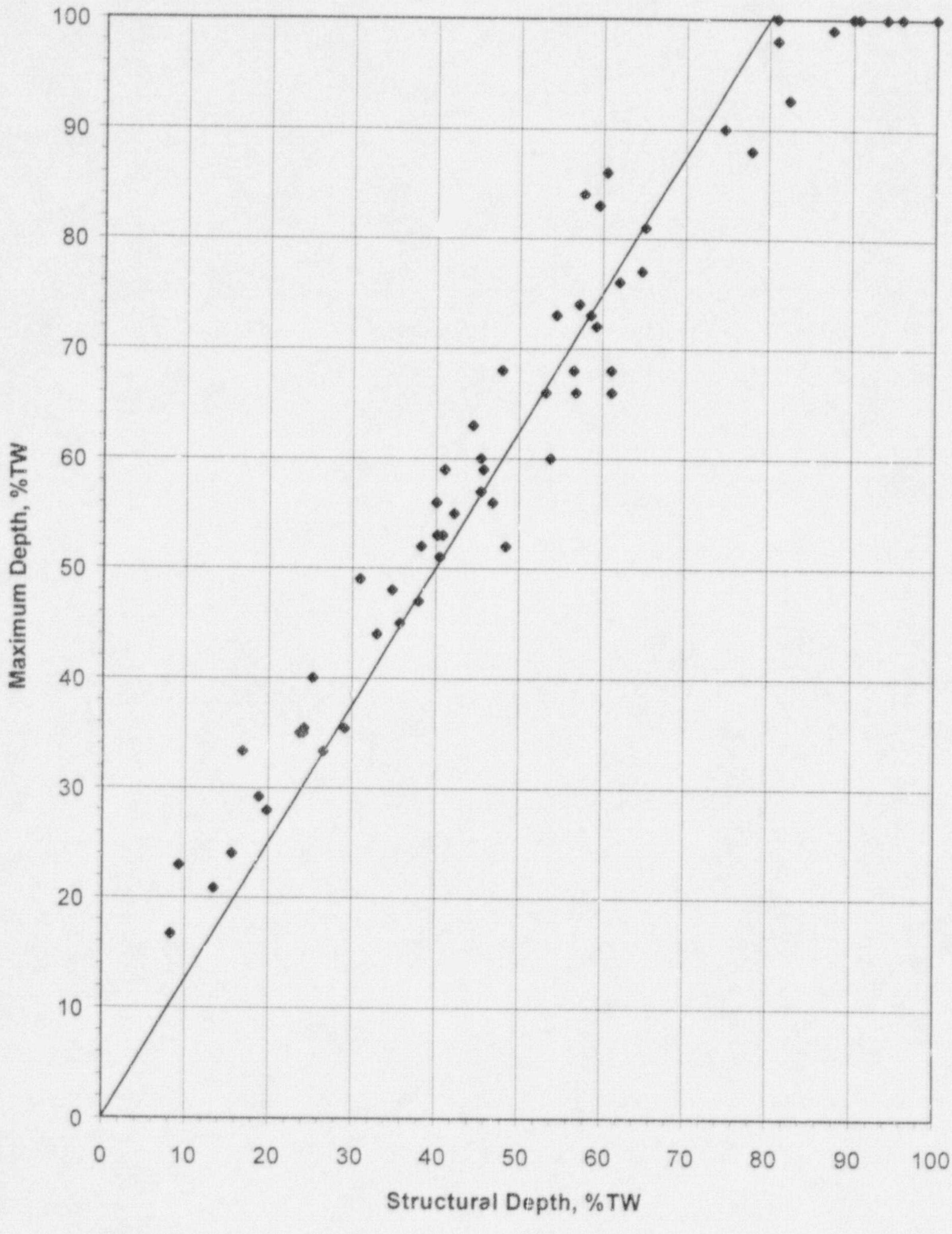


Figure 2.2 Maximum Depth Versus Structurally Significant Depth, Pulled Tube Data.

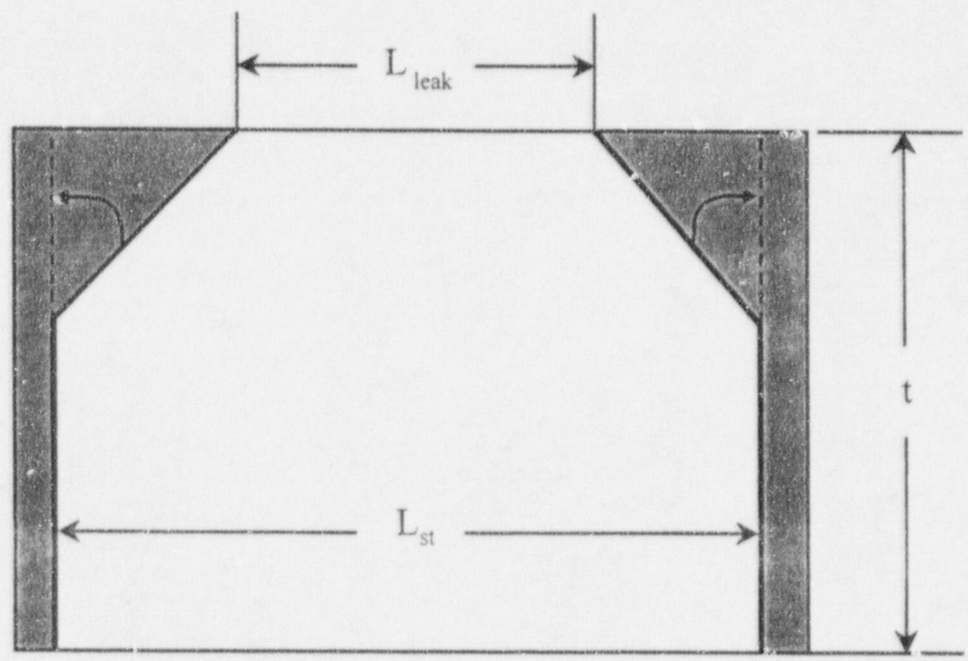


Figure 2.3 Idealized Leakage Crack Profile After Throughwall Penetration.

