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ANALYSIS OF ODSCC/IGA AT TUBESHEET AND TUBE SUPPORT LOCATIONS AT ST. LUCIE UNIT 1

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TABLE OF CONTENTS

Section		Page
	EXECUTIVE SUMMARY	iii
1	INTRODUCTION	1
1.1	IGA/ODSCC at Top of the Tubesheet	1
1.2	IGA/ODSCC at Lattice Supports	2
1.3	GA/ODSCC at Drilled Supports	3
1.4	IGA/ODSCC at Freespan Locations	3
2	STRUCTURAL REQUIREMENTS AND GENERAL CONSIDERATIONS	5
2.1	Axial Defects	5
2.2	Circumferential Defects	7
3	ANALYSIS INPUT PARAMETERS	16
3.1	Tubing Mechanical Properties	16
3.2	Degradation Length Distribution	16
3.3	Probability of Detection and Sizing Accuracy	17
3.4	Degradation Growth Rates	19
4	PROBABILISTIC MODELS	31
4.1	Circumferential Cracking	31
4.2	Axial Cracking with Repair on Detection	33
4.3	Axial Cracking with Repair on Sizing	36

5 STRUCTURAL MARGIN EVALUATION 41

5.1 Application of the Repair on Sizing Model 41

5.1.1 Benchmarking the Repair on Sizing Model 43

5.1.2 Computation of Burst Probabilities as a Function of Run Time for the Average Support 44

5.1.3 Burst Probabilities for IGA/ODSCC at Eggcrates, Tubesheet, and Vertical Supports 45

5.2 Application of the Repair on Detection Model for Axial Degradation 45

5.3 Application of the Repair of Detection Model for Circumferential Degradation 47

5.4 Summary of All Mechanisms 47

6 LEAKAGE EVALUATION 59

6.1 Projected Leak Rates for Axial Degradation in the Sludge Pile and at Lattice Type Supports 60

6.2 Projected Leak Rates for Circumferential Degradation 61

6.3 Projected Leak rates from Degradation at Drilled Support and Freespan Locations 61

6.4 Total Projected Leak Rate 62

7 SUMMARY AND CONCLUSIONS 66

REFERENCES 68

EXECUTIVE SUMMARY

An evaluation of the significance of corrosion degradation on the structural integrity of Alloy 600 steam generator tubing at St. Lucie Unit 1 was performed. Outer diameter stress corrosion cracking/intergranular attack was considered at five types of locations. These locations and degradation modes included:

- circumferential degradation at explosive expansion transitions at the top of the tubesheet
- axial degradation at the top of the tubesheet in the sludge pile
- axial degradation at eggcrate and vertical strap (lattice type) tube support structures
- axial degradation at drilled tube support structures
- axial degradation at upper bundle freespan locations.

Several probabilistic run time models were employed. Modeling included scenarios of both plug on detection and plug on sizing, depending on the mode and location of degradation. Circumferential degradation at the top of the tubesheet, as well as axial degradation at freespan and drilled tube support locations, was modeled using a plug on detection scenario coupled with an RPC inspection scheme. Modeling of axial degradation at other locations employed a bobbin probe inspection with a plug on sizing scenario. Probabilistic computations of the conditional probability of burst and the magnitude of leakage under accident conditions were developed. Calculational procedures were benchmarked by comparing predictions of the number and severity of eddy current indications with actual observations and by comparing predicted versus observed leakage during in situ testing.

The results of probabilistic calculations indicate a conditional probability of tube burst summed over all corrosion mechanisms after a 14 month period of operation of 0.018. For longer run times an upsweep in the conditional probability of burst is noted. Hence, after 15 months of operation, the conditional probability of tube burst is calculated to be 0.044. The total projected 95% upper bound leak rate after 15 months of operation is less than 4 gpm. The conditional probability of very large leak rates is roughly on the same order as the conditional probability of burst. The conditional probability of tube burst under postulated accident conditions is the limiting concern.

SECTION 1
INTRODUCTION

Steam generator tubing at St. Lucie Unit 1 has experienced substantial corrosion degradation over the past 12 years of operation. From eddy current inspection data and pulled tube examinations this degradation is outer diameter intergranular attack and stress corrosion cracking. Axial degradation has been found at the top of the tubesheet in the sludge pile region, at all types of tube support structures and, most recently, at a few upper bundle freespan locations. Circumferential degradation has been observed on the outer diameter of tubing near the explosive expansion region at the top of the tubesheet.

Corrosion degradation and tube plugging has progressed to the point where the steam generators will be replaced at the end of the current cycle of operation. This report describes an evaluation of the effect of corrosion degradation on the structural and leakage integrity of the steam generator tubing during the current cycle of operation. Probabilistic methods are employed and several Monte Carlo simulation models have been used. The following sections of the introduction provide an overview of the corrosion degradation experienced at various locations in the St. Lucie steam generators and the type of analyses which have been conducted to evaluate the significance of this degradation.

1.1 IGA/ODSCC AT TOP OF THE TUBESHEET

As noted earlier, outer diameter circumferential degradation has been observed near the explosive expansion region at the top of the tubesheet. At the last inspection 165 indications were found during a 100% RPC inspection (hot leg and cold leg) of this location in both steam generators. These indications were removed from service. Structural and leakage integrity were evaluated using a computer code developed as part of an industry sponsored EPRI project. As described in a later section, this code makes projections of end- of-cycle conditions regarding degraded cross sectional areas with a procedure that essentially follows the method specified in NRC Generic Letter 95-05[1] for bobbin probe voltages.

Axial degradation at the top of the tubesheet in the sludge pile region was observed in the last inspection as well as several previous inspections. The Monte Carlo simulation model applied to this circumstance is the same as that used for indications at lattice type tube support structures. This model is summarized below.

1.2 IGA/ODSCC AT LATTICE SUPPORTS

Axial corrosion degradation of tubing at tube support structures in ABB-CE steam generators is not a new phenomena. This degradation process has been active at a slow but steady rate at St. Lucie Unit 1 since the mid 1980's. Full bobbin probe eddy current inspections have been performed over the past 9 cycles of operation. Bobbin probe inspections have proven to be an effective tool for the management of corrosion degradation. Tubes with indications equal to or greater than the 40% through wall technical specification limit have been removed from service. The past performance of St. Lucie Unit 1 in terms of operational leakage has been excellent. In situ testing of tubes with large bobbin voltages and large phase angle depth calls demonstrated that Regulatory Guide 1.121 margins were maintained during the last cycle of operation. The last cycle had a duration of 13.9 EFPM.

Structural and leakage integrity evaluations for axial degradation at tube support structures were performed using a Monte Carlo simulation model. This model has been highly successful in previous applications[2, 3, 4]. The processes of crack initiation, crack growth and detection of degradation via eddy current inspections are simulated in the Monte Carlo model. This model has been updated to include depth sizing after degradation is detected. Measurement uncertainties are part of the simulation. For degradation at support structures, bobbin probe probability of detection characteristics are applied as are bobbin depth call sizing errors. Cracks with a perceived size less than 40% of the wall thickness are left in service in the simulation. The true simulated depth versus perceived depth is tracked so that appropriate burst pressures and leak rates are calculated. Detected and undetected crack populations are explicitly calculated and followed from cycle to cycle.

1.3 IGA/ODSCC AT DRILLED SUPPORTS

During the (EOC-13) outage, drilled support plate locations were inspected using an RPC probe. All detected indications were removed from service. Approximately 800 tubes total were plugged due to RPC indications in drilled support plate crevices. This number does not indicate a sudden surge in the indication population. The previously applied plugging criteria was based on bobbin probe depth sizing. The Monte Carlo simulation model of degradation of drilled support locations employed an RPC probability of detection curve coupled with a plug on detection repair criterion.

1.4 IGA/ODSCC AT FREESPAN LOCATIONS

Bobbin indications and heightened concern for freespan degradation in the upper bundle, as experienced in similar steam generator designs[4], led to an increase in the RPC examination scope. Approximately 13,000 tubes were examined via RPC in the upper bundle. A total of 44 axial, non-volumetric freespan indications were removed from service. This represents an early, mild incidence of freespan corrosion degradation. In-situ pressure testing, during the EOC-13 refueling outage, demonstrated that the most limiting freespan indications exceeded the structural requirements of Regulatory Guide 1.121. The initiation, growth, MRPC detection and repair on detection Monte Carlo simulation model was applied to freespan degradation. Hence, freespan indications and indications at drilled support plates were analyzed with the same type of simulation model.

The probabilistic evaluations of structural and leakage integrity of steam generator tubing at St. Lucie Unit 1 are the most sophisticated and complete run time analyses to date using a physically based approach. The following sections of this report describe the models used in these evaluations, input data, benchmarking studies and finally, the end results.

SECTION 2
STRUCTURAL REQUIREMENTS AND GENERAL CONSIDERATIONS

The focus of probabilistic structural integrity and leakage evaluations presented in subsequent sections is on a postulated main steam line break accident. This is consistent with a new draft Regulatory Guide[5] in support of steam generator rule making. The appropriate limiting accident case pressure differential is 2500 psi for St. Lucie Unit 1. Leakage and bursting are evaluated at this loading severity. The conditional probability of burst at postulated accident conditions should not exceed 0.05 when all tube degradation mechanisms are considered. The leak rate at a postulated accident event at end of cycle should not exceed the total charging pump capacity of the primary coolant system, provided that radiological dose consequences do not exceed General Design Criteria 19 and 10 CFR Part 100 guidelines at this leak rate.

The following paragraphs describe the basis of structural integrity analyses for axial and circumferential degradation. Characterizations of crack morphologies are presented. Leak rate calculations are summarized. These concepts form the framework of the probabilistic models used to project leak rate and burst behavior.

2.1 AXIAL DEGRADATION

From the perspective of leak rate and burst strength calculations, all axial corrosion degradation is idealized as single planar cracks. This is conservative in the sense that the strengthening and leak limiting effects of ligaments between crack segments in crack arrays are neglected. The entire spectrum of IGA/ODSCC degradation morphologies can be represented as arrays of axial and circumferential cracks of varying diffuseness. Leak and burst calculations are based on the single planar crack extreme of the spectrum of possible morphologies. Only the ligaments in the depth direction are considered to provide strengthening and leak limiting effects.

As in past APTECH models of axial cracking, the structural minimum method of computing the burst pressure associated with an arbitrary crack depth profile is utilized. Figure 2.1 illustrates this approach using a triangular crack shape. A selected portion of the total crack profile is first considered. The average crack depth over this selected length is calculated. This length and associated average depth is used as input to the Framatome axial partial through wall burst equation[6]. Burst pressures for successively larger portions of the total crack profile are computed. There exists some section of the total profile with a minimum burst pressure. The length of this critical section of the total crack is termed the structurally significant length and the average depth over the structurally significant length is termed the structurally significant depth. Figure 2.1 illustrates the minimum burst pressure calculation which identifies the critical section of the triangular crack profile. The dotted rectangle shows the structurally significant length and the associated structurally significant depth.

Pulled tube burst data from Plant A first validated the structural minimum method and the use of the Framatome equation[7, 8]. See Figure 2.2. Almost all calculated burst pressures are conservative with respect to measured burst pressures. This is mostly due to neglecting the strengthening effects of ligaments between axial crack segments and only considering ligaments in the depth direction. Burst tests of laboratory specimens with EDM machined slots support this contention. Figure 2.3 illustrates the machined slots shapes. Figure 2.4 shows that use of the Framatome equation with the structural minimum method provides excellent predictions of actual burst behavior for long, deep cracks. The predicted behavior of very short cracks is overly conservative. A long crack is shown to be on the order of 1.5 inches. It is important to use the Framatome equation and the structural minimum method to characterize the behavior of long cracks which penetrate the wall.

Figure 2.5 illustrates the relationship between maximum crack depth and structurally significant depth for pulled tubes from Plant A. The ratio of these depths together with the structural minimum method define a crack shape. In probabilistic analyses, crack shapes were obtained by sampling the pulled tube data of Plant A. Tube examination reports and eddy current inspection data support the use of Plant A data in St. Lucie Unit 1 analyses.

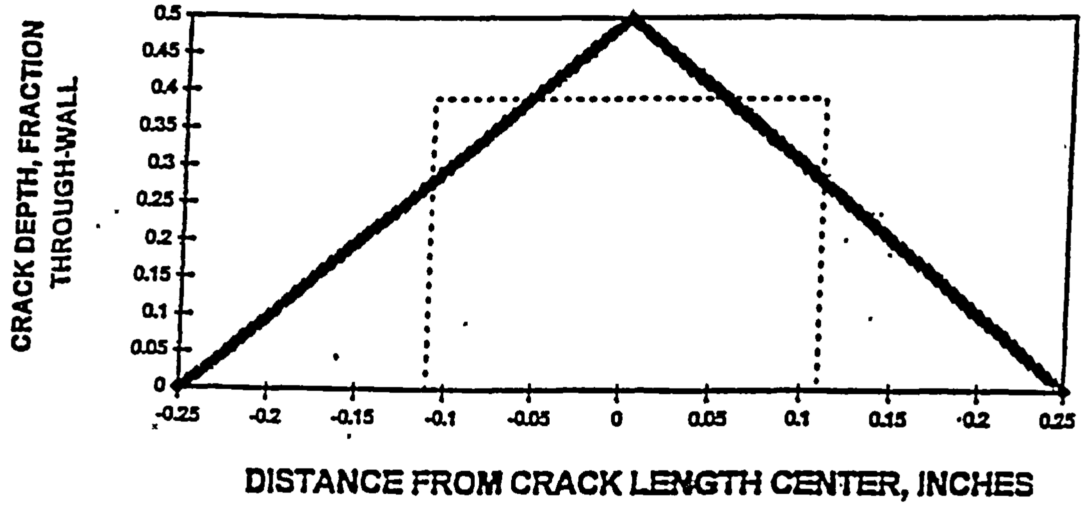
Figure 2.6 shows that distributions of crack lengths needed for probabilistic analyses of axial degradation can be obtained from MRPC eddy current results. Data from Plant A, where destructive examinations verified structurally significant crack lengths, shows that the MRPC indicated lengths are usually longer, and sometimes much longer, than the structurally significant lengths. Hence, use of the distribution of MRPC crack lengths in probabilistic analyses of axial degradation is conservative. The MRPC crack lengths distribution is more adverse than the distribution of structurally significant lengths.

2.2 CIRCUMFERENTIAL DEGRADATION

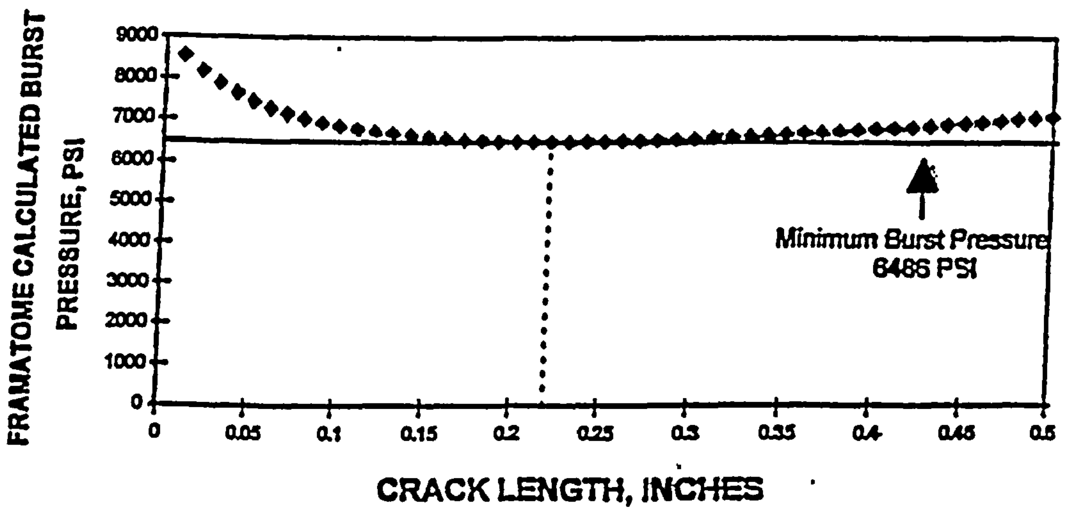
Circumferential degradation is modeled as cracking. In computing burst pressures, the total degraded cross sectional area of the tube is assumed to be present in the form of a single through wall crack with an equivalent area.

This morphology leads to a maximum bending effect and a lower bound burst pressure. There are several burst pressure equations for tubing containing circumferential cracks[9]. All are some version of plastic collapse or limit load approaches. There are relatively small differences in burst pressure predictions since the various equations agree well with test data. Results of a plastic zone instability analysis are illustrated in Figure 2.7. At postulated accident conditions, approximately 80% of the tube cross sectional may be degraded without a tube burst. At this loading level, in plane crack morphology and bending effects are relatively unimportant and the burst pressure is simply based on the resultant axial load, the net area of the cross section and the average flow strength of the material. One area of conservatism is the neglect of the strengthening effects of out-of-plane ligaments. These ligaments between out-of-plane crack segments must rupture in a burst event.

With regard to leakage, the degraded cross sectional area is apportioned to an array of through wall cracks in a manner which maximizes the leak rate for a given level of degraded area. For leak rate calculation purposes, crack array morphologies are selected according to the following procedures developed as part of the industry-wide EPRI program on circumferential cracking. Examination of 37 pulled tube profiles shows that circumferential degradation can be effectively modeled as several depth crack segments with a shallower degradation background. The number of deep crack segments ranges from 0 to 4. There is approximately a 2% chance of either 0 or 4 deep crack segments and a 32% chance of either 1, 2 or 3 deep crack segments. The circumferential arc length of the deep crack segments is selected from a Weibull distribution of deep crack segment lengths. This Weibull distribution has been constructed from a combination of pulled tube destructive examination data and field call phase angle crack profiles of explosive expansion transitions.