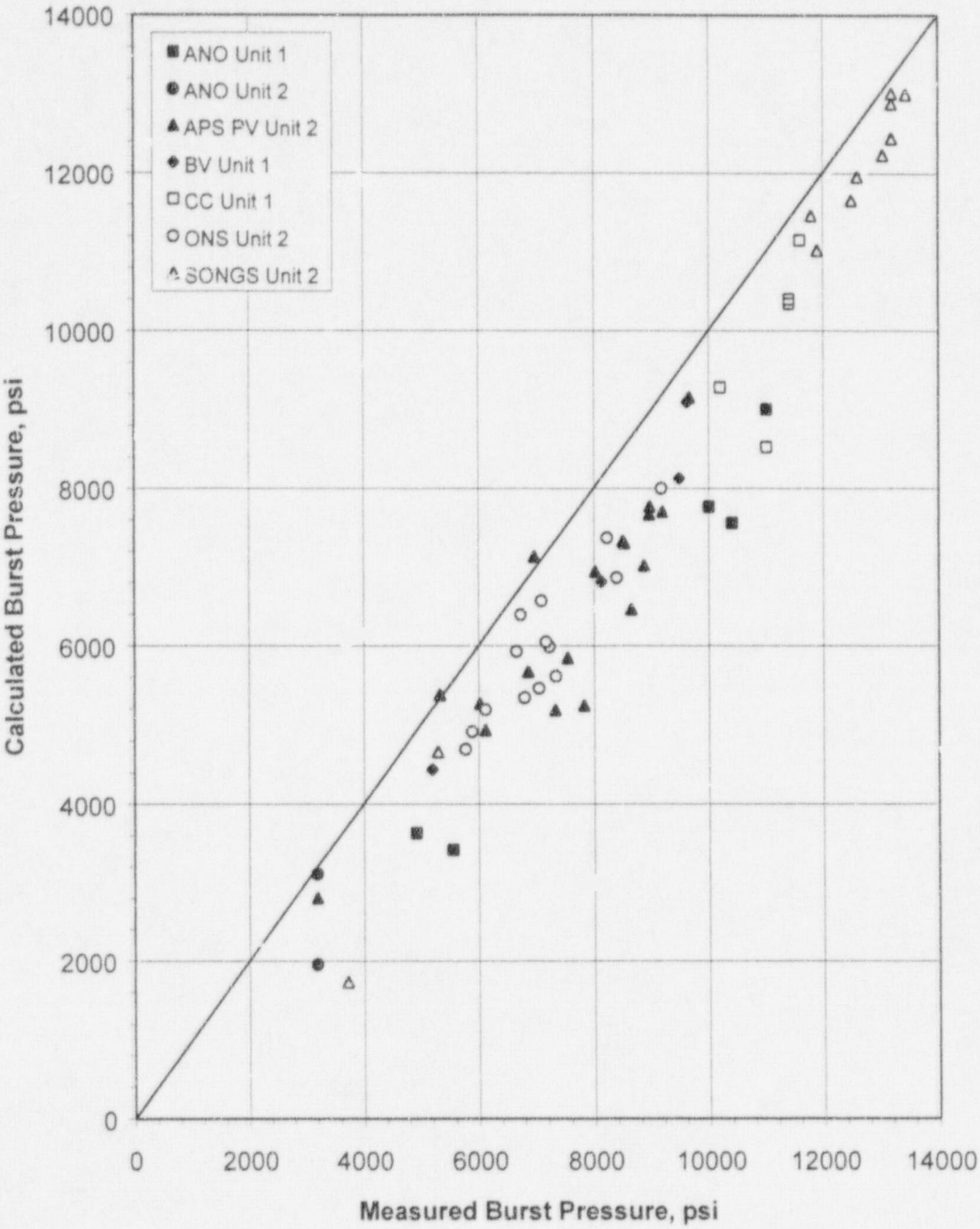


Figure 2.4 Calculated Versus Measured Burst Pressure Using the Structural Minimum Method and the Framatome Burst Equation.

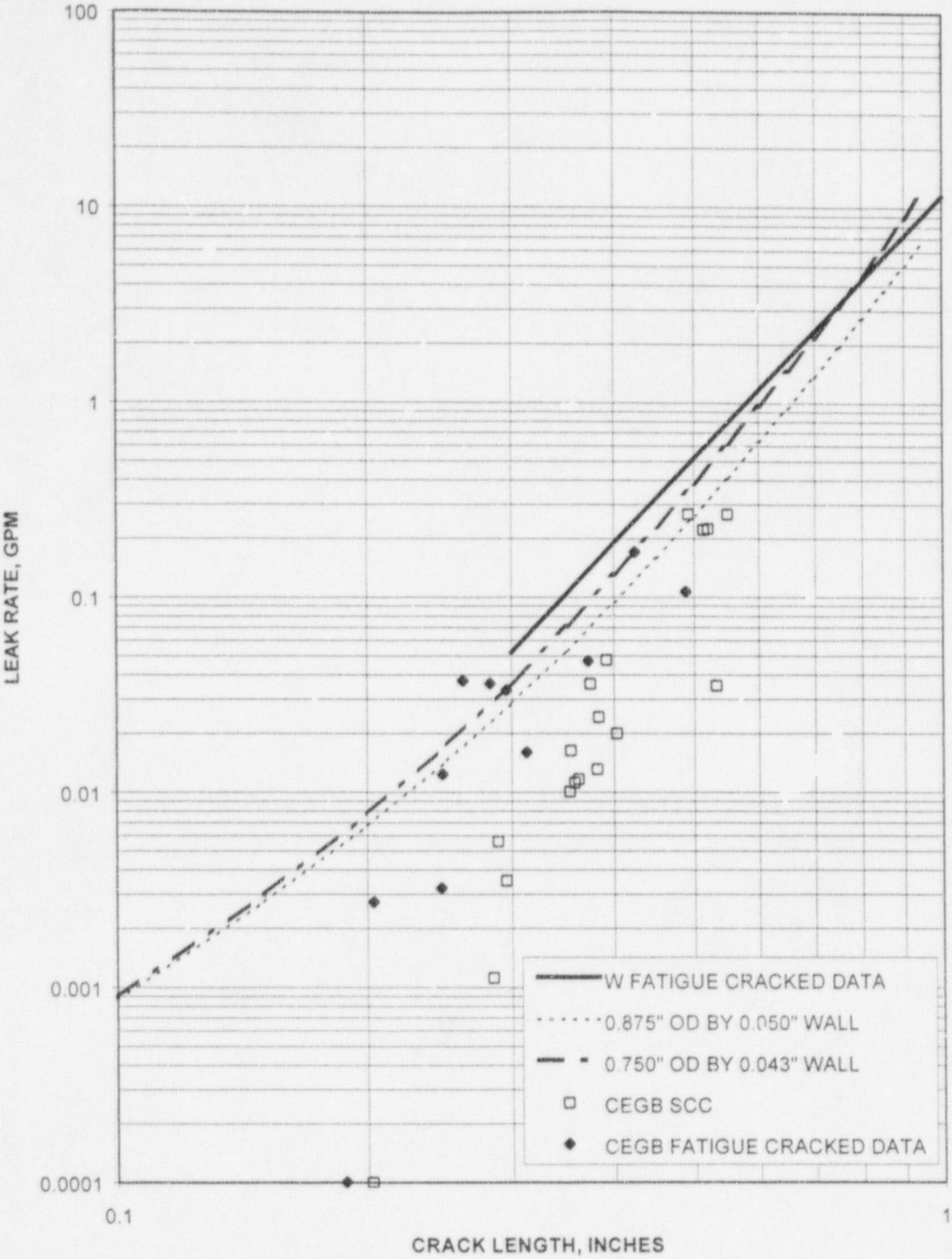


Figure 2.5 Calculated and Measured Leak Rates for Axial Cracks in Alloy 600 Tubing at Normal Operating Conditions.

SECTION 3

PROBABILISTIC ANALYSIS INPUT PARAMETERS

A number of input parameters are needed for the Monte Carlo simulation model. A range of material properties is considered rather than a lower bound strength value. Hence the distribution of tensile properties of the steam generator tubing is needed. The distribution of structurally significant axial crack lengths is equated to the distribution of measured lengths as found by the RPC eddy current probe. Thus a sampling distribution of axial crack lengths is needed. The simulation model conducts virtual inspections. This requires knowledge of the probability of detection of degradation as a function of degradation severity for the various eddy current probes that are used. Since degradation growth is simulated, distributions of crack growth rates for both freespan and roll transition axial degradation are required.

3.1 Tubing Mechanical Properties

Figure 3.1 shows the distribution of strength values used in the analysis. The distribution of the sum of yield and ultimate tensile strengths at elevated temperature is plotted. The distribution is normal with a mean value of 138.7 ksi with a standard deviation of 7.24 ksi. The distribution is truncated at a lower value of 115 ksi and an upper value of 162 ksi. This is the distribution of strength values used in the OTSG generic analysis of freespan axial cracking[2].

3.2 Degradation Length Distribution

During the most recent eddy current inspection at Crystal River Unit 3, crack length measurements were recorded for axial degradation at upper tubesheet roll transition locations. Since a Plus Point probe was used, the measured length distributions are considered to be conservative relative to actual structurally significant crack lengths. A site specific freespan axial crack length distribution obviously could not be determined for Crystal River since only one indication was detected. Therefore, the freespan axial crack length sampling distribution was obtained from data from a plant of the same design. Measured crack length distributions and fitted log normal distributions to these datasets are shown in Figure 3.2. Note the larger percentage of long crack lengths in the freespan distributions. This is commonly observed in plants of other designs.

3.3 Detection Capabilities of Eddy Current Probes

In the computer simulations, a probability of detection (POD) function is used to model the detection capability of an eddy current probe. Because the effectiveness of the eddy current probe dictates the percentage of cracks that are able to grow deep enough to threaten the structural integrity of the steam generator, it is important to employ a POD function that accurately reflects actual inspection practices.

Several types of eddy current probes have been used at Crystal River Unit 3 depending on the type and location of degradation. Axial degradation at the upper tubesheet location was detected in the last inspection with a rotating probe. Although pancake coils were included, the primary probe used for detection was the Plus Point probe. A Plus Point POD curve for axial degradation has been developed from pulled tube data. It is considered to be applicable for the present case of axial degradation near roll transitions even though it is based on data for thicker walled tubing.

Freespan inspections utilized the bobbin probe. A B&W Owners Group program focussed on a thorough evaluation of the detection properties of the bobbin probe for various types of degradation in OTSG tubing[14]. A supplemental performance demonstration format was followed using field eddy current data and pulled tube destructive examination results. The bobbin probe POD curve used in this analysis for freespan axial cracking was developed from this BWOG program data. Plus Point and bobbin probe POD curves are shown in Figure 3.3.

3.4 Degradation Growth Rates

During the simulation process, crack growth rates are sampled from a distribution of crack growth rates. Different crack growth rate distributions were used for axial degradation depending on location. A large set of growth rate data for axial freespan ODSCC/IGA was evaluated as part of a BWOG project dealing with a generic operational assessment of freespan axial degradation in OTSG tubing. Depth sizing uncertainties and probability of detection effects were considered as described in Reference 3. The best estimate crack growth rate distribution is a log normal distribution of crack growth rates with an average growth rate of 3.6%TW/EFPY with a standard deviation of 0.65. Crack growth rates are resampled after each inspection simulating the effect of changing chemistry conditions in local regions due to shutdown and startup transients. Twenty percent of the time a zero growth rate is selected.

For axial cracking at roll transitions the selected growth rate distribution is an essentially bounding distribution developed from a large number of evaluations of axial growth rate data. This dataset of growth rate distributions is comprised of all the probabilistic analyses of axial cracking conducted by APTECH over the past several years[2,4,8,15]. Again a log normal distribution was used. The average growth rate is 7%TW/EFPY. Actually the average natural logarithm of the growth rate is 1.95. The standard deviation of the natural logarithms of the growth rates is 0.65. The cumulative distributions of both the freespan and roll transition axial crack growth rate distributions are plotted in Figure 3.4.

Note that growth rates are based on change in average crack depth rather than maximum depth. The average depth growth rate is used in the simulation model. For any particular crack, maximum depths are calculated based on a known distribution of ratios of maximum depth to structural (average) depth.

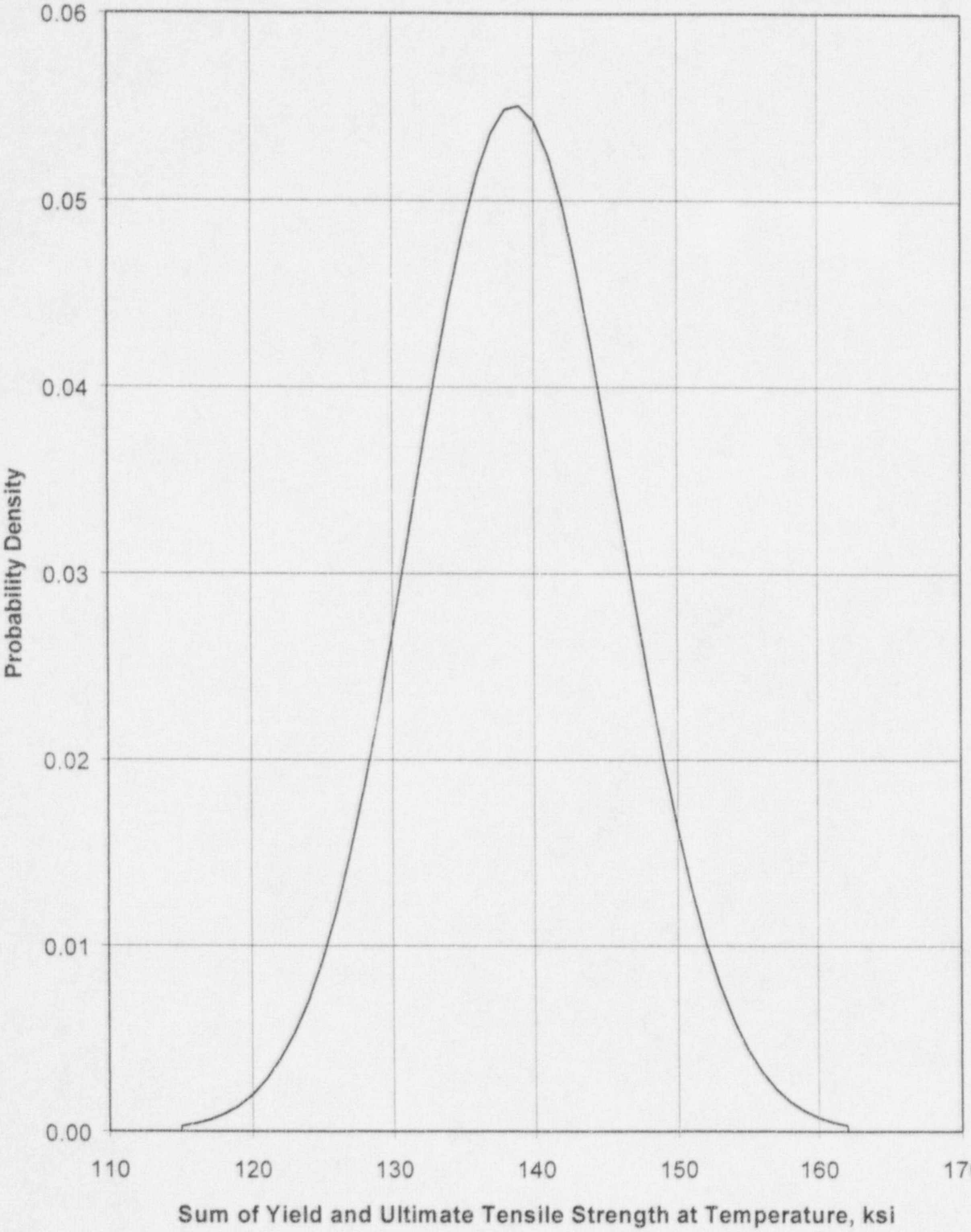


Figure 3.1 Distribution of Tubing Strength Properties Used in Probabilistic Calculations.