(A) TRIANGULAR CRACK PROFILES



(B) CALCULATED BURST PRESSURE VERSUS LENGTH OF CENTRAL CRACK SECTION

Figure 2.1 ILLUSTRATION OF THE STRUCTURAL MINIMUM METHOD

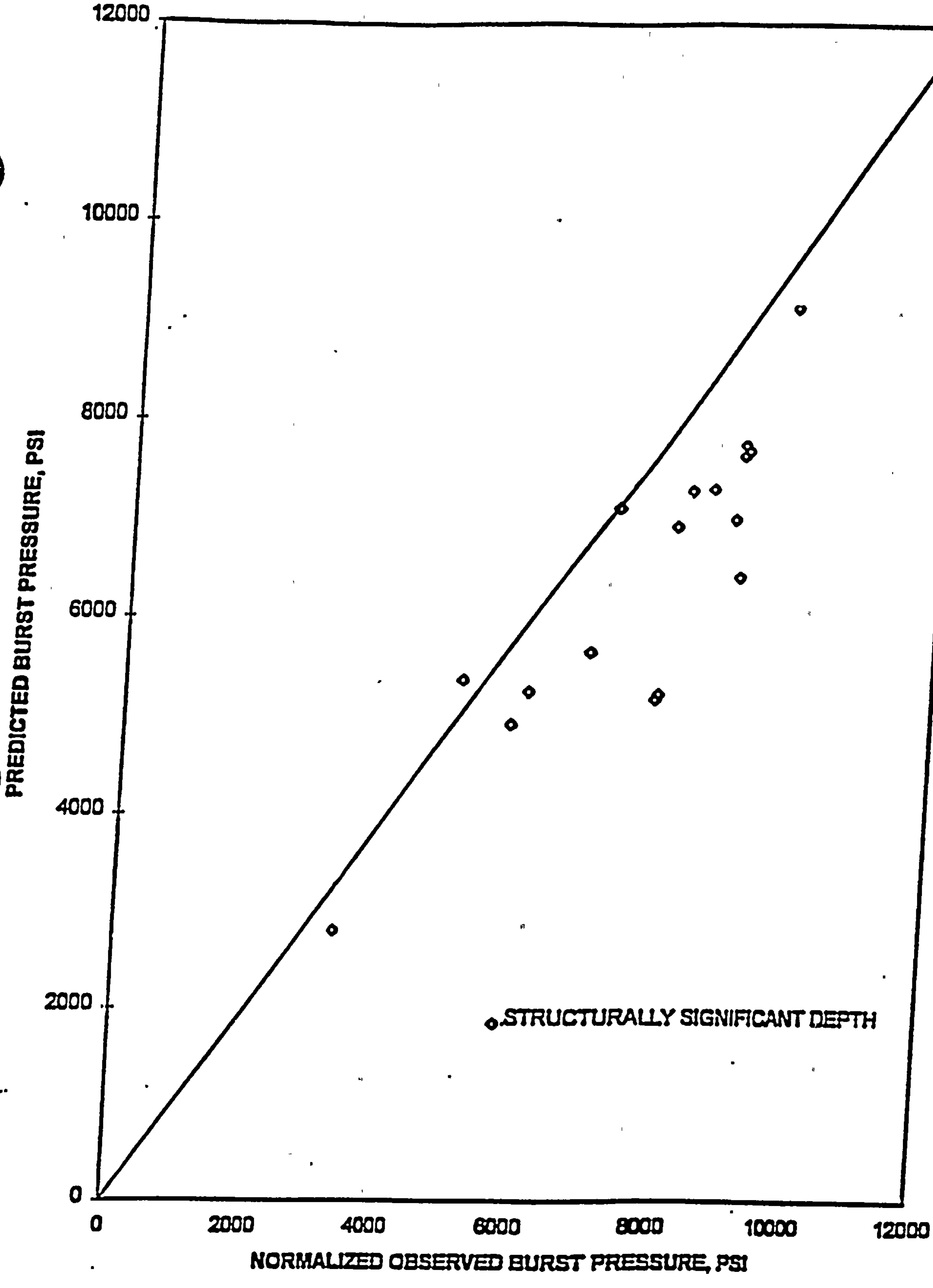


Figure 2.2 PREDICTED BURST PRESSURE VERSUS NORMALIZED OBSERVED BURST PRESSURE, PLANT A PULLED TUBE DATA

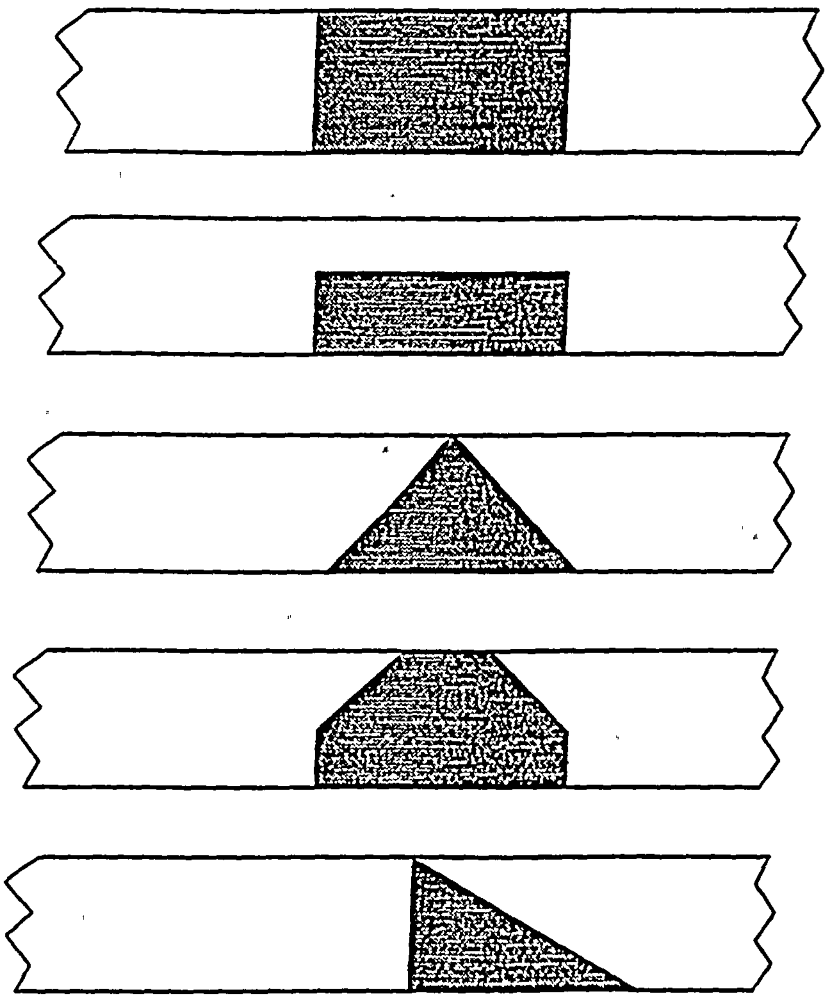


Figure 2.3 CRACK SHAPES INCLUDED IN TEST PROGRAM

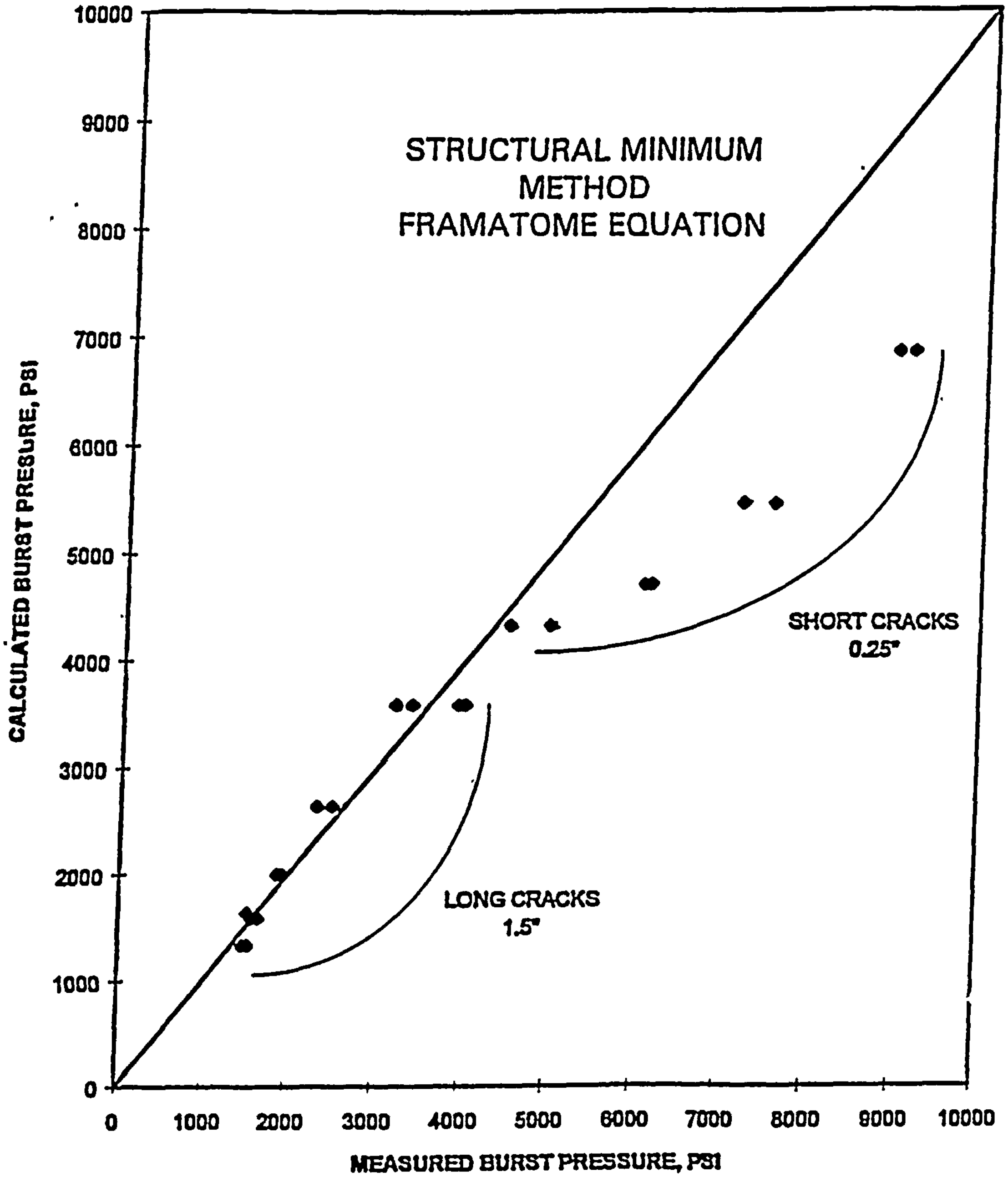


Figure 2.4 RESULTS OF EDM SLOT MACHINED SAMPLE BURST TEST PROGRAM

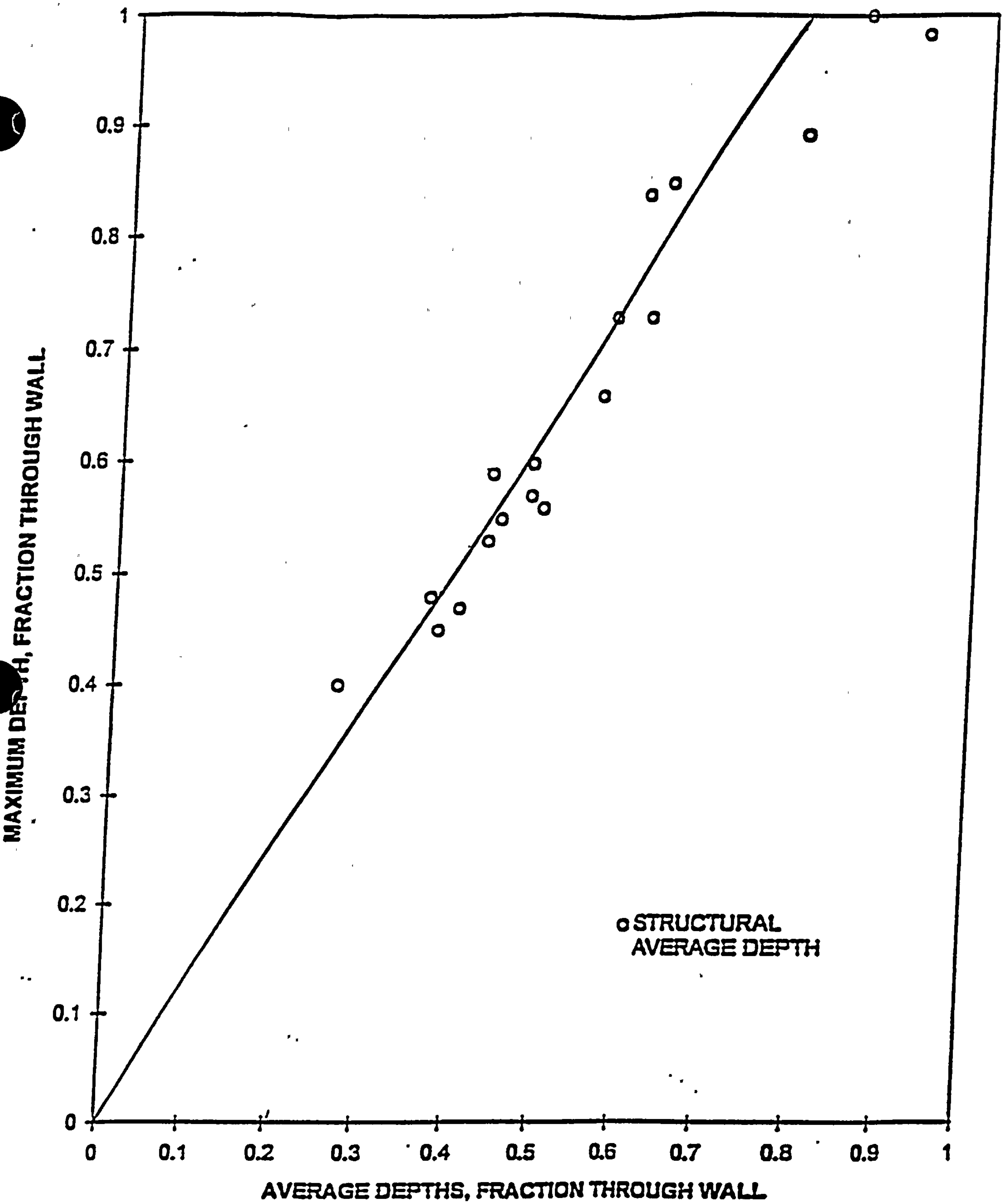


Figure 2.5 MAXIMUM CRACK DEPTH VERSUS STRUCTURAL CRACK DEPTH, PLANT A PULLED TUBE DATA

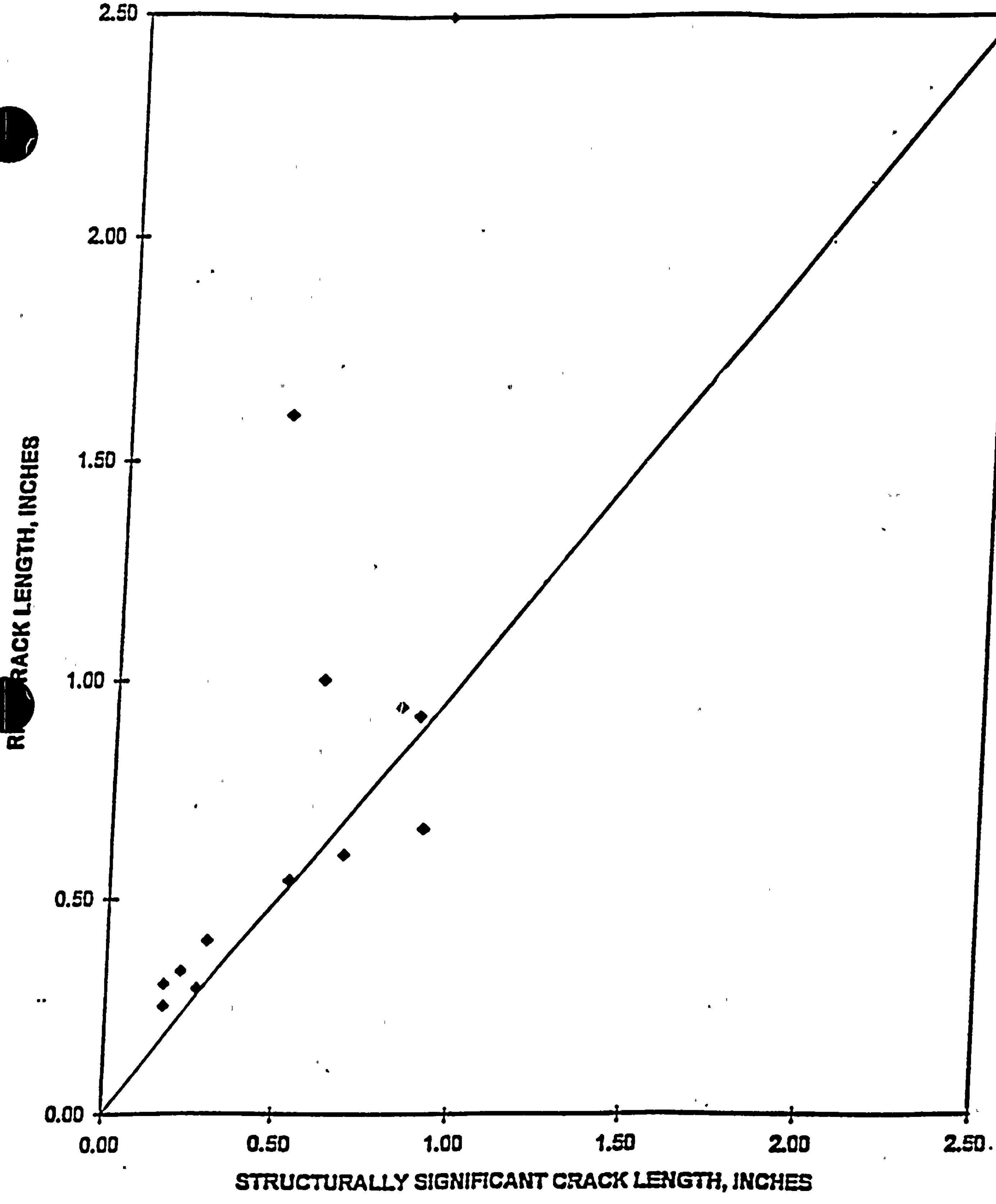


Figure 2.6 RPC CRACK LENGTH VERSUS STRUCTURALLY SIGNIFICANT CRACK LENGTH, PLANT A PULLED TUBE DATA

TUBE INTERACTION WITH SUPPORT STRUCTURES IS ASSUMED.
LATERAL DEFLECTION IS RESTRICTED.

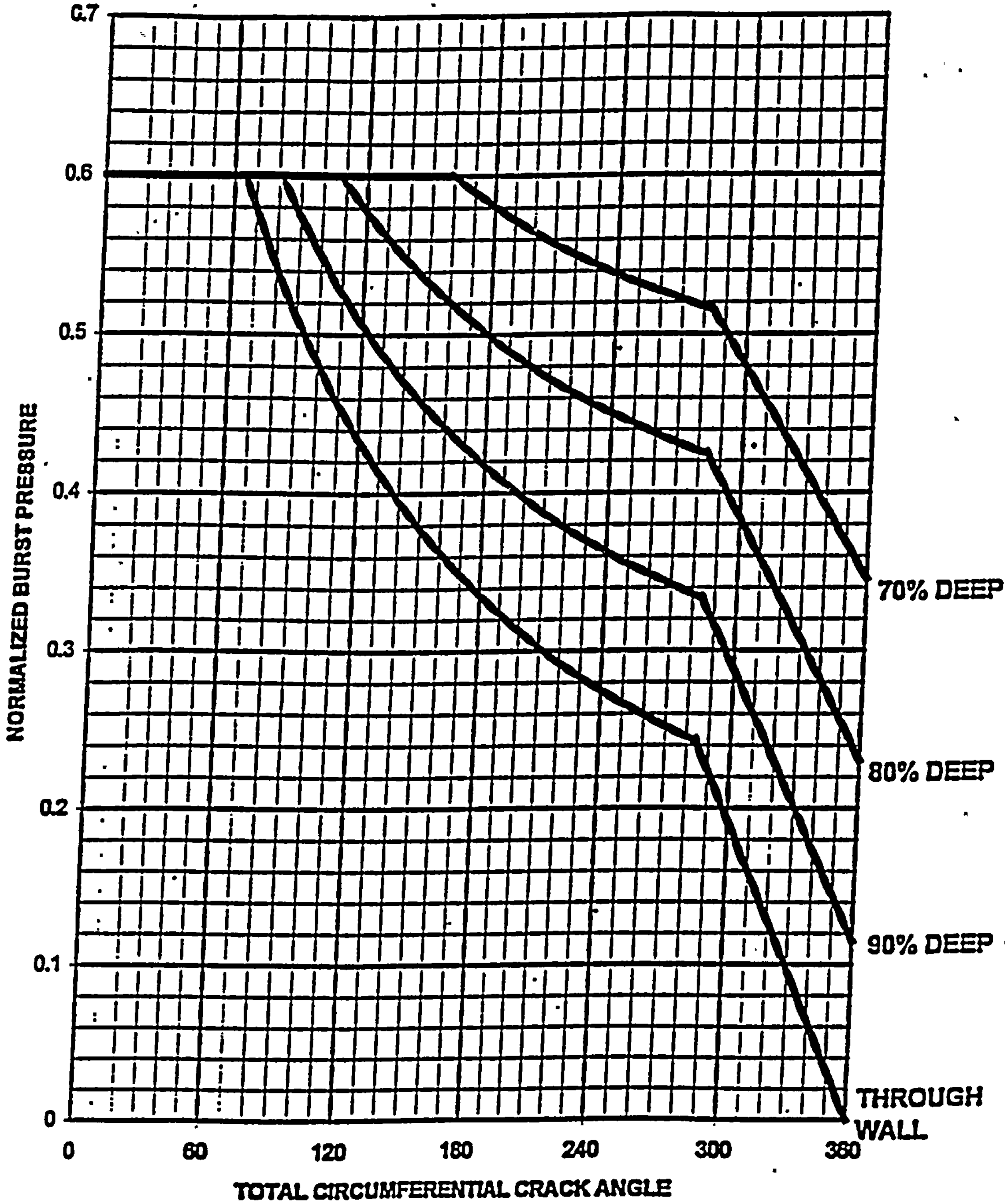


Figure 2.7 NORMALIZED BURST PRESSURE VERSUS TOTAL CRACK ANGLE FOR THROUGH WALL DIAMETER CIRCUMFERENTIAL CRACKS IN 0.750" by 0.048" TUBE WALL TUBING, PLASTIC INSTABILITY MODEL

SECTION 3

ANALYSIS INPUT PARAMETERS

Input parameters to probabilistic evaluations of structural and leakage integrity are presented in this section. The distribution of strength properties is not a major issue. These properties are remarkably similar across a broad range of steam generator designs. Degradation length distributions are based on plant specific data from St. Lucie Unit 1and agree well with observations at other units[2, 3, 4]. The analysis inputs which have the most effect on burst and leakage probabilities are the degradation growth rates and the efficacy of NDE inspection procedures both with respect to detection capability and depth sizing uncertainty. Attention is focused on these most important input elements.

3.1 TUBING MECHANICAL PROPERTIES

A histogram of the sum of yield and ultimate strengths for tubing in Plant B is shown in Figure 3.1[10]. This plant is essentially a sister plant to St. Lucie Unit 1. The tubing is the same size and the processing procedures are equivalent. Use of Plant B data for St. Lucie Unit 1 is appropriate. As noted above, strength distributions are similar even for plants of different designs and vendors. In particular, lower tolerance limit properties are nearly equivalent even for different heat treatment procedures. This includes high temperature and low temperature mill annealed, thermally treated and sensitized tubing.

3.2 DEGRADATION LENGTH DISTRIBUTION

The concept of structurally significant crack lengths and depths was discussed in section 2. It has been shown that the distribution of axial degradation lengths from RPC eddy current data is a good to conservative estimate of the distribution of structurally significant degradation lengths. When whole data sets are considered rather than selected individual indications, the portions of actual physical degradation not detected by the RPC probe are not structurally significant. Over 200 RPC characterizations of axial degradation lengths at the last outage of St. Lucie Unit 1 were used to construct the sampling distribution for structurally significant lengths. This distribution is illustrated in Figure 3.2.

3.3 PROBABILITY OF DETECTION AND SIZING ACCURACY

In the present evaluation, the issue of sizing uncertainty is pertinent to axial degradation at lattice type tube support locations and in the sludge pile. Here probabilistic modeling is conducted with a plug on sizing criterion. Indications with bobbin probe depth calls equal to or greater than 40% of the wall thickness are removed from service. The true degradation depth may be greater or less than the measured or perceived depth. Since burst and leakage properties depend on the true depth of degradation, sizing uncertainties must be properly considered.

Florida Power and Light has compiled bobbin probe sizing data from pulled tubes and some laboratory produced corrosion degraded tubes. Data from tubes removed from St. Lucie Unit 1 are included. Figures 3.3 and 3.4 illustrate a comparison of axial corrosion degradation depth from bobbin probe phase angle data versus maximum degradation depth determined from destructive examination. Figure 3.3 deals with sludge pile and lattice type crevice degradation while Figure 3.4 is devoted to axial degradation at drilled tube support crevices. From Figure 3.3 it is evident that, in general, the bobbin probe underestimates the maximum depth of degradation. An indicated depth is about 0.85 of the actual maximum degradation depth. For axial degradation in the sludge pile and at lattice type support structures, the standard error of estimate of actual maximum depth from bobbin probe measured depth is slightly less than 11% of the wall thickness. It should be noted than one point was deleted from the database where the bobbin depth call grossly over-estimated the actual maximum depth and was considered to be an outlier. Systematic and random bobbin probe sizing errors have been identified and included in probabilistic modeling.

The data in Figure 3.4 can be used to construct a curve of the probability of detection of axial corrosion degradation as a function of maximum degradation depth. Note the number of points where there is no indication of a bobbin probe depth call but a plotted actual maximum depth. These instances of degradation were undetected by the bobbin probe. This data together with the detected instances of degradation can be used to construct a curve or probability of detection versus degradation depth. In Figure 3.5, detected degradation is plotted at an ordinate value of 1 while a value of 0 represents undetected degradation. In this figure, data from laboratory samples are excluded as are four instances of cold leg degradation and two low level (13% and 19%) instances of degradation detected by the bobbin probe.

A log logistic fit to the data is shown in Figure 3.5. Cauchy, Gauss and Weibull fits were examined. The log logistic fit was selected as the best representation of the probability of detection versus depth. Use of the logarithm of degradation depth is physically realistic. For corrosion degradation, signal amplitude is insensitive to depth at very low depths but highly sensitive at large depths. The actual curve of probability of detection for the bobbin prove which was used in calculations is shown in Figure 3.6 As a measure of conservatism, all detected bobbin indications less than 40% in actual depth were eliminated and a new log logistic fit to the data was obtained. The resultant probability of detection curve is shifted to higher levels of degradation. At a degradation depth of 40%, the probability of detection drops from about 0.62 to about 0.42.

In the case of axial degradation at freespan and drilled tube support locations, RPC inspections were simulated in the probabilistic model. A probability of detection curve determined from pulled tube data from Plant A was used in these calculations. This curve is shown in Figure 3.7. The abcissa is the structurally significant degradation depth. The maximum depth is higher by a factor of approximately 1.27. The RPC probability of detection curve is viewed as conservative. It is more adverse than the industry wide curve of Reference 2. Differences in tubing manufacturing processes indicate that detection of freespan degradation at St. Lucie Unit 1 may be somewhat less difficult than in Plant A. A supporting fact is that the bobbin probe at both St. Lucie Unit 1 and Plant B detected nearly half of the RPC freespan indications. The hit rate of the bobbin probe versus RPC results at Plant A is significantly lower.

3.4 DEGRADATION GROWTH RATES

Growth of degradation for circumferential cracking was characterized in terms of changes in the percentage degraded cross sectional area. The EPRI sizing approach was used for determining degradation depth at many locations around the circumference of a degraded tube. Degradation depth versus circumferential location was converted to total degraded area and expressed as a percentage of tubing annular cross sectional area.

Circumferential indications detected by RPC inspections in the recent outage were sized and records were searched for precursor signals in the previous outage. Approximately 150 growth data points were obtained. The resulting distributions of growth rates are illustrated in Figure 3.8. The cumulative fraction of observations is plotted versus growth rate for steam generator A and B at St. Lucie Unit 1. Data from Plant B is also plotted for comparison.

It should be noted that sizing of circumferential cracks in explosive expansion transitions is not as difficult as sizing of circumferential cracks in hard roll transitions. Explosive expansions have a more gradual transition from expanded to unexpanded regions. Comparisons of measured degraded areas from RPC data with destructive examination results for explosive expansion transition are reasonably good. These comparisons are much better for explosive transitions than for hard roll transitions.

For axial degradation, a plug on sizing approach with bobbin probe eddy current inspections led to an extensive set of growth data. Stringent location criteria were applied to make certain that the same indication was compared from one outage to the next. Over 2300 pairs on bobbin depth growth pairs were used to construct an apparent growth rate distribution.

A histogram of bobbin depth growth rates is shown in Figure 3.9. The global average apparent growth is slightly below 1%. This indicates that sizing error is a major contributor to the apparent growth rates. The average of the positive growth rates is about 4.5% through wall per effective power year. The maximum apparent growth rate is 35% EFPY. In probabilistic evaluations, negative growth rates were considered as zero growth. The growth rate data was then sampled directly.

For any given growth rate data point, the true growth rate may be larger or smaller than the apparent growth rate because of sizing errors. However, when a large population or distribution of growth rates is considered, measurement errors must increase both the high and low extreme tails of the measured or apparent growth rates compared to the extremes of the distribution of true growth rates. In the present case of a very large number of data points, the apparent growth rates, used as described above, provide a conservative estimate of true degradation growth.