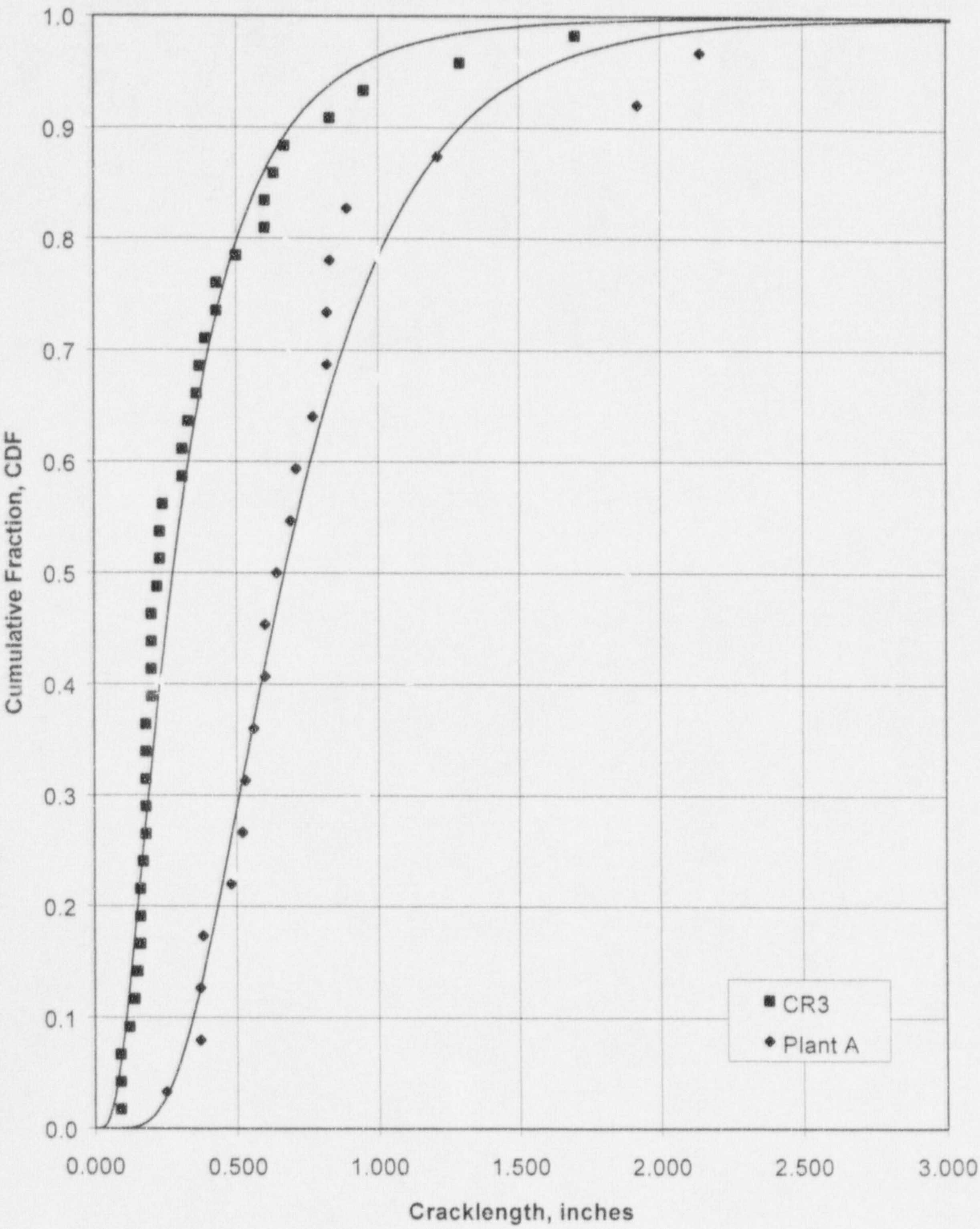


Figure 3.2 Axial Crack Length Distributions Used in Probabilistic Calculations.

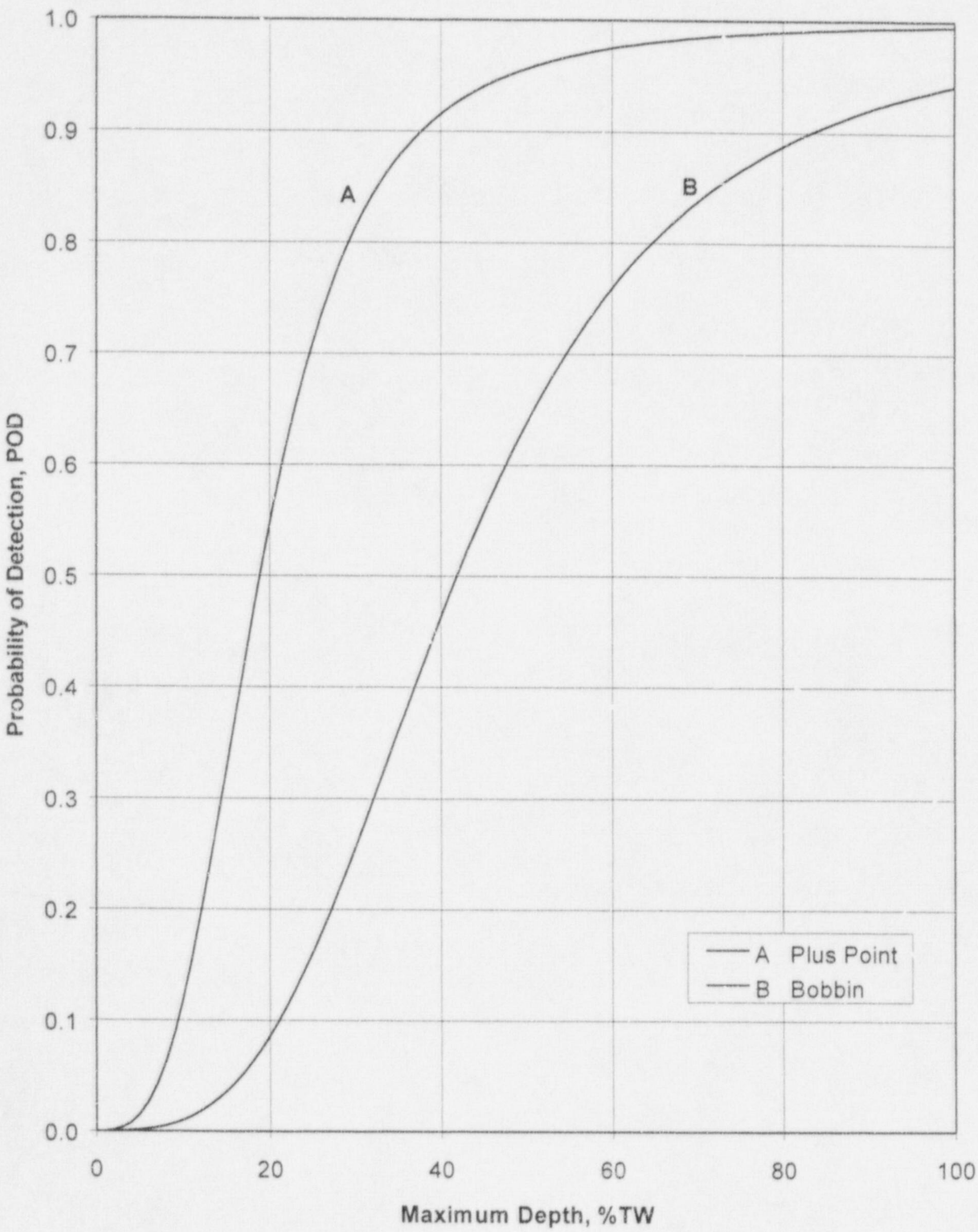


Figure 3.3 Probability of Detection Versus Maximum Axial Crack Depth, Plus Point and Bobbin Probes.