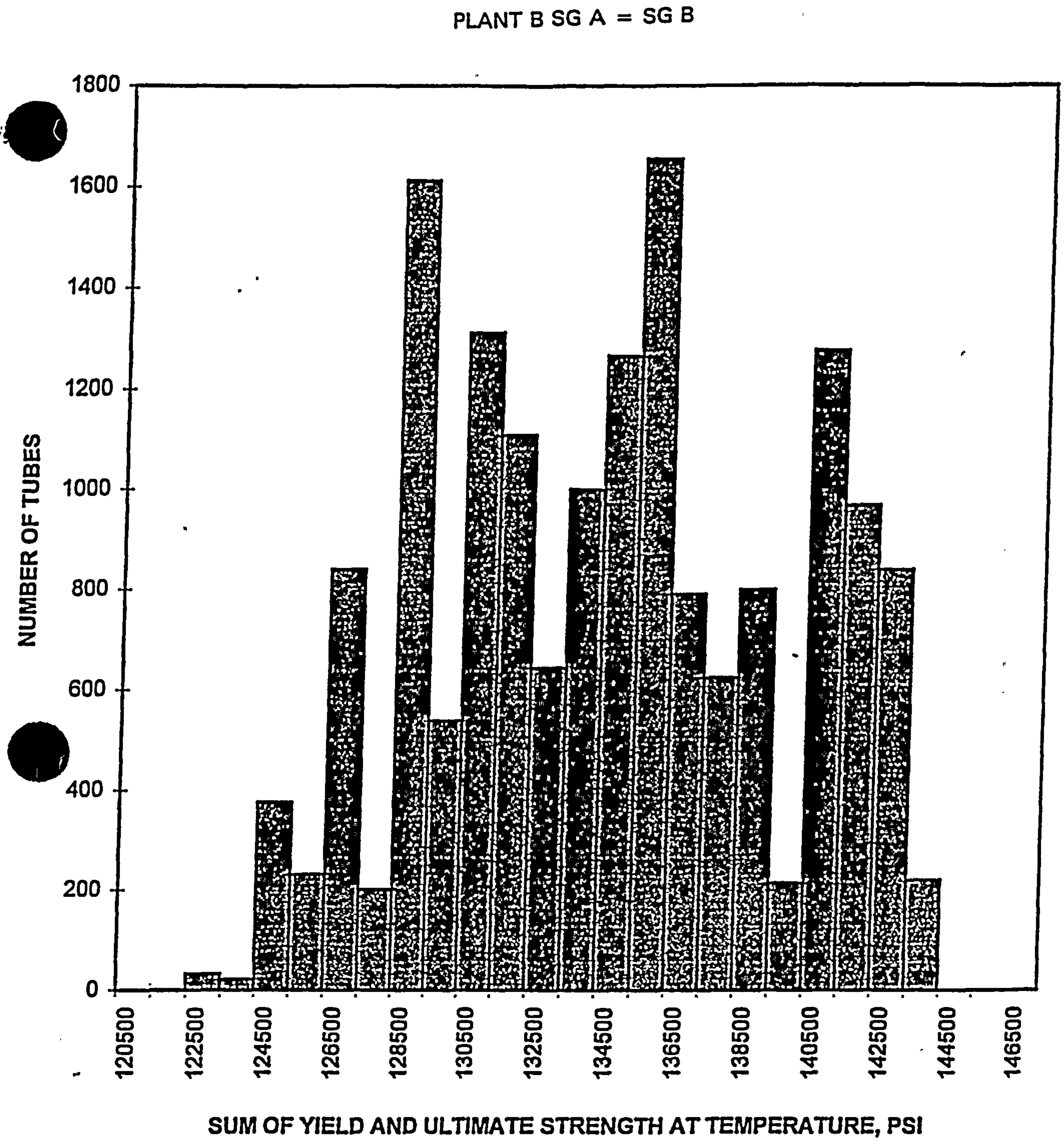


Figure 3.1 TUBING TENSILE PROPERTIES USED IN PROBABILISTIC ANALYSES

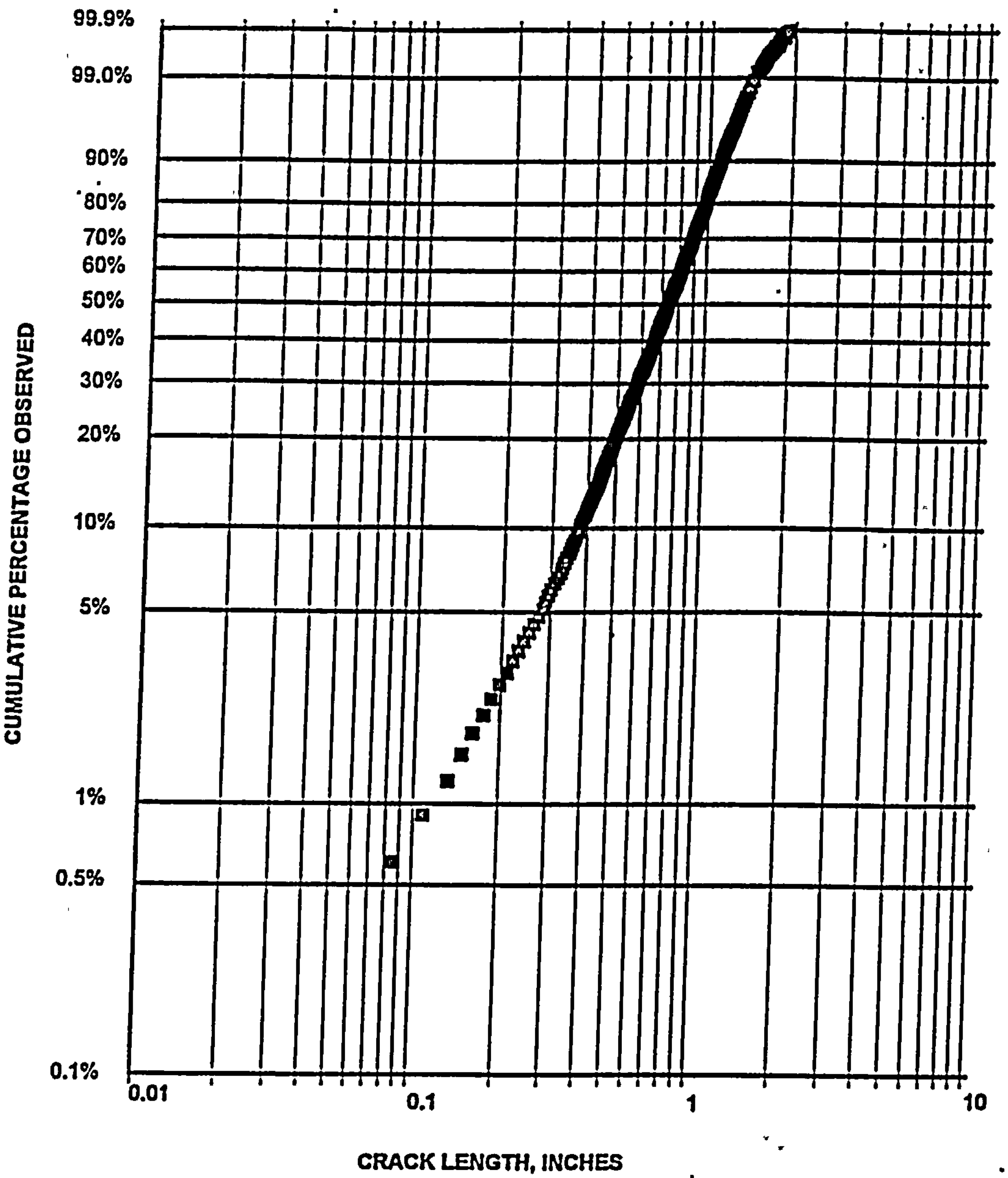


Figure 3.2 TYPICAL DISTRIBUTION OF STRUCTURALLY SIGNIFICANT CRACK LENGTHS BASED ON ST. LUCIE UNIT 1 MRPC DATA

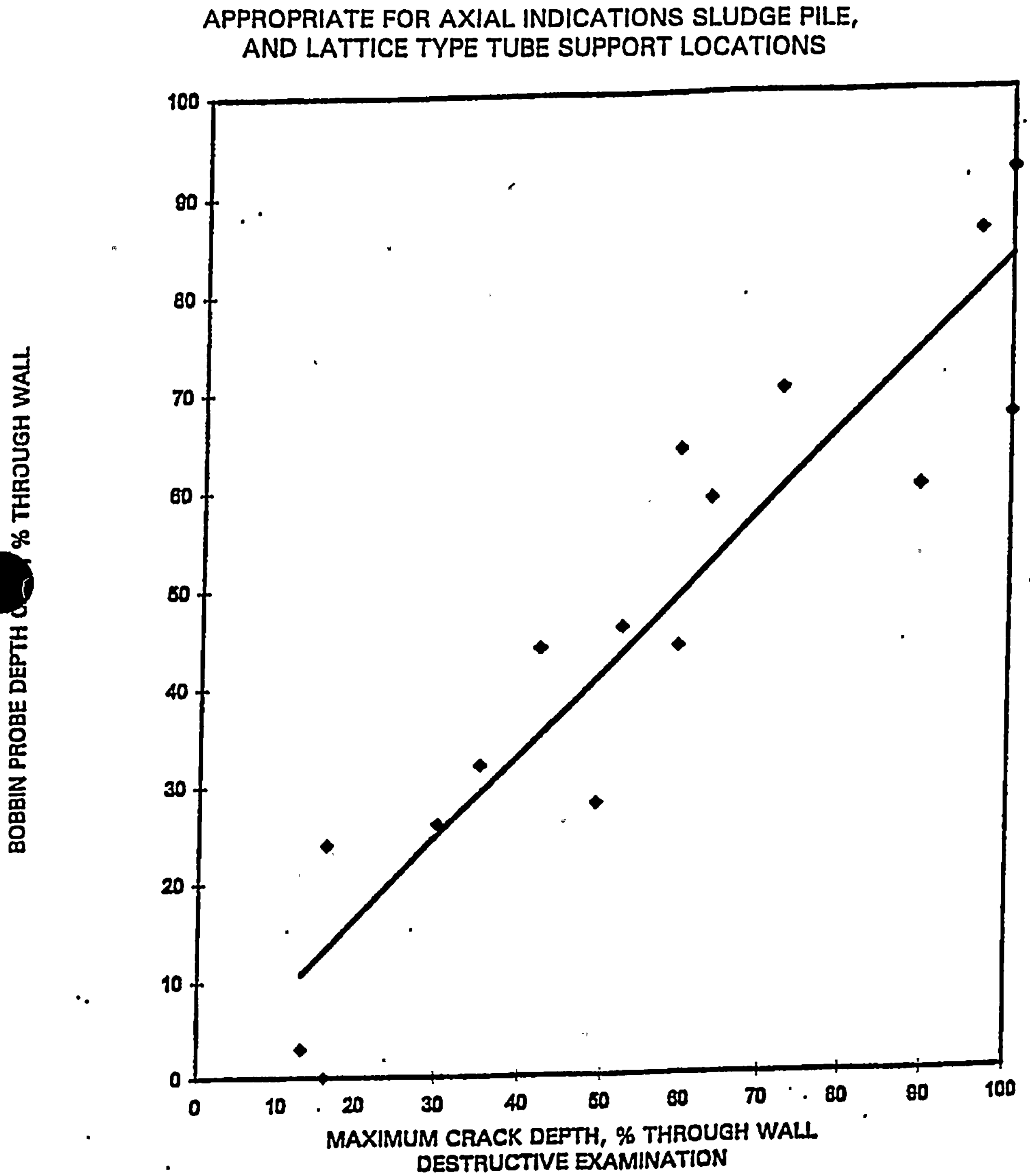


Figure 3.3 BOBBIN PROBE DEPTH CALLS VERSUS MAXIMUM DEPTH DESTRUCTIVE EXAMINATION RESULTS (FPL SIZING PROCEDURES APPLIED)

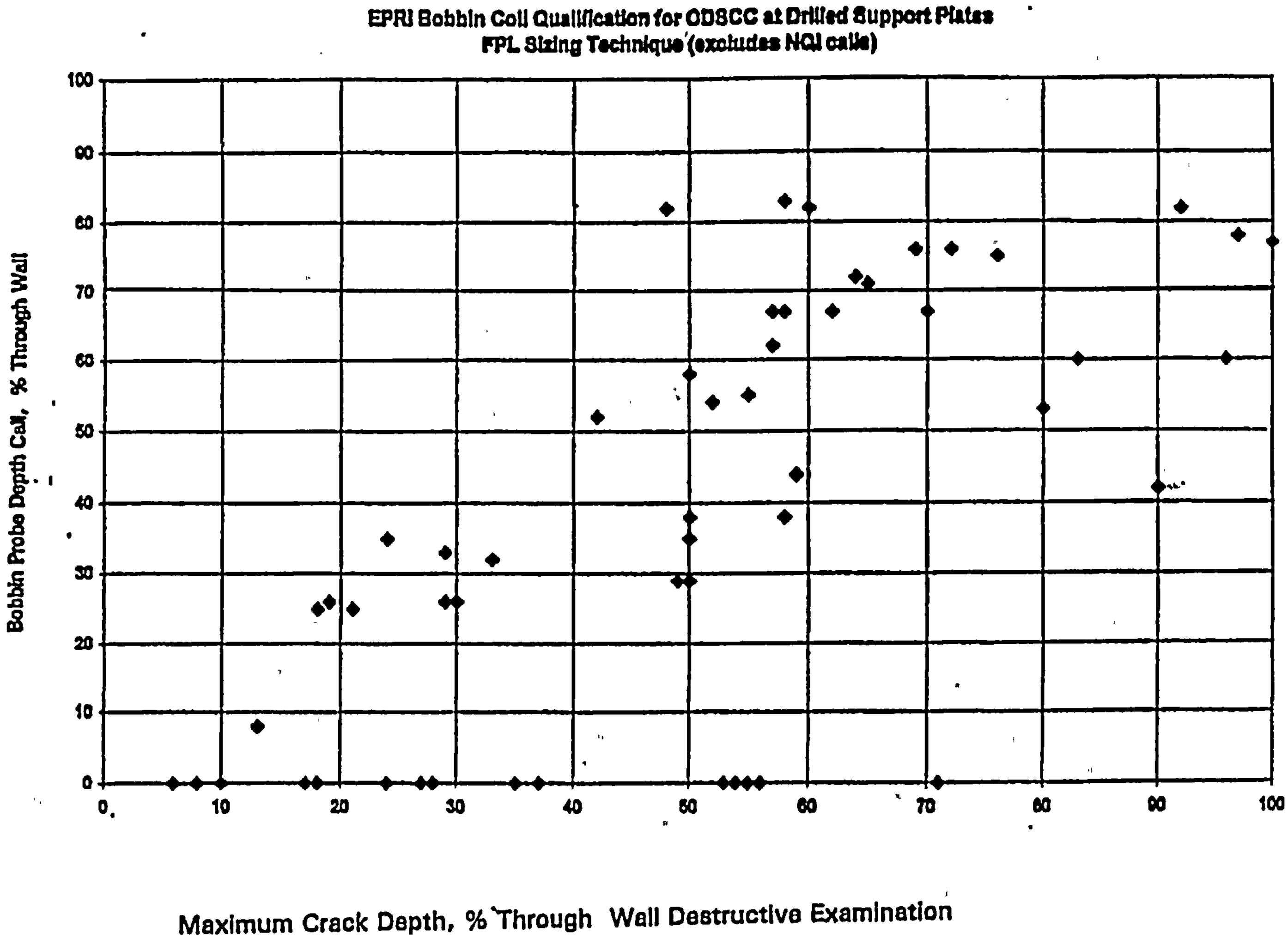


Figure 3.4 BOBBIN DEPTH CALLS VERSUS MAXIMUM DEPTH DESTRUCTIVE EXAMINATION RESULTS, DRILLED TUBE SUPPORT PLATES

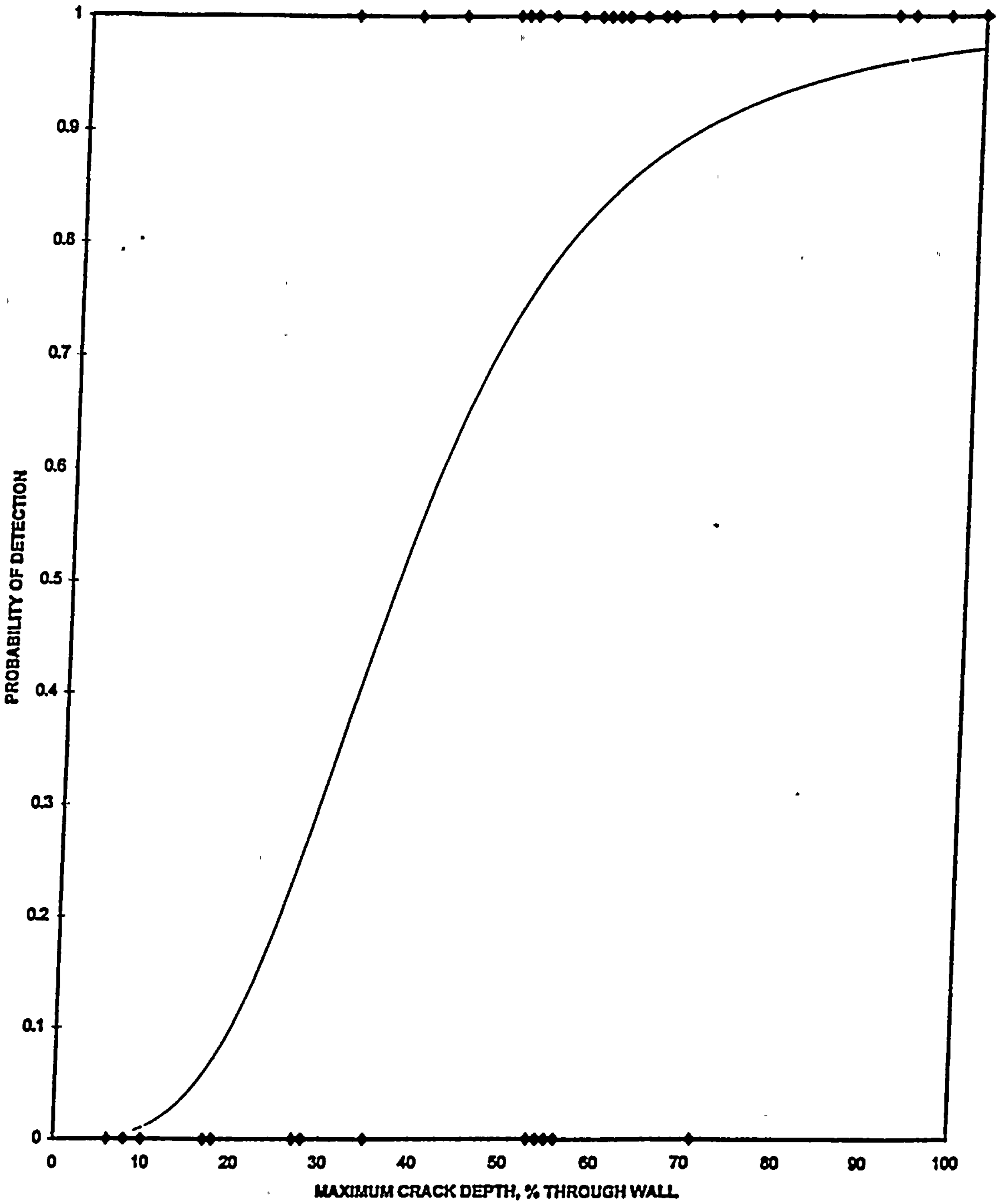


Figure 3.5 BOBBIN PROBE LOG LOGISTIC PROBABILITY OF DETECTION CURVE BASED ON PULLED TUBE DATA

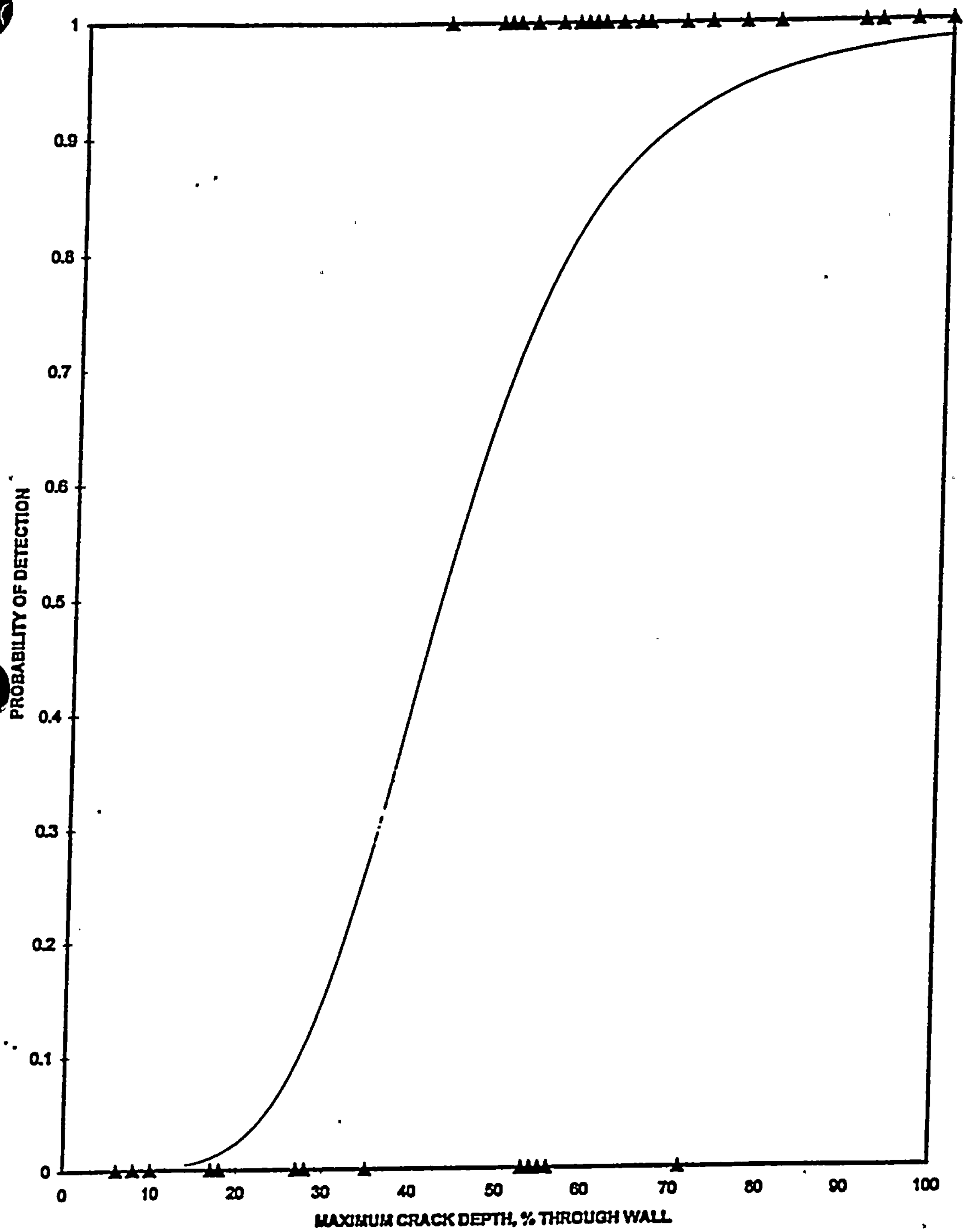


Figure 3.6 BOBBIN PROBE LOG LOGISTIC PROBABILITY OF DETECTION CURVE USED IN PROBABILISITC EVALUATIONS. INSTANCES OF BOBBIN PROBE DETECTED DEGRADATION LESS THAN 40% EXCLUDED