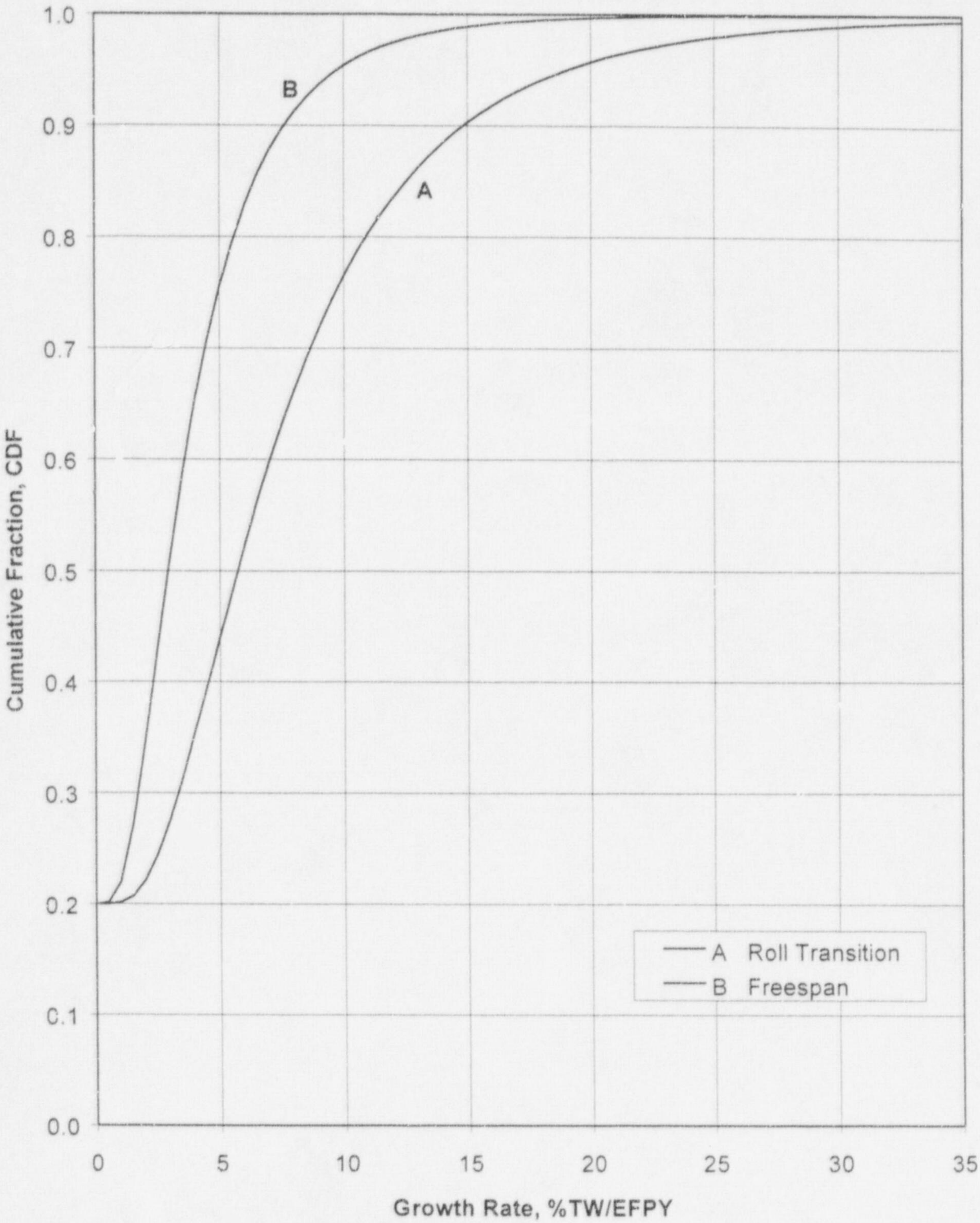


Figure 3.4 Axial Crack Growth Rate Distributions Used in Probabilistic Calculations.

SECTION 4

PROBABILISTIC MODEL DESCRIPTION

The probabilistic run-time model projects the processes that have contributed to tube degradation over the history of a steam generator in order to assess the structural condition of the generator at a future inspection. Specifically, Monte Carlo simulation of the processes of crack initiation, crack growth, eddy current inspection, and removal or repair of degraded tubes provides information necessary to estimate the probability of tube burst and the magnitude of leakage at the next scheduled inspection, given a postulated steam line break event.

The state of degradation of the steam generator tubing is simulated by a defect population that is defined by several parameters. These are: the size of the population at risk, the initiation function that describes crack inception, the distributions of the defect geometries, and the growth rate distribution that determines the change in crack depth over time.

The population at risk, in combination with the initiation function, determines the total number of defects simulated in the analysis. The choice of population size primarily influences the computational time and memory requirements of the simulation. In cases where the choice of population at risk is not obvious from physical considerations, care must be taken to avoid an unreasonably low value that can prematurely exhaust the initiated defect population. For degradation near expansion transitions the obvious population at risk is the number of tubes in the bundle. For cracking at freespan locations, some multiple of the number of tubes in the bundle is appropriate. If the total population of degraded sites is small compared to the total number of sites at risk, then the choice of the number of sites at risk is not of concern other than perhaps creating unwarranted memory requirements.

The initiation function for defects is based on a modified Weibull function, which requires a scale parameter and a slope parameter. The scale parameter reflects the length of time required to initiate a given percentage of all potential crack sites. This parameter may be on the order of several decades. The slope parameter is a measure of the rate of increase in initiated defects over time. The scale and slope parameters are adjusted iteratively until the number of indications produced by the simulation matches the actual number of flaws detected at recent plant inspections. Having matched the number in indications observed at recent inspections, other key benchmarking items include: predicting the measured severity of degradation, confirming notable in situ test results, and reproducing observed inspection transients.

The present study considers past inspections for which eddy current inspection results are available. Since axial cracking at roll transition and freespan locations was only detected in the last inspection, the parameters of the Weibull initiation function were set by; (1) assuming a Weibull slope of 6 and (2) adjusting the scale factor until the predicted number of indications matched the results of the last inspection. A Weibull slope value of 6 is a good conservative estimate of the rate of increase of initiated cracks. This is supported by extensive studies of degradation progression rates in steam generator tubing[16].

A probabilistic analysis of degradation within a steam generator includes many thousands of simulations that track the condition of the steam generator through several past inspection periods to develop benchmark statistics. The model then projects the degradation mechanism through the current operating cycle in order to predict the structural condition of the generator as a function of cycle duration.

Each mock operating cycle and inspection event within a single steam generator simulation consists of several steps that trace the initiation and development of individual cracks. For each potential crack site, a crack initiation time is drawn at random from a cumulative initiation function. A certain percentage of the crack sites will have initiated during or prior to the operating cycle of interest.

For each initiated crack, a set of descriptive parameters is drawn at random from appropriate distributions to describe the crack in detail. These parameters include the crack length, the crack form factor, and the strength properties of the tube in which the crack resides. The crack retains these particular features throughout its entire life. A growth rate is then sampled from the growth rate distribution. The growth rate is applied to the crack depth over the interval of time between inspections. The growth is assumed to be linear in time. A new growth rate is sampled after each simulated inspection and applied over the ensuing operating cycle, which accounts for potential changes in local growth environments due to start-up transients. The average depth of the crack increases with time, and the maximum depth is correspondingly adjusted according to the crack form factor.

Simulated inspections are performed according to the plant-specific inspection schedules. The crack depth at the end of a completed operating cycle, together with the POD curve, determine the probability that a particular crack will be detected during an inspection. A random number is drawn from a uniform distribution and compared to the POD. If the random draw is less than the POD, the crack is detected and removed from service. Undetected cracks are left in service and allowed to grow throughout the following operating cycle, and the process is repeated at subsequent inspections.

All cracks, whether detected or undetected, are examined at the end-of-cycle inspections to assess the probability of tube burst and leakage under steam line break conditions. The algorithm records a burst if the accident pressure differential exceeds the burst pressure for a particular flawed tube. If the maximum crack depth exceeds the tube thickness, the flaw is considered to be leaking. A potentially high leak rate can result from a "pop-through" event, which occurs when the length of a particular defect is not sufficient to cause a full burst, but the average depth of the crack is such that the crack breaks throughwall over its entire structural length.

When all initiated cracks have been inspected over the course of prescribed past and future operating cycles, a single Monte Carlo trial of the steam generator is complete. Many thousands of such trials are necessary to generate the distributions of tube burst and leakage rates required in the structural margin assessments.

The output from the simulation algorithm consists of a record of all tubes that have burst during the simulation, and all defects that have penetrated throughwall and are assumed to be leaking. Other pertinent data such as the operating cycle during which the burst or leak event occurred, the tube material properties, flaw length, and form factor are also recorded.

For a given operating cycle of interest, the number of burst events are tallied and a 95% upper confidence bound for the probability of burst is computed using an appropriate F-distribution, as in Reference 16. For example, if 10,000 simulations of the steam generator produce 1 or more bursts in 30 of the trials, the 95% confidence probability of burst is calculated to be POB = 0.00407.

A leak rate is assigned to each throughwall defect according to the methods presented in Section 2. The total leak rate for each steam generator simulation is then computed, the simulation leak rates are sorted in ascending order, and the 95/95 probability/confidence leak rate is determined as described in Reference 16. For example, for 10,000 steam generator simulations, the 9537th highest computed leak rate represents the 95th percentile leak rate with 95% confidence.

SECTION 5

PROBABILISTIC STRUCTURAL MARGINS AND LEAK RATE EVALUATIONS

Monte Carlo simulation models were used to project the progression of axial corrosion degradation at Crystal River Unit 3. Probabilistic analyses were conducted for axial degradation at both freespan and upper tubesheet roll transition locations. These locations are considered separate degradation mechanisms. The severity of degradation was projected for a total of 1.8 EFPY after the last inspection. Assuming a worst case end of cycle degradation severity, the conditional probability of tube burst at postulated steam line break conditions was calculated for each mechanism. Also, the contribution of corrosion related, accident induced leakage was evaluated.

Table 1 lists the inspection schedules, probe types, number of indications found and number of indications projected for the two axial degradation mechanisms in a composite worst case generator. It is apparent that axial freespan cracking is in its earliest stages. Projections regarding the number of cracks expected at the next inspection are therefore uncertain for this case. But even an increase from 3 to 30 does not have a substantial impact on the calculated conditional probability of tube burst. The large number of indications at roll transitions leads to more confidence in correctly predicting the number of indications expected at the next inspection. The prediction of 99 has an associated standard deviation of 10. These projections are conservative in the sense that the run time before the next inspection is expected to be less than 1.8 EFPY.

The results of probabilistic analyses for axial degradation of steam generator at Crystal River Unit 3 are summarized in Table 5.2. The conditional probability of tube burst at postulated steam line break conditions is seen to be quite low for freespan axial ODSCC/IGA being 0.0012. The probability of any leakage at SLB conditions from this mechanism is 0.0026. Hence the 95/95 upper bound SLB leak rate is zero. As an operational rather than a safety concern, there is a very small probability, 0.0008 of leakage exceeding a value of 50 gpd at normal operating conditions.

The conditional probability of tube burst at postulated SLB conditions due to axial cracking at roll transitions is calculated as 0.0074. This is a misnomer since the restraining effect of the tubesheet is ignored. An axial burst is not possible. However, projected leak rates are of interest. The probability of any leakage at SLB conditions is 0.15. However, the 95/95 upper bound projected SLB leak rate is 0.001 gpm. This is well inside the 1.0 gpm limit discussed in DG-1074. The probability of observing a leak rate greater than 50 gpd at normal operating conditions is reasonably low at 0.012.

The probabilistic structural performance criteria of a maximum of 0.01 for the conditional probability of tube burst at SLB conditions for any one degradation mechanism and a total of less than 0.025 for all mechanisms is easily met, even for a conservative operating period of 1.8 EFPY beyond the last inspection. Projected upper bound leak rates at postulated SLB conditions are minimal and do not challenge radiological dose limits.

TABLE 5.1

INSPECTION SCHEDULES, PROBE TYPES, RESULTS AND PROJECTIONS FOR AXIAL DEGRADATION

TIME (EFPY)	EDDY CURRENT PROBE	FRACTION OF BUNDLE INSPECTION	INDICATIONS FOUND	INDICATIONS PROJECTED
Upper Tubesheet Axial Cracking Near Roll Transitions				
8.7	Bobbin	0.54	0	0
10.2	Bobbin	0.25	0	1
11.9	Bobbin	0.21	0	4
12.1	Plus Point	1.00	51	51
13.9	Plus Point	1.00	--	99
Axial Freespan ODSCC/IGA				
8.7	Bobbin	0.54	0	0
10.2	Bobbin	0.25	0	0
11.9	Bobbin	0.21	0	1
12.1	Bobbin	1.00	1	1
13.9	Bobbin	1.00	-	3

TABLE 5.2

RESULTS OF PROBABILISTIC ANLAYSIS FOR 1.8 EFPY OPERATING TIME BEYOND LAST INSPECTION

DEGRADATION TYPE	CONDITIONAL PROBABILITY[a] OF BURST AT SLB	PROBABILITY OF LEAKAGE AT SLB	95/95 SLB PROJECTED LEAK RATE (GPM)[b]	PROBABILITY OF >50 GPD LEAKAGE AT NOP
Freespan Axial ODSCC/IGA	0.0012	0.0026	0.000	0.0008
Upper Tubesheet Axial Roll Transitions PWSCC	0.0074	0.153	0.001	0.012

(a) 95% confidence estimate

(b) Room temperature density, multiply by 1.47 for volumetric leak rate at temperature

SECTION 6

DETERMINISTIC OPERATIONAL ASSESSMENT FOR FIRST SPAN PIT-LIKE IGA

This section describes a deterministic operational assessment of tubing with volumetric IGA located in the first span above the lower tubesheet face. This degradation has a local, pit-like nature. As described in an earlier submittal to the NRC, a reliable depth sizing methodology has been developed based on pulled tube data from Crystal River[3]. First span, volumetric IGA in steam generator B is sized using this methodology and left in service if the measured depth is less than 40% throughwall. Steam generator B is the limiting case since a plug on detection scenario is followed for steam generator A.

There are three limiting cases of interest in terms of bounding the structural integrity of localized, volumetric IGA. The first is the lower bound, axial throughwall crack length which meets the deterministic structural performance criteria of a minimum burst strength of three times the operating pressure differential. In the present case the $3\Delta P$ value is 4050 psi. This length is 0.38 inches based on the industry standard EPRI equation[17] and 95/95 lower tolerance limit tensile properties.

The second limiting case of interest is the lower bound throughwall circumferential crack extent which will withstand the upper limit axial load of 1408 pounds caused by differential thermal expansion of tubing and the steam generator shell during postulated worst case accident conditions. Based on 95/95 lower tolerance tensile properties and a net section tensile plastic collapse criterion, the limiting circumferential throughwall crack size is 1.24 inches. This calculation uses a flow stress equal to the average of the yield and ultimate tensile strengths, which is supported by test data. A no net section yielding criterion based on ASME Code minimum yield strength leads to a limiting throughwall crack length of 0.48 inches. If a more realistic minimum yield strength is selected, the no yield throughwall circumferential crack length is 0.64 inches.

The third applicable limiting case is that of a partial throughwall axial crack. As noted in Section 2, the Framatome equation provides a good lower bound burst pressure estimate for this geometry. Figure 6.1 shows a plot of the combinations of axial crack length and crack depth which have a lower bound burst pressure of 4050 psi using 95/95 LTL tensile properties. The curve is conservative in that an axial crack could have a length of 0.38 inches and be 100% throughwall and still maintain a burst pressure of 4050 psi. At lengths less than 0.38 inches the curve of Figure 6.1 actually represents the depth required for crack popin without burst. In the present case of volumetric degradation, this curve can be interpreted as a conservative no SLB leakage condition.