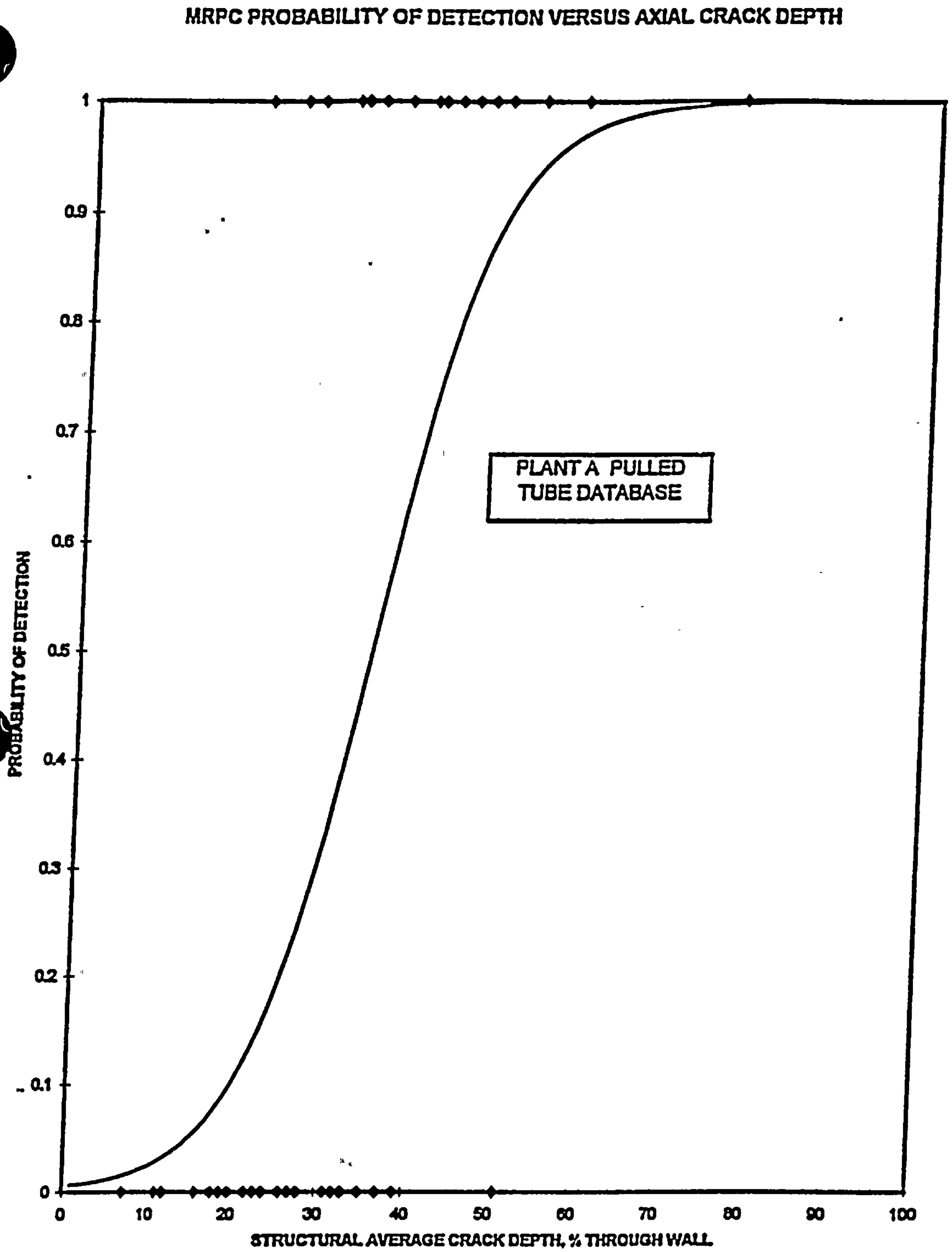


Figure 3.7 RPC PROBABILITY OF DETECTION CURVE BASED ON PLANT A PULLED TUBE DATA

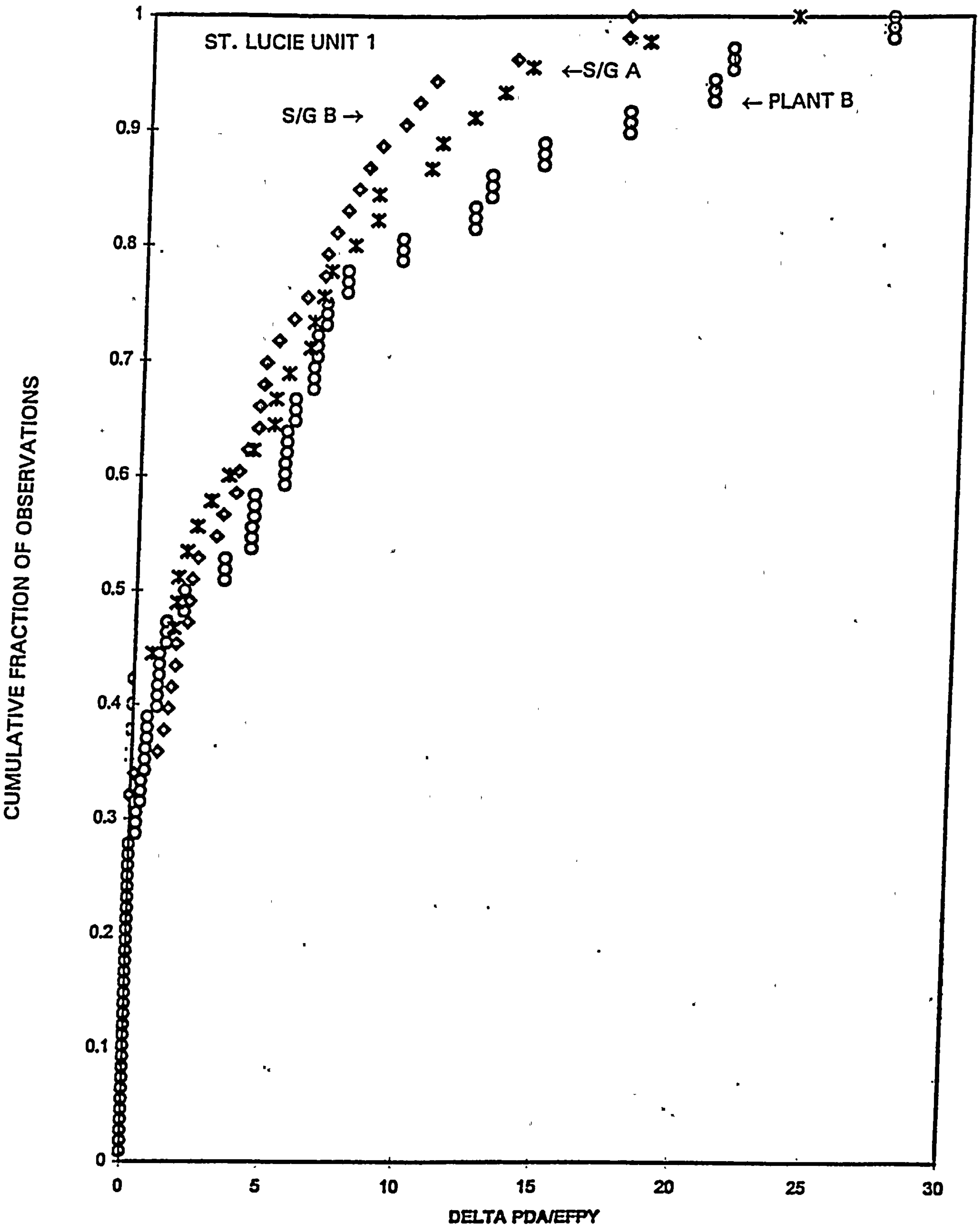


Figure 3.8 CHANGE IN PERCENT DEGRADED CIRCUMFERENTIAL AREA PER EFPY

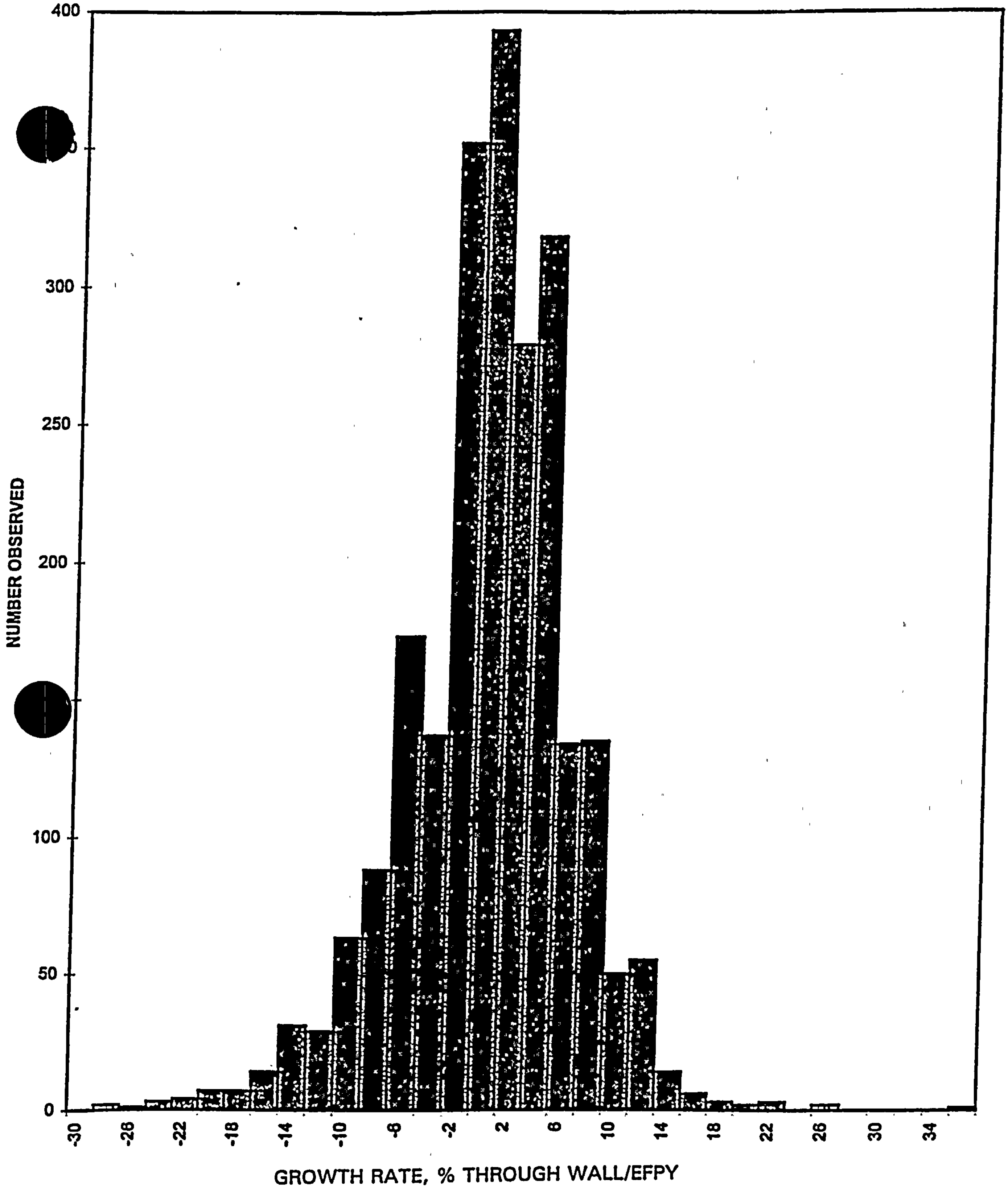


Figure 3.9 AXIAL DEGRADATION GROWTH RATES FROM BOBBIN INDICATIONS AT ST. LUCIE UNIT 1

SECTION 4
PROBABILISTIC MODELS

Three variants of probabilistic structural and leakage integrity models were used in the overall evaluation of the significance of corrosion degradation in steam generator tubing at St. Lucie Unit 1. These models are:

- circumferential degradation, MRPC inspection, repair on detection
- axial degradation, MRPC inspection, repair on detection
- axial degradation, bobbin probe inspection, repair on sizing

Each of these models is described in turn in the following subsections.

4.1 CIRCUMFERENTIAL CRACKING

For burst evaluations, circumferential degradation is modeled as a single planar crack. The characterizing parameter is degraded area expressed as a percentage of the cross sectional area of the tube, PDA. Projections of end of cycle conditions regarding number of degraded tubes and the severity of degradation, PDA, are patterned after NRC Generic Letter 95-05. Instead of projected end of cycle bobbin voltages, PDA values are projected.

Details of the method of projection are as follows. The probability of detection is a constant value of 0.6. The number of degraded tubes at beginning of cycle with a given PDA is given by:

$$N_{EOC} = N_{LAST}\left(\frac{1}{0.6}\right) - N_{REP}$$

where N_{LAST} is the number of tubes found in the last inspection at the PDA value of interest and N_{REP} is the number repaired. With a plug on detection repair criterion, N_{REP} is equal to N_{LAST}. The beginning of cycle PDA is adjusted for random measurement error and a random growth increment is added to determine the severity of degradation at end of cycle. Monte Carlo simulation is used. A lower bound burst curve is used as described in Section 2. Naturally, variations in tensile properties are included. Growth rates are sampled directly from as measured growth rate data. Negative growth rates are included as zero growth rates.

At a given PDA value, a wide variety of crack morphologies are possible. Leak rates depend sensitively on the actual crack morphology. It is totally unrealistic to assign the total degraded area to a single through wall crack. The very large degradation tolerance for circumferential cracking would lead to huge leak rates if this bounding assumption were uniformly applied. Instead, as described in Section 2, the degraded area is apportion to an array of cracks. These crack arrays are developed from a Monte Carlo sampling process based on pulled tube actual crack profiles. The sampling process allows for both occasional very large single through wall cracks and very large axisymetric non-leaking cracks. Within a given crack array, the total degraded area is apportioned to produce the largest total leak rate per tube. The final analysis produces an EOC cycle distribution of leak rates. The upper bound 95 percentile leak rate is selected as the characterizing value.

The computer code used for the analysis of circumferential degradation is termed CIRC95. It was developed jointly by Westinghouse and APTECH as part of an industry-wide program on circumferential cracking at expansion transitions.

4.2 AXIAL CRACKING WITH REPAIR ON DETECTION

The probabilistic model for axial cracking with repair on detection is a slightly modified version of the APTECH model used for the Plant A analyses of IGA/ODSCC at freespan locations. The probabilistic model consists of a Monte Carlo simulation of the processes of crack initiation, growth, eddy current inspection and repair/removal of degraded tubes. The current APTECH model simulates the behavior of up to 10,000 individual cracks for five operating periods. Larger populations are accommodated by dividing the steam generator into several risk groups, each of which can be individually simulated.

The actual simulation process is shown in Figure 4.1, which describes the execution of one Monte Carlo trial. The first step in the process is that of defect tagging in which the attributes that define the nature of the defect for the entire period of analysis, are determined. These defect attributes include:

- Initiation time
- Growth rates for each operating period
- Tube material properties (flow stress)
- Defect characteristic length

Each of these attributes is obtained by sampling from an appropriate probability distribution function as described in Section 3 of this report.

The second step in the simulation process is to compute the size of the defect at each inspection time. The result of this step is a matrix of crack structural depths (D_{ij}) corresponding to time values (T_j) where the index $_j$ denotes the $_j$th inspection and the index $_i$ denotes the $_i$th defect. At this point in the simulation the characteristics necessary to determine the structural integrity of each simulated defect have been obtained.

The third step in the simulation process is to numerically inspect each defect to determine at which inspection the defect is detected and removed from service. This is accomplished by random selection using the appropriate eddy current POD function. A detection/repair state identity matrix is developed (ID_{ij}) in which a value of 0 denotes an undetected defect, a value of 1 denotes a detected defect and a value of 2 denotes a repaired defect. For the repair-on-detection simulation, a value of 2 is assigned for the following inspection immediately on detection.

The final step in the simulation process is the identification of defects which have progressed to the point where tube burst or leakage can be expected. For a given inspection ($_j$), each defect has three important attributes, which in combination, determine the structural and leakage integrity:

- Structural average depth (D_{ij})
- Structural length
- Maximum depth ($4/\Pi \times D_{ij}$)

Two attributes determine if a defect is to be counted as a burst in the simulation. These are the critical crack length and critical structural depth for the defect which are computed from the Framatome equations discussed in Section 2. A defect is counted as a burst in the $_j$th inspection if three conditions are met:

- The defect structural depth is greater than or equal to the critical depth

- The defect characteristic length is greater than or equal to the critical length
- The defect is undetected or newly detected

Defects which are too short to cause a burst, but of sufficient depth, are counted in a separate category which affects leakage integrity. These defects can "pop-through" under accident loading to their full structural length, and are assumed to behave in this manner. The characteristics of each defect of this type are stored in a special output file for use in separate leakage calculations.

The third class of important defect is the stable through wall defect for which the maximum computed depth exceeds 100% of the tube wall thickness. The characteristics of each defect of this type are stored in the same output file as those of the "pop-through" defects for subsequent leakage analysis. Figure 4.1 shows the logic structure for the defect classification process.

At this point, one trial of the Monte Carlo simulation is complete. The key information available from this stage of the simulation includes numbers of:

- Defects detected
- Bursts predicted
- Pop-through defects predicted
- Stable leakage defects predicted

The probabilistic run-time analysis consists of many thousands of repeated trials which are used to obtain probability distribution functions for the frequencies and magnitudes of defects which can comprise the structural and/or leakage integrity of a steam generator.

4.3 AXIAL CRACKING WITH REPAIR ON SIZING

The probabilistic model for axial cracking with repair on sizing, while identical in concept with that for repair on detection, has two important distinctions. The first of these is the incorporation of an additional simulation component which simulates the sizing process by bobbin coil phase angle and its measurement uncertainty. The implication of this feature is that a defect cannot be removed from service until two conditions are met:

- Detection
- Measured depth greater than 40% through wall

This, of course, results in simulated defect structural depths of greater than 40% through wall remaining in service. The consequence of this is less tolerance in the simulation to extremes in defect growth rate.

The second important distinction between the repair on sizing and repair on detection probabilistic models is the incorporation of an additional probabilistic defect attribute in the first step in the Monte Carlo process. This additional attribute is the form factor which relates the crack maximum depth to the average structural depth. As with other attributes, such as defect characteristic length and material properties, the form factor remains with the simulated defect throughout the simulation trial. The effect of a randomized form factor on the simulation outcome is to increase the number of through wall defects for large defect populations such as for lattice support and tubesheet axial IGA/ODSCC in the present analysis. The derivation of the form factor probability distribution function and implications regarding the range of defect shapes are discussed in Section 2.

The simulation of the repair on sizing process is a modification of the inspection step discussed in Section 4.2 and described in Figure 4.1 for the repair on detection model. In that case the detection/repair state identity matrix (ID_{ij}) was automatically updated to repaired status (2) in the cycle following detection. In the repair on sizing simulation the process is more complex, requiring a separate process to simulate bobbin coil inspection results. The repair on sizing process is shown in Figure 4.2. The first step in this process is to create a bobbin coil depth matrix (DB_{ij}) from the defect structural depth matrix (D_{ij}). Each element of the bobbin coil depth matrix is given by:

$$Db_{ij} = A_o + A_1'Dij + R_{ij}$$

where:

Db_{ij} = apparent bobbin depth

A_o, A_1 = coefficients from Appendix H qualification regression analysis

A_1' = A_1 x Form Factor (MAX DEPTH/STRUCTURAL AVERAGE DEPTH)

R_{ij} = random error component from Appendix H correlation

The bobbin coil depth matrix provides the basis for removing a defect from further service. As shown in figure 4.2, if the defect has been detected and the apparent bobbin depth is greater than 40% through wall, the detection/repair state identity matrix (ID_{ij}) value is set to 2 for the following inspection. If the defect has been detected and the bobbin coil apparent depth is less than 40%, the detection/repair state identity matrix value is set to 1 for the following cycle and the defect remains in service. It should be noted that the random error component (R_{ij}) can be of the order of $\pm$20% through wall resulting in simulated repair of defects with structural depths considerably under 40% through wall and continued service of defects with structural depths considerably over 40% through wall. This behavior is accommodated in the probabilistic run time model.

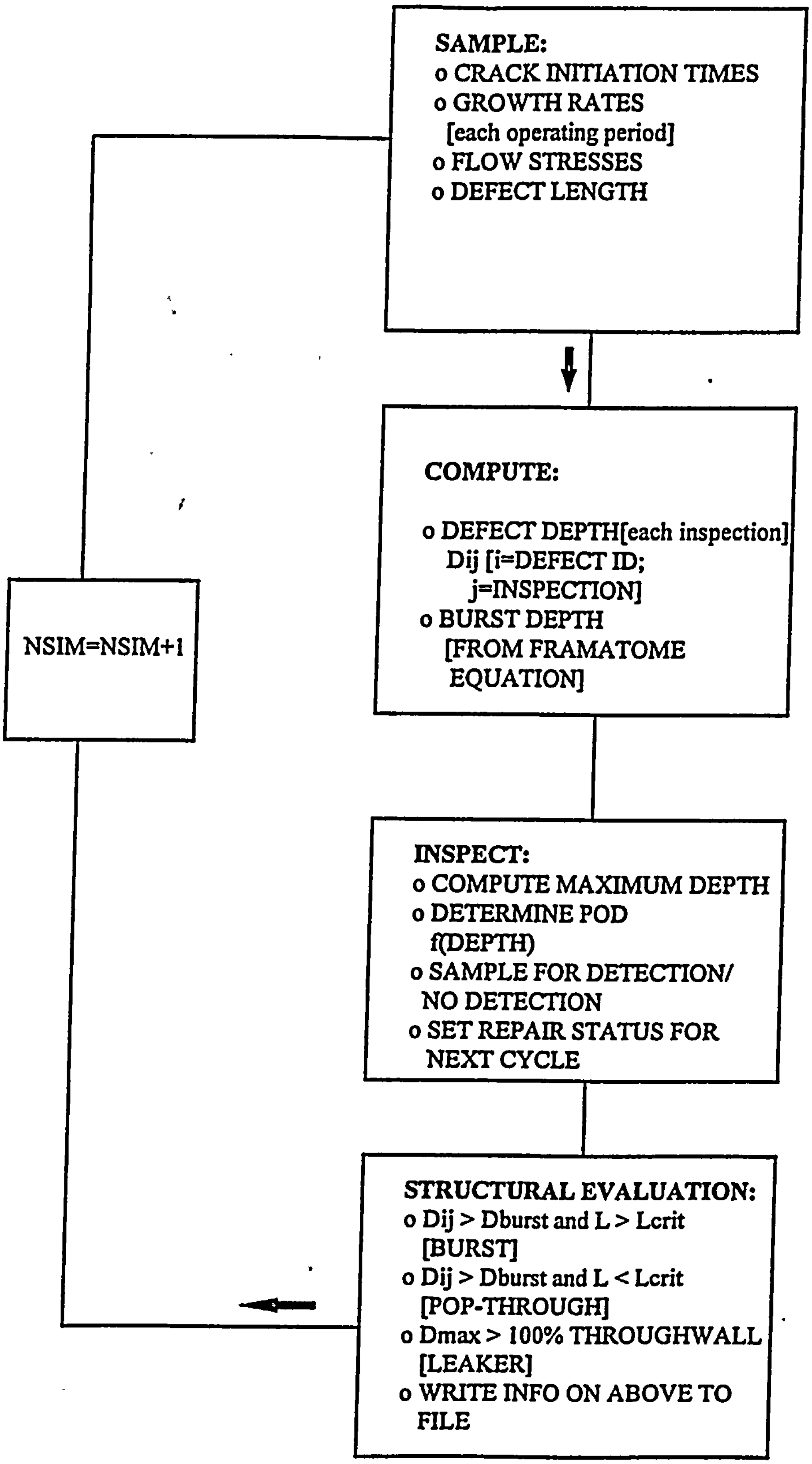


Figure 4.1 SIMULATION SCHEMATIC FOR REPAIR ON DETECTION MODEL

[IDENTICAL FOR ALL DEFECTS]

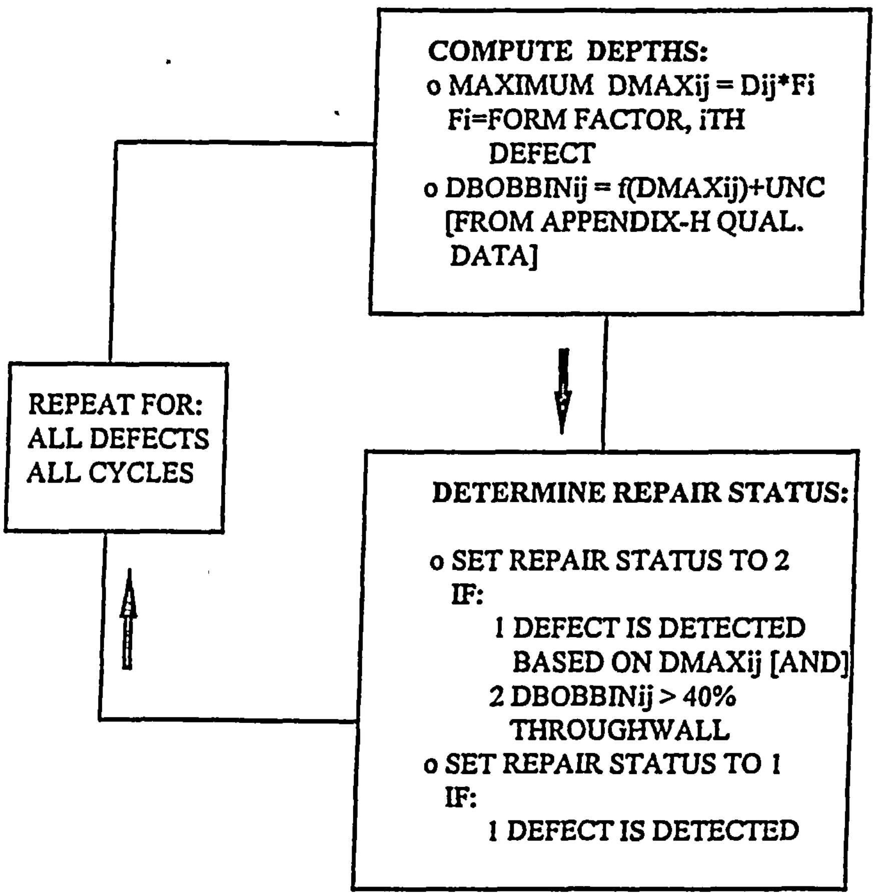


Figure 4.2 REPAIR ON SIZING SCHEMATIC

SECTION 5
STRUCTURAL MARGIN EVALUATION

The probability of a tube burst, given a postulated main steam line break (MSLB) accident at end of cycle, is the basic parameter of interest in the structural margin evaluation. A reasonable figure of merit for the conditional probability of a MSLB tube burst is provided by a historical value of 0.05. A value less than 0.01 provides a recognized benchmark of structural integrity.

The purposes of this section are threefold. The first is to describe the application of the probabilistic models described in Section 4 to the various degradation modes present in the St. Lucie Unit 1 steam generators. The second purpose is to describe the various model benchmarks with St. Lucie Unit 1 data. The third purpose is to summarize the results of the structural margin evaluations for the various modes of degradation present at St. Lucie Unit 1.

5.1 APPLICATION OF THE REPAIR ON SIZING MODEL

The repair on sizing (ROS) probabilistic run time model was specifically designed for the simulation of structural margin in three degradation modes present at St. Lucie Unit 1:

- IGA/ODSCC at eggcrate supports
- IGA/ODSCC at the tubesheet (axial only)
- IGA/ODSCC at vertical supports

A summary of defects at these locations for outages beginning in 1991 is given in Tables 5.1 and 5.2 for the A and B steam generators. For the 1996 outage, which is the primary benchmark for the probabilistic model, a combined total of 11.3 thousand defects were recorded for steam generator A for the three degradation modes considered by the repair on sizing model. Of these, approximately 9 thousand had been recorded in previous inspections. Steam generator B was significantly less affected with a total of 7.2 thousand indications recorded in 1996 attributed to the three degradation modes.

The sheer number of defects involved in the analysis required a division of the problem into computationally manageable subregions. This necessity resulted in the development of a model representing an "average" support. The average support model for the St. Lucie Unit 1 steam generators consists of 10,000 defect initiation sites. The 1993, 1994, 1996 outages are explicitly modelled with the current operating period as the final inspection point at which MSLB burst probabilities are computed. The other required input for the model is described in Section 3. The average support model is generic in that it is applied to all axial IGA/ODSCC modes in the St. Lucie Unit 1 steam generators with a repair on sizing plugging criterion.

Figure 5.1 shows the behavior of the average support model in terms of defects initiated and defects detected at several inspection points. Figure 5.2 shows the average support behavior normalized to the number of observed defects in the A steam generator for the 1996 inspection. The normalization factor required is approximately 14.4 for the most affected steam generator, A. Since the postulated MSLB accident results in a high structural loading only in the one steam generator A, which has substantially more degraded tubes, was chosen for structural margin computations.

The overall probability of burst under MSLB loading for a steam generator with various numbers of observed defects at several support levels can be expressed as:

$$P_B = 1. - (1-P_1)\,(1-P_2)\,......(1-P_N) \qquad [5.1]$$

where: P_B = overall burst probability

$P_N = P_R \times N_N/N_R$

N_N = number of observed defects at N^{th} support

N_R = number of observed defects at average support

P_R = probability of burst at average support

5.1.1 Benchmarking the Repair on Sizing Model

The situation where a defect can progress to become a burst "candidate" under MSLB loading is shown conceptually in Figure 5.3. In essence, the allowable defect growth is probabilistically defined by the difference between the distributions of beginning of cycle, BOC, structural depths and end of cycle allowable depths. This suggests that two benchmarks are of particular importance in the case of St. Lucie Unit 1.

The first is related to the BOC distribution and consists of a comparison of the portion of the population with observed depths greater than 40% through wall for the 1996 outage with that simulated in the model. This comparison is shown in Figure 5.4 for the worst supports in each steam generator. The model predictions are shown to be conservative in this regard.

The second benchmark is related to the extremes at EOC. The comparison of numbers of observed defects in 1996 exceeding 80% through wall with

those predicted by the model provides the second benchmark. Figure 5.5 is the distribution of number of defects exceeding 80% through wall (bobbin coil phase angle) as predicted by the model for steam generator A in 1996. The actual number observed is 6. This is considerably lower than the best estimate of 12 from the simulation. These obvious elements of conservatism in the benchmark results are, in fact, an unavoidable result of the "recipe" for inferring the apparent growth rate distribution from NDE data which inherently includes sizing errors.

5.1.2 Computation of Burst Probabilities as a Function of Run Time for the Average Support

The repair on sizing model was run for three simulated operating cycle lengths to evaluate the variation of burst probability with run time for the current St. Lucie Unit 1 operating cycle. Operating periods of 13, 14 and 15 months were simulated. The 13 month and 14 month simulations consisted of 20,000 trials each. The 15 month simulation consisted of 40,000 trials.

The "raw" outcome from each simulation is shown in Table 5.3 in terms of number of simulated bursts under MSLB loading at end of cycle. Because of the relatively low frequency of burst observed in these cases, the probabilities were adjusted to give high confidence estimates of the frequency of burst. The frequencies were adjusted such that the probability of observing N (or less) occurrences was less than 5%, where N occurrences were observed in the simulation.

As can be seen from Table 5.3 and Figure 5.6, the risk of tube burst versus run time has a characteristic upsweep in the 14 month/15 months run time interval. Also shown in Figure 5.6 is an overall risk for steam generator A due to the IGA/ODSCC attack at eggcrate, tubesheet (axial only), and vertical supports. The overall probabilities were approximately by:

$$P_B = 1 - (1 - P_A)^M \qquad [5.2]$$

where: P_B = burst probability at all supports

P_A = P_{95} at average support

M = 15 = number of average supports in steam generator (generator A = 14.4)

5.1.3 Burst Probabilities for IGA/OSDCC at Eggcrates, Tubesheet, and Vertical Supports

The results obtained for the average supports can be used to apportion the risk of tube rupture to the three subgroups defined by location within the steam generator. The first subgroup consists of defects at eggcrate locations. As seen from Table 5.1, approximately 6,500 of the 11,300 indications present in the A steam generator are at eggcrate locations. Also from Table 5.1, approximately 1,000 indications are present in the vertical supports and 3,800 are present in the tubesheet region.

Table 5.4 shows the risk of tube rupture apportioned to the three degradation modes using Equation 5.1. It can be seen that the most significant component of risk is associated with the eggcrate locations due to the relatively larger number of indications present in the 1996 inspection.

5.2 APPLICATION OF THE REPAIR ON DETECTION MODEL FOR AXIAL DEGRADATION

The repair criterion in the original probabilistic initiation, growth and inspection model was simply one of detection. This model has been well benchmarked in the past. Predicted end of cycle conditions have been demonstrated by later actual inspections to be on the conservative side of very good. This model has been applied to axial degradation at St. Lucie Unit 1 at freespan and drilled tube support locations with results as described below.

The number of additional freespan indications expected at the end of the current cycle for a 15 month run time is about 12. The additional run time represents an increase in total operating time of about 10% relative to the cumulative operating time at the last inspection when 24 freespan indications were found in the worst steam generator. Even for very high slopes in the Weibull initiation function, the total number of expected freespan indications is very low. It is no surprise that in 10,000 simulations of steam generator operation for up to 15 months of operating time no instances of burst under postulated accident conditions were encountered. Similarly no instances of through wall penetration occurred. The conditional probability of burst at postulated accident conditions is less than 0.0001. This is negligible compared to the total conditional probability of burst when other mechanisms are considered. The same is true for the risk of leakage at postulated accident conditions. Freespan degradation as analyzed is not a significant factor in the total structural and leakage integrity analysis.

A more substantial number of indications of axial degradation are expected at drilled support plates in the upper bundle. Approximately 280 additional indications is the expectation after 15 months of operation. With this time frame, the contribution to the conditional probability of tube burst is 0.0017. This is not a substantial term relative to recognized figures of merit.

5.3 APPLICATION OF THE REPAIR ON DETECTION MODEL FOR CIRCUMFERENTIAL DEGRADATION

With a projection scheme the same as NRC Letter 95-05, the expected number of circumferential indications at the end of the current cycle is 61. This number, in essence, refers to the expected number of substantially sized indications. With a plug on detection repair criterion, approximately 0.66 of the previously plugged indications are considered to be present at beginning of cycle. The severity of these BOC indications is effectively increased by the application of a sizing error. The extremes of the distribution of assumed BOC percent degraded area values are increased by this process.

After the severity of the BOC population of circumferential degraded tubes is defined, growth allowances are added to develop the projected end of cycle conditions. Monte Carlo simulations are used to include sizing errors and growth allowances. Typically 10,000 simulations of a steam generator operating cycle are performed. The number of observed bursts at postulated accident conditions at EOC allow calculation of the conditional probability of burst. For a 15 month run period, the contribution of circumferential degradation to the conditional probability of tube burst is 0.0025 using a very conservative projection of end of cycle conditions.

5.4 SUMMARY OF ALL MECHANISMS

As discussed in the preceding paragraphs, the following locations and modes of corrosion degradation were evaluated:

- Axial degradation at the top of the tubesheet in the sludge pile
- Axial degradation at eggcrate and vertical strap (lattice type) tube support structures

- Circumferential degradation at explosive expansion transitions at the top of the tubesheet
- Axial degradation at drilled tube support structures
- Axial degradation at upper bundle freespan locations

The dominant contributors to the conditional probability of burst at postulated accident conditions are axial degradation at lattice type tube supports and in the sludge pile at the top of the tubesheet. Figure 5.7 shows a plot of conditional probability of tube burst versus operating time for the limiting steam generator. Two curves are shown, a summary curve including all mechanisms and a curve showing the contribution of axial degradation in the sludge pile and at lattice type supports.

An upsweep in conditional probability of tube burst begins in the vicinity of 14 months of operation. At 14 months the calculated conditional probability of tube burst is 0.018. At 15 months, the calculated conditional probability of tube burst is 0.044.