By combining limiting cases, the limiting dimensions of volumetric degradation can be established. A maximum linear length, axial or circumferential, of 0.64 inches combined with a maximum depth of 66% throughwall will meet the required deterministic structural performance criteria and maintain leakage integrity at SLB conditions. The maximum linear extent of first span, volumetric IGA at the last inspection was 0.30 inches. Over 90% of the time this dimension is less than 0.20 inches. At a length of 0.3 inches, the allowable depth at end of cycle increases to 74% throughwall.

An extensive growth rate study of volumetric IGA at Crystal River has been documented[3]. Figure 6.2 shows the cumulative distribution of measured changes in crack depth over two time periods, the 1996 to 1997 inspections and the 1992 to 1997 inspections. The first time period amounts to 0.2 EFPY and the second time period is 2.7 EFPY. The average change in depth is essentially zero and no significant difference is noted between two time periods which differ by a factor of 10. The apparent depth changes are basically due to measurement error. Based on limited pulled tube data, the standard deviation of depth measurement error is about 9.8%TW. The data of Figure 6.2 is actually consistent with negligible growth and a measurement error of about 6.4% TW.

Assuming the worst case length observed in the last inspection, a starting IGA depth of 39% TW and a 95th percentile depth measurement error of 16% TW leads to an allowance for growth over one cycle of 19% TW. The data of Figure 6.2 shows that any growth is minimal. Worst case assumptions of initial depth and length, depth sizing error, tensile properties, growth rate, and a bounding burst pressure relationship show that deterministic structural performance criteria will be maintained and no contribution to leakage at postulated SLB conditions is expected. Structural and leakage integrity margins are very large and contributions to conditional probability of tube burst and leak rates at SLB conditions are a small fraction of values calculated for other degradation mechanisms.

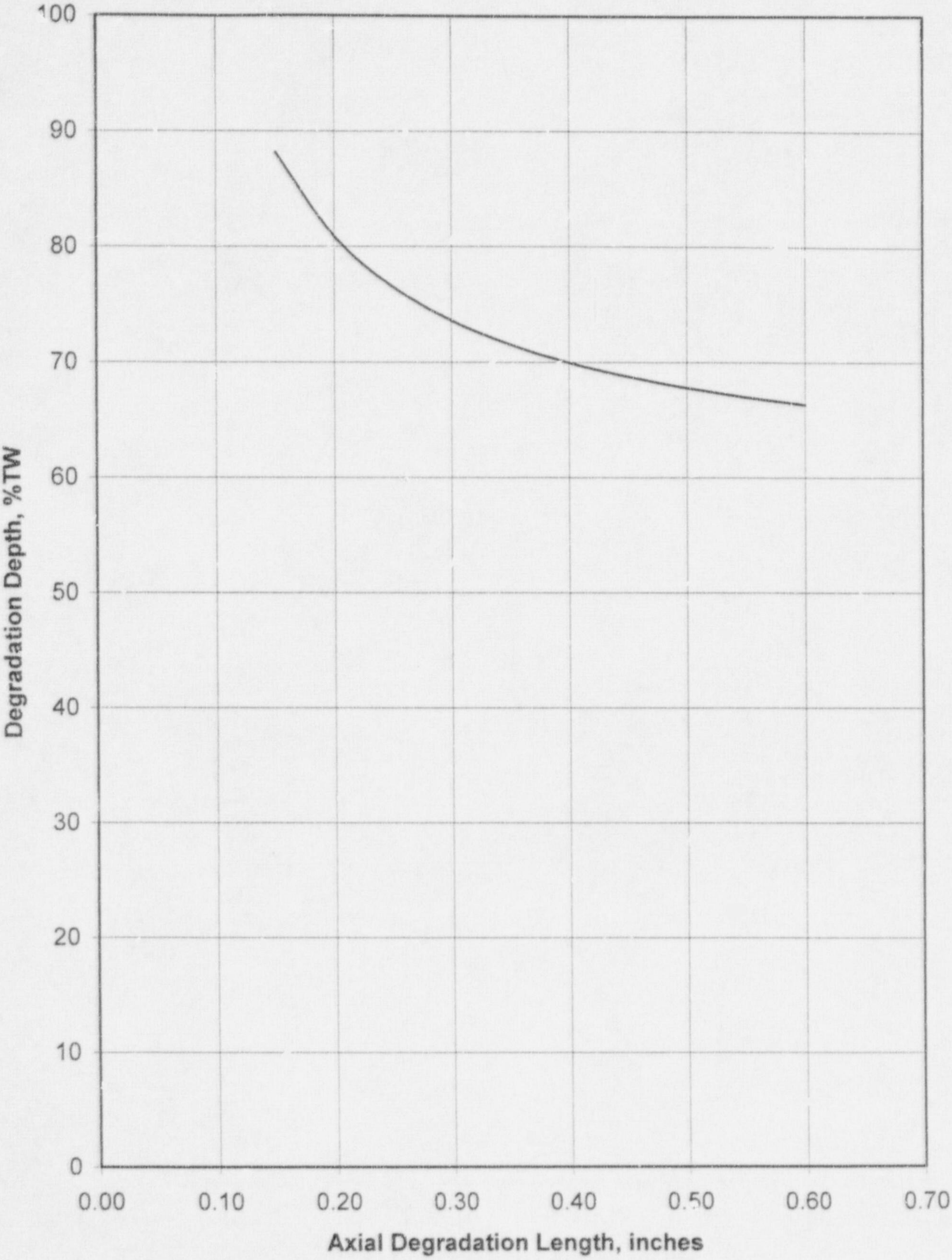


Figure 6.1 Limiting Depths and Extents of Volumetric IGA Which Meet Deterministic Structural Performance Criteria.