Table 5.1

STEAM GENERATOR A SUMMARY

TABLE 5.1
STEAM GENERATOR A SUMMARY

SG A	91	91	93	93	93	94	94	94	96	96	96
	0%-19%	20%-39%	0-19%	20-39%	40%+	0-19%	20-39%	40%+	0-19%	20-39%	40%+
Elevation	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count
01 H	440	275	603	342	10	523	476	19	608	659	172
02 H	351	222	471	276	14	443	394	8	482	478	113
03 H	301	167	394	227	6	377	281	4	417	378	67
04 H	229	107	327	139	5	326	201	2	354	260	38
05 H	169	85	244	93	3	239	147	1	278	235	32
06 H	108	39	160	68		177	70	1	193	136	12
07 H	54	14	73	19		90	36		116	53	7
08 H	18	13	37	24		46	18	2	48	31	1
09 H	104	102	141	130	4	139	155				
10 H			1			2			1	1	
01 C	125	41	167	45		169	69		186	88	9
02 C	105	39	152	45		148	61		186	83	8
03 C	86	32	113	49		131	63		142	89	8
04 C	51	22	93	37		77	42		101	58	9
05 C	39	22	62	25		76	34		82	49	5
06 C	27	14	50	19		43	26		59	33	2
07 C	18	8	34	13		37	29		32	34	7
08 C	6		4	5		5	1		9	4	1
09 C	129	96	179	133	1	190	138				1
10 C	1		1	29		2	1				
VS 1	17	10	39	27		67	38	3	75	74	2
VS 2	131	45	257	115	5	332	140		502	337	6
VS 3	4		9	3		11	7		18	15	
TS H	1046	603	1615	649	5	1538	1086	4	1837	1690	73
TE H			4			2			1	1	
TS C	47	21	112		1	113	45	1	140	55	
TE C			1								
DC B			1	2		4	3		3	3	
DH B		1	2	1		2	2		4	2	
DH T	2		1	1						4	
DC H									4		
DH H									8		
DC T						2				1	
TOTALS	3608	1978	5347	2516	54	5311	3563	45	5886	4851	573

TABLE 5.2
STEAM GENERATOR B SUMMARY

SG B	91	91	93	93	93	94	94	94	96	96	96
	<20	>=20	<20	20-39%	>=40%	<20	20-39%	>=40	<20	20-39%	>=40
Elevation	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count	Count
01 H	291	232	392	338	24	477	442	17	531	646	279
02 H	163	130	237	181	8	254	222		278	305	108
03 H	96	52	134	92	2	137	127	3	178	187	62
04 H	56	32	74	56	2	94	70	1	106	92	31
05 H	53	25	78	37	1	86	49	1	124	75	21
06 H	32	12	48	26		66	32		78	53	10
07 H	21	8	37	15		38	27		49	43	7
08 H	3	4	11	9		8	12		18	9	8
09 H	47	38	73	53	4	78	41				
10 H		1		1	1	0	1		1	0	
TS H	523	342	855	479	5	1010	591		1113	872	42
TE H			1			0	1				
01 C	93	34	148	47		148	44		169	71	11
02 C	58	36	91	44	1	79	46		102	60	7
03 C	44	13	74	27	1	76	45	1	86	49	6
04 C	40	22	66	36		73	38		78	51	8
05 C	36	18	58	30	2	50	39		53	52	6
06 C	24	8	25	22		32	24		37	25	8
07 C	18	5	24	15		23	19		27	17	7
08 C	4	4	7	6	1	6	6	1	8	7	5
09 C	83	55	124	65		123	54				
10 C	1	2	4	2		3	3				1
VS 1	4	2	11	12		36	14		55	46	9
VS 2	72	45	182	109	5	241	142	1	343	260	18
VS 3			3			2	5		5	8	1
TS C	56	35	115	61	1	116	53		118	62	4
TE C									1		
DC B			1			3			3	1	
DH B	1	1	1	1		2	1		2	2	
DH T	1	1	1	3		6	3		14	5	
DC H											
DH H											
DC T			1			1			3	2	
TOTALS	1820	1157	2876	1767	58	3268	2151	25	3580	3000	659

TABLE 5.2
STEAM GENERATOR B SUMMARY

TABLE 5.3

BURST PROBABILITY AS FUNCTION OF RUN TIME

[AVERAGE SUPPORT]

OPERATING CYCLE (LENGTH MONTHS)	NUMBER OF OCCURRENCES	P (Best Estimate)	P (95)	$P_T = [1.0 - P(95)]^{15}$
13	7	0.00035	0.00066	0.0098
14	12	0.0006	0.00098	0.0145
15	44 (88 for 40,000 simulations)	0.0022	0.00263	0.0387

TABLE 5.4

ALLOCATIONS OF TUBE BURST PROBABILITY TO SPECIFIC MODES

14 AND 15 MONTH RUN TIMES

SG-A		1996 INDICATIONS	N/NSIM	P_{BURST} [14 MONTHS]	P_{BURST} [15 MONTHS]
	Eggcrates	6486	8.24	0.0080	0.0215
	Vertical Supports	1029	1.31	0.0013	0.0034
	Tubesheet (Axial)	3795	4.82	0.0047	0.0126
SG-B					
	Eggcrates	4283	5.44	0.0053	0.0142
	Vertical Supports	745	0.946	0.00093	0.0024
	Tubesheet (Axial)	2211	2.809	0.0027	0.0073

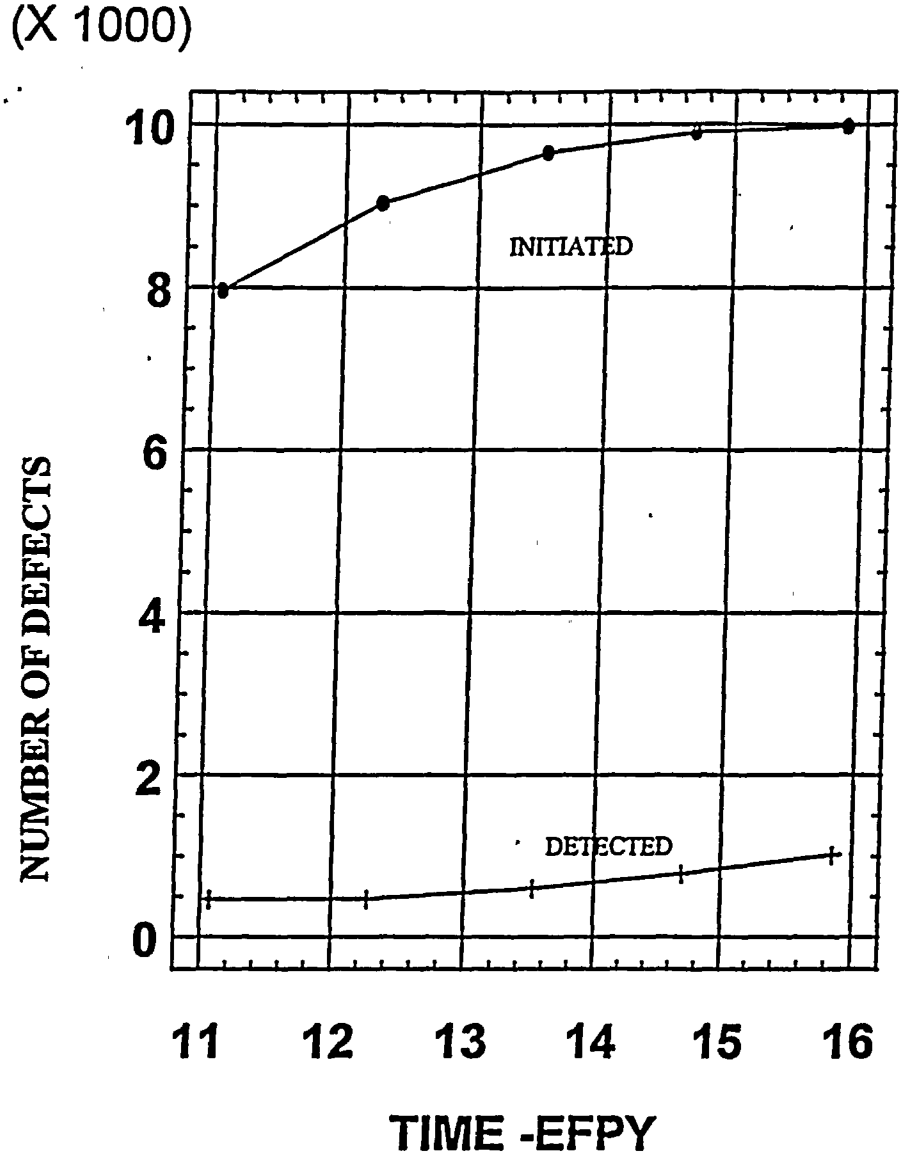


Figure 5.1 ST. LUCIE UNIT 1 SIMULATION RESULTS
INITIATED AND DETECTED DEFECTS VS. TIME

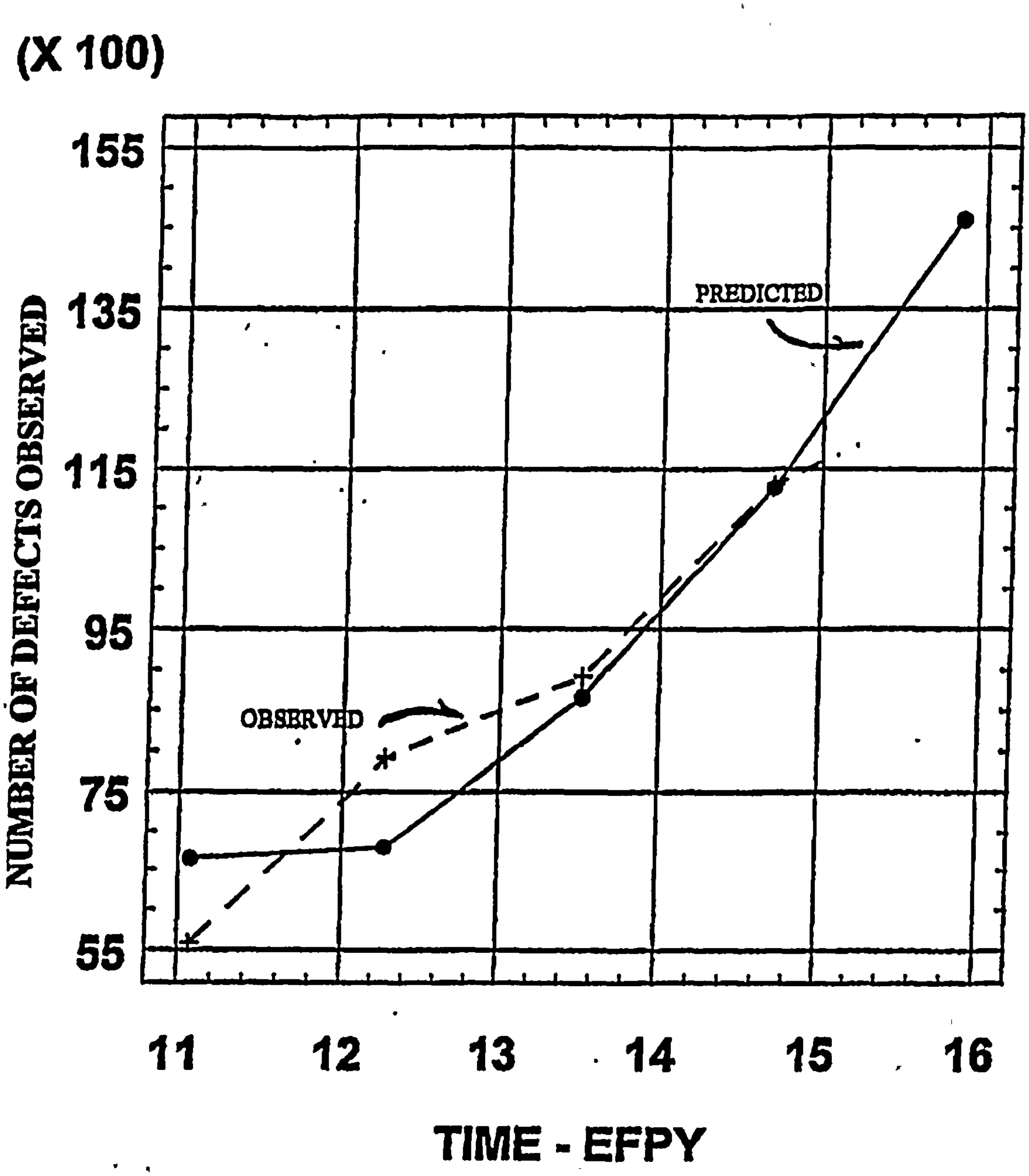


Figure 5.2 ST. LUCIE UNIT 1 SIMULATION RESU LTS - SG-A PREDICTED (NORMALIZED) AND OBSERVED DEFECTS VS. TIME - EFPY

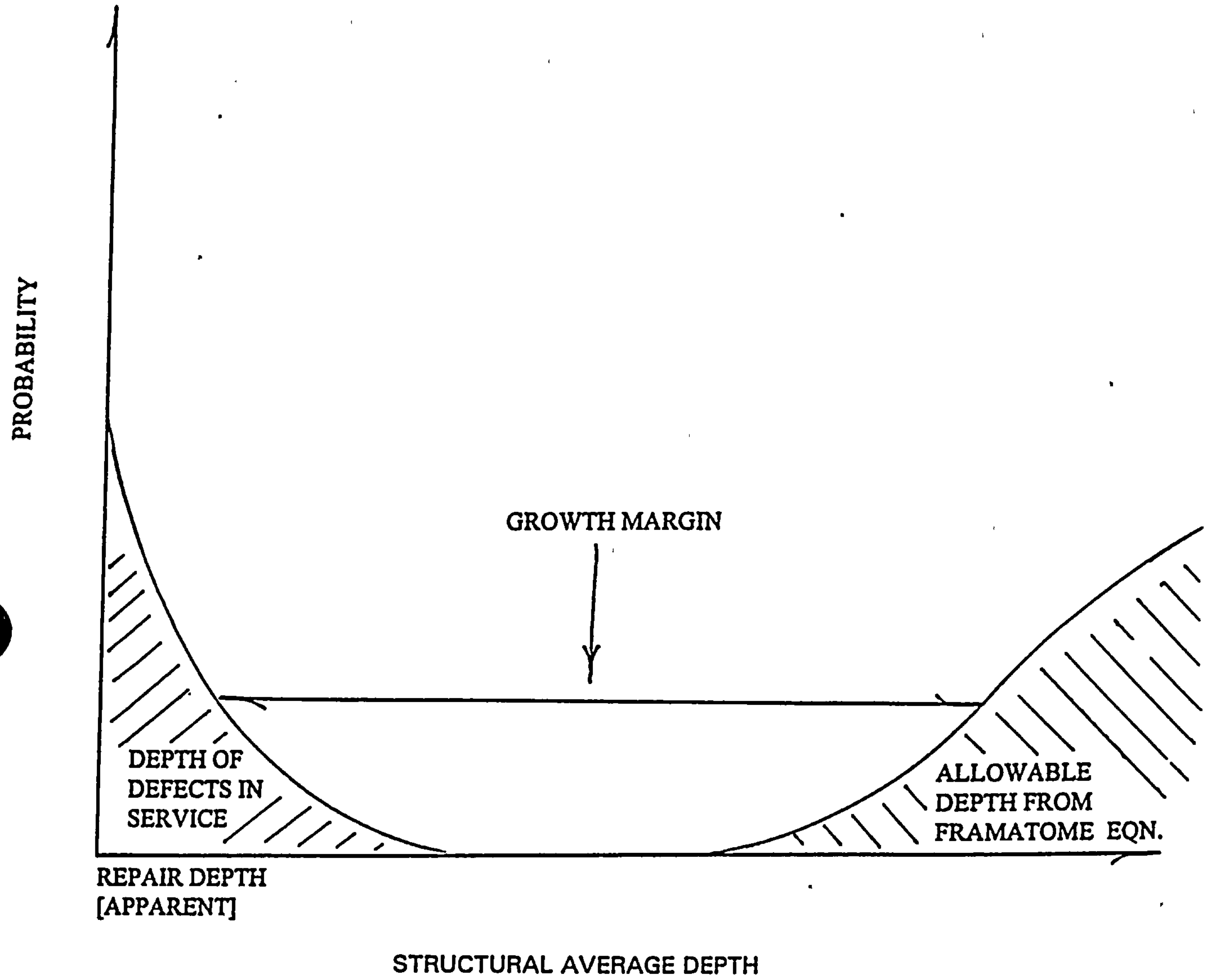


Figure 5.3 SCHEMATIC OF GROWTH MARGIN

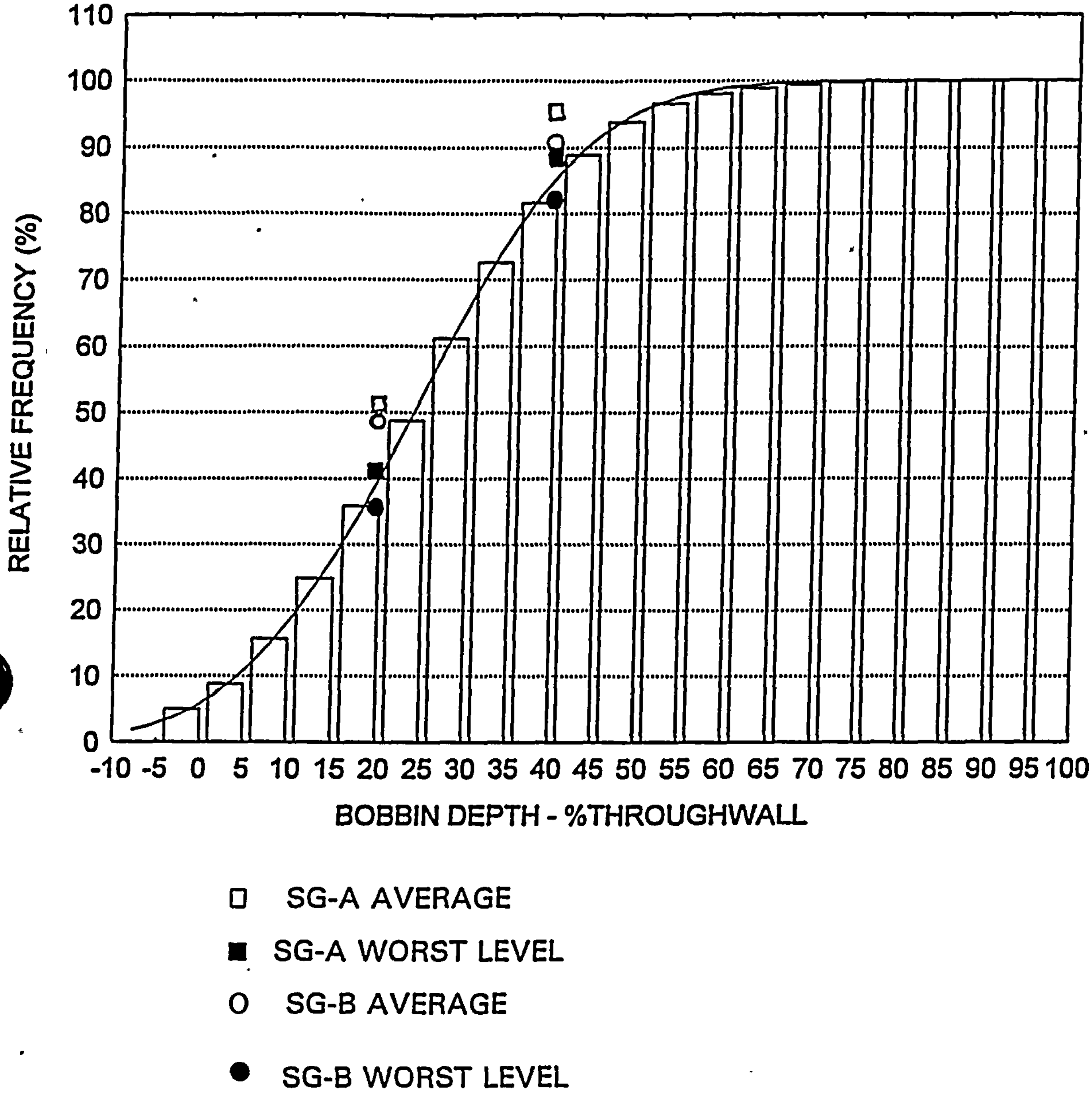


Figure 5.4 ST. LUCIE UNIT 1 SIMULATION RESULTS
PREDICTED DISTRIBUTION OF BOBBIN DEPTHS [1996]