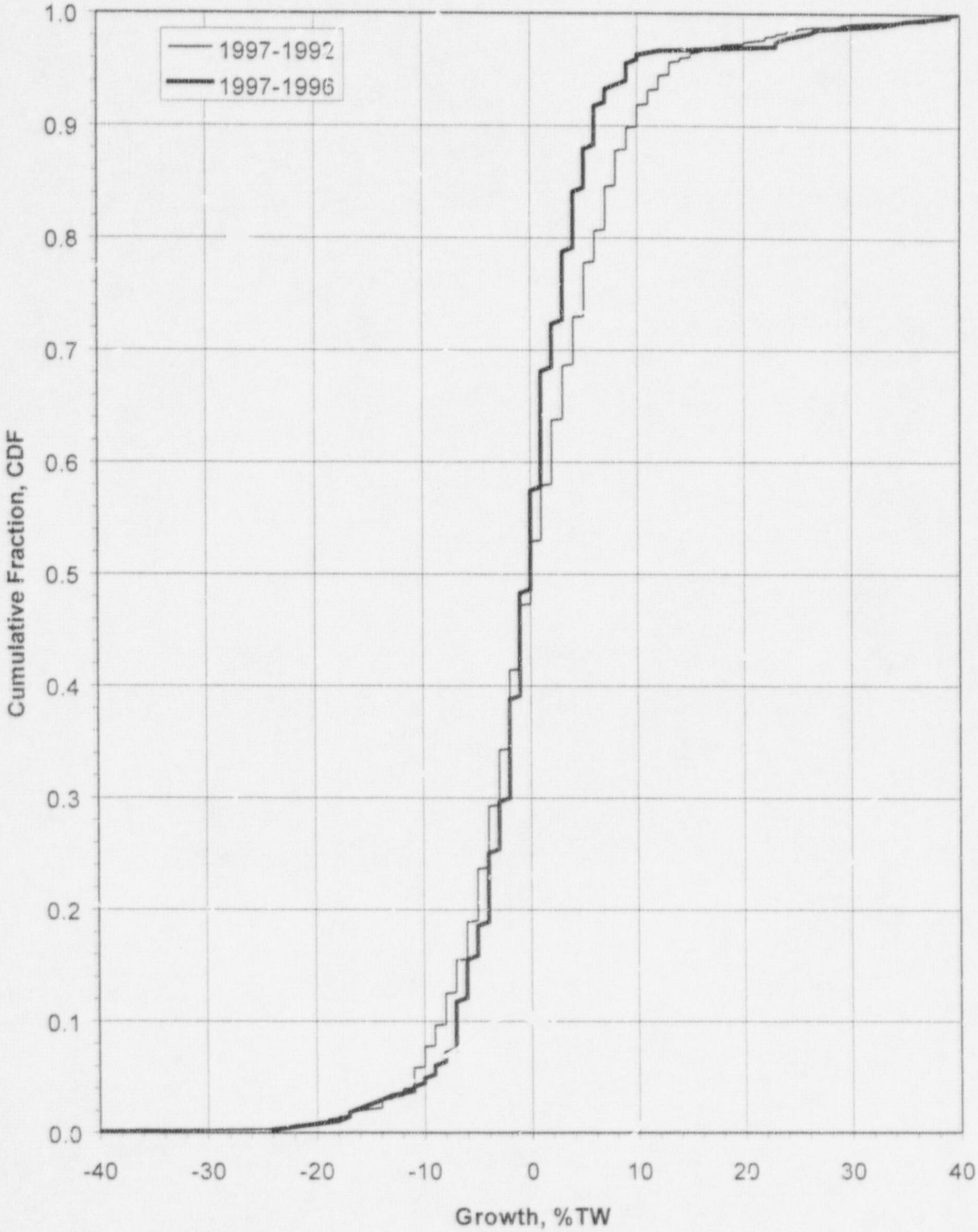


Figure 6.2 Distribution of Apparent Growth of First Span Volumetric IGA, Steam Generator B at Crystal River Unit 3.

SECTION 7

SUMMARY AND CONCLUSIONS

Operational assessments of corrosion degradation of steam generator tubing at Crystal River Unit 3 have been performed. Assessments of freespan axial ODSCC/IGA and axial PWSCC at roll expansion transitions in the upper tubesheet were conducted using a probabilistic approach and the probabilistic structural performance criteria of the draft NRC document DG −1074 on tube integrity. Volumetric intergranular attack, IGA, of a pit-like nature in the first tube span was evaluated according to the deterministic structural performance criteria of DG−1074. Projected leak rates at postulated steam line break conditions were considered as part of both the probabilistic and deterministic operational assessments.

At the last inspection, after 12.1 EFPY of operation, axial indications were found near roll expansion transitions in the upper tubesheet. In the limiting steam generator, 51 indications were found in 49 tubes through use of the Plus Point eddy current probe. This experience is consistent with that of other OTSG plants. Although the restraining presence of the tubesheet prevents an axial tube burst, both burst and leakage calculations ignored the effect of the tubesheet. This is grossly over conservative for burst but reasonable for leak rate calculations.

One freespan axial indication, interpreted as ODSCC/IGA, was found during the last bobbin probe inspection. The performance of other OTSG plants and the relative operating times indicate that onset of freespan axial corrosion degradation at Crystal River Unit 3 is a reasonable expectation. A generic probabilistic analysis of this degradation mechanism was previously conducted for OTSG plants. The present analysis for freespan cracking represents an update and refinement of the generic analysis.

Volumetric IGA with a pit-like character has been present in the first span of Crystal River Unit 3 for a considerable period of time[3]. Growth of this degradation has been negligible for several cycles of operation, as demonstrated by extensive growth studies. Depth sizing techniques have been developed and sizing uncertainties have been quantified. A 40% throughwall measured depth plugging criteria has been applied to the first span region of steam generator B.

The basic calculational technique employed for probabilistic analyses of freespan and roll transition axial cracking is one of simulating the processes of crack initiation, crack growth and detection via eddy current inspection using Monte Carlo methods[4-8]. The Monte Carlo simulation model follows these processes over multiple cycles of operation. End of cycle degradation severity in quantified in terms of number of cracks, depths, lengths and shapes. This information allows calculation of the conditional probability of tube burst and upper bound leak rates for postulated SLB conditions.

The calculated conditional probability of tube burst at postulated steam line break conditions is seen to be quite low for freespan axial ODSCC/IGA being 0.0012. The probability of any leakage at SLB conditions from this mechanism is 0.0026. Hence the 95/95 upper bound SLB leak rate is zero. The conditional probability of tube burst at postulated SLB conditions due to axial cracking at roll transitions is calculated as 0.0074. This is a misnomer since the restraining effect of the tubesheet is ignored. An axial burst is not possible. However, projected leak rates are of interest. The probability of any leakage at SLB conditions is 0.15. However, the 95/95 upper bound projected SLB leak rate is 0.001 gpm. This is well inside the 1.0 gpm limit discussed in DG-1074[1].

The probabilistic structural performance criteria of a maximum of 0.01 for the conditional probability of tube burst at SLB conditions for any one degradation mechanism and a total of less than 0.025 for all mechanisms is easily met, even for a conservative operating period of 1.6[illegible] Y beyond the last inspection. Projected upper bound leak rates at postulated SLB conditions are minimal and do not challenge radiological dose limits.

With respect to volumetric IGA in the first tube span, worst case assumptions of initial depth and length, depth sizing error, tensile properties, growth rate, and a bounding burst pressure relationship show that deterministic structural performance criteria will maintained and no contribution to leakage at postulated SLB conditions is expected. Structural and leakage integrity margins are very large and contributions to conditional probability of tube burst and leak rates at SLB conditions are a small fraction of values calculated for other degradation mechanisms.

REFERENCES

1. Draft NRC Regulatory Guide DG-1074, Steam Generator Tube Integrity, September, 1997.

2. Begley, C.J., and Begley, J.A., "A Generic Probabilistic Analysis of the Effect of Axial Freespan Corrosion on the Structural Performance and Leak Rate Behavior of OTSG Tubing", APTECH Report, AES96102886-1Q-1, June 1997.

3. Rencheck, M.W., "Florida Power Corporation, Crystal River Unit 3, Docket No. 50-302, Special Report 97-05, December, 1997.

4. Sweeney, K., "Palo Verde Nuclear Generating Station Unit 2 Steam Generator Evaluation", Arizona Public Service Co. Report, August 1995.

5. Begley, J.A., "Analysis of ODSCC/IGA at Tubesheet and Tube Support Locations at St. Lucie Unit 1," APTECH Report AES 96052749-1-1, dated October 1996.

6. Begley, J.A., Woodman, B.W., "An Analysis of ODSCC/IGA at Eggcrate Support Locations at Arkansas Nuclear One (ANO) Unit 2, APTECH Report AES 95102556-1-1, dated March 1996.

7. "Palo Verde Nuclear Generating Station Unit 3 Cycle 6 Steam Generator Evaluation," Arizona Public Service Co., Submitted to the NRC, July 1996.

8. Woodman, B.W., Begley, J.A., "Palo Verde Unit 2 Run Time Analysis Regarding the Impact of Upper Bundle corrosion Degradation During Cycle 7, AES 96072812-1-1 Rev. 1, dated December 1996.

9. Cochet, B., "Assessment of the Integrity of Steam Generator Tubes – Burst Test Results – Validation of Rupture Criteria (FRAMATOME DATA)," Palo Alto, CA, Electric Power Research Institute, NP-6865-L, Vol. 1, June, 1991.

10. "PICEP: Pipe Crack Evaluation Program (Revision 1)", Electric Power Research Institute, December, 1987, NP-3596-SR, Revision 1.