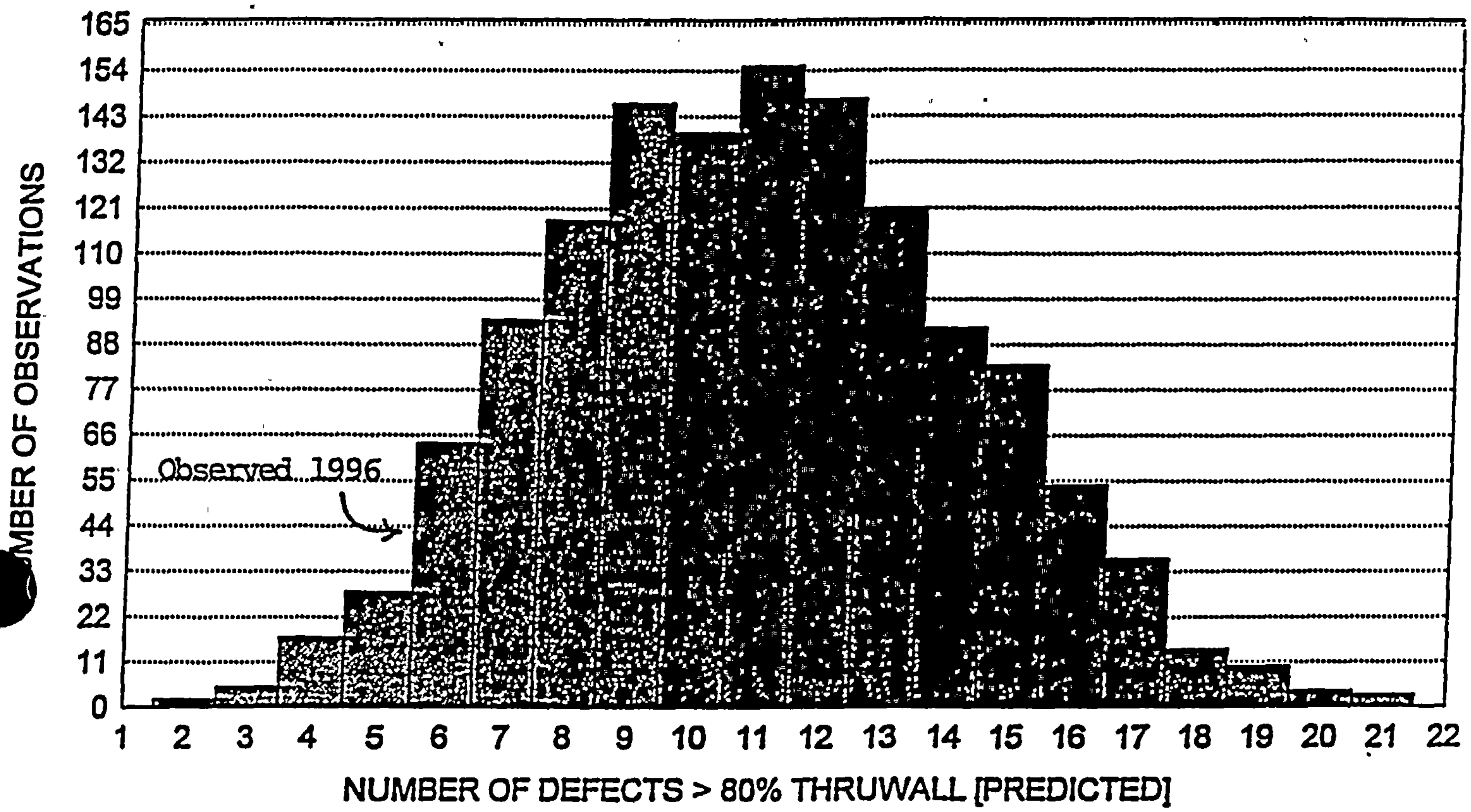


Figure 5.5 PREDICTED NUMBER OF LARGE DEFECTS - SG A
[FROM SIMULATION RESULTS]

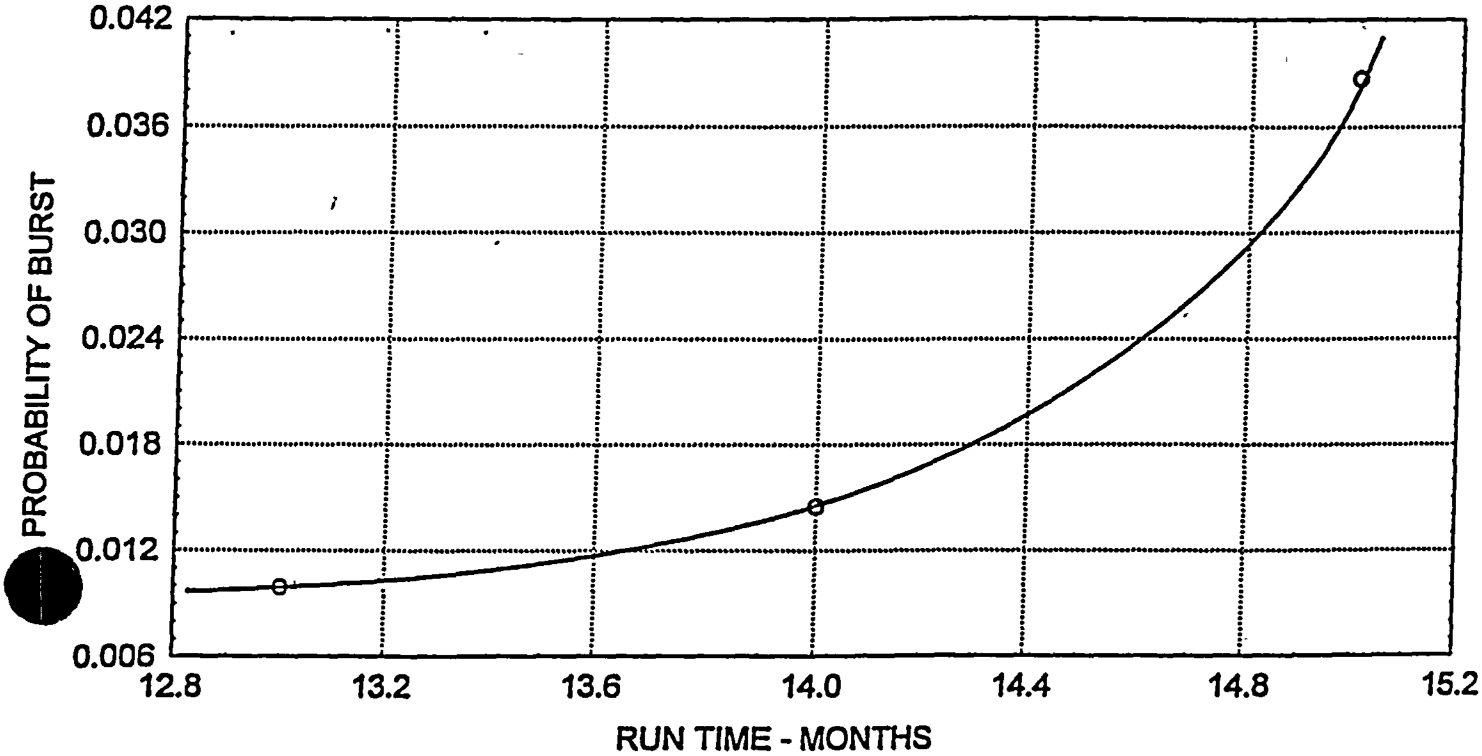


Figure 5.6 ST. LUCIE UNIT 1 SIMULATION RESULTS - SG A
PROBABILITY OF BURST VS. RUN TIME
IGA/ODSCC AT: EGGCRATES, TUBESHEET, AND VERTICAL SUPPORTS

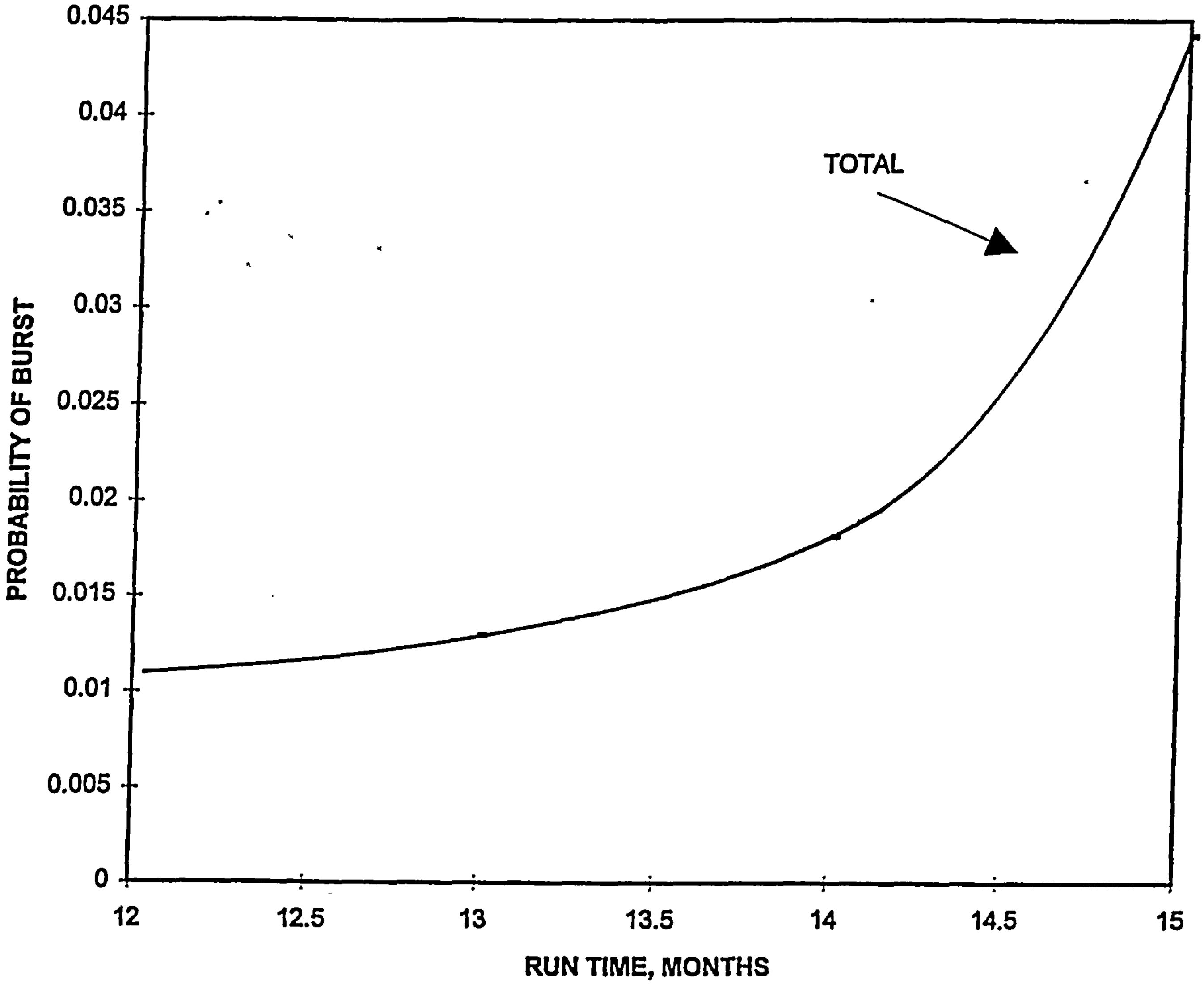


Figure 5.7 CALCULATED CONDITIONAL PROBABILITY OF TUBE BURST AT POSTULATED ACCIDENT CONDITIONS VERSUS RUN TIME

SECTION 6

LEAKAGE EVALUATION

Three types of leakage analyses were conducted. The most sophisticated models were applied to axial degradation in the sludge pile and at lattice type supports and to circumferential degradation at explosive expansion transitions. An early leakage model for axial freespan cracking was applied to axial degradation at freespan and drilled tube support locations. As expected, the mechanisms which were dominant relative to probability of burst are the mechanisms of most concern relative to leakage.

Treatments of leakage from circumferential degradation, with plug on detection and from axial degradation with a plug on sizing repair criterion included a probabilistic treatment of crack morphologies. Apportioning of circumferential degraded area to leakage paths was described in Section 2.2. Two elements of conservatism are the absence of ligament effects as cracks penetrate the wall and a scheme to maximize the leak rate for a given array of cracks by devoting all of the degraded area to drive the largest leaking cracks through wall. Variations of crack morphology for axial degradation were obtained by sampling of the ratios of maximum crack depth to structurally significant crack depth. Actual data was obtained from pulled tubes from Plant A and applied to St. Lucie Unit 1. For a given structurally significant depth, there exists a range of possible crack shapes. Self similar propagation of these sampled shapes was used to define the extent of through wall penetration needed for leak rate calculations. The much fewer instances of freespan and drilled tube support axial degradation were modelled using only a semi-elliptical physical crack shape.

6.1 PROJECTED LEAK RATES FOR AXIAL DEGRADATION IN THE SLUDGE PILE AND AT LATTICE TYPE SUPPORTS

The plug on sizing structural integrity simulation provides an output file containing information describing every through wall crack encountered in the simulation process In addition, a similar description is provided for each defect which can pop-through under MSLB loading. The information for each defect includes:

- Structural average depth
- Maximum depth
- Structural length
- Flow stress

The frequency and character of the defects determine the probability of various levels of leakage under postulated MSLB conditions at end of cycle.

The basic frequency of leakage was computed for the "average" support for operating periods of 13 months, 14 months and 15 months. These results are shown in Table 6.1 together with estimates of the probability of leakage for steam generator A.

The probabilities associated with various amounts of leakage were computed using the LEAKMC algorithm described in Figure 6.1. The LEAKMC algorithm is a straightforward Monte Carlo simulation which computes the number and magnitude of leaks in a complete steam generator. The number of simulated leaking defects in the entire steam generator is obtained by first sampling from a binominal distribution using the average level frequency of leak computations and the number of equivalent levels in the steam generator.

For each leaking defect obtained in the above process, a leak rate is sampled from the ROS (burst) model output file. All leakage for a given Monte Carlo trial is obtained by summing the individual leak rates. The distributional output is shown in Figure 6.2 for 5,000 simulations. The upper 95/95 projected leak rate for a 15 month run time is 2.94 gpm.

6.2 PROJECTED LEAK RATES FOR CIRCUMFERENTIAL DEGRADATION

Leak rates for circumferential degradation were determined using the CIRC95 program developed on the industry-wide EPRI circumferential cracking program. The principal authors of this program are APTECH and Westinghouse. A distribution of EOC leak rates at postulated accident conditions was constructed for various run times. There was no large variation in the 95% upper bound leak rates for run time from 12 to 15 months. The 95% upper bound leak rate from 10,000 simulations after a 15 month run time is 0.85 gpm. This leak rate can be converted to a mass flow rate using the density of water at room temperature.

6.3 PROJECTED LEAK RATES FROM DEGRADATION AT DRILLED SUPPORT AND FREESPAN LOCATIONS

The issue of leakage from freespan indications can be settled quickly. No through wall leaking freespan cracks are expected. In contrast, leakage at postulated accident conditions is expected from axial degradation at drilled tube support locations, albeit at low levels of probability. For this degradation mode, after 15 months of operation the estimated probability of leakage is less than 2%. Given that any leakage occurs, the 95% upper bound leak rate is about 1 gpm. Since 98% of the time no leakage is expected, the contribution to the 95% bound leak rate is zero. Hence, leakage from axial degradation at either freespan or drilled tube support plates is expected to be inconsequential.

6.4 TOTAL PROJECTED LEAK RATE

The main contributors to projected end of cycle leakage at postulated accident conditions are axial degradation in the sludge pile and at lattice type supports and expansion zone circumferential degradation. The sum of the 95% upper bound leak rates is less than 4 gpm for 15 months of operation. The risk of very large leak rates is roughly comparable to the risk of tube burst. The projected 95% upper bound total leakage is far removed from allowable leak rates from a site specific radiological dose consequence St. Lucie Unit 1 analysis. This analysis indicated an allowable leak rate substantially in excess of charging pump capacity. Conditional probability of burst rather than projected leak rates is the limiting consideration at St. Lucie Unit 1.

TABLE 6.1

SUMMARY OF LEAKAGE PROBABILITIES

[SLUDGE PILE AND LATTICE TYPE SUPPORTS]

RUN TIME (MONTHS)	NUMBER OF LEAKERS (20K SIMULATIONS)	P (LEAK) (AVERAGE SUPPORT	P (LEAK) SG-A
13	1122	0.059	0.59
14	1843	0.0966	0.78
15	3068	0.154	0.92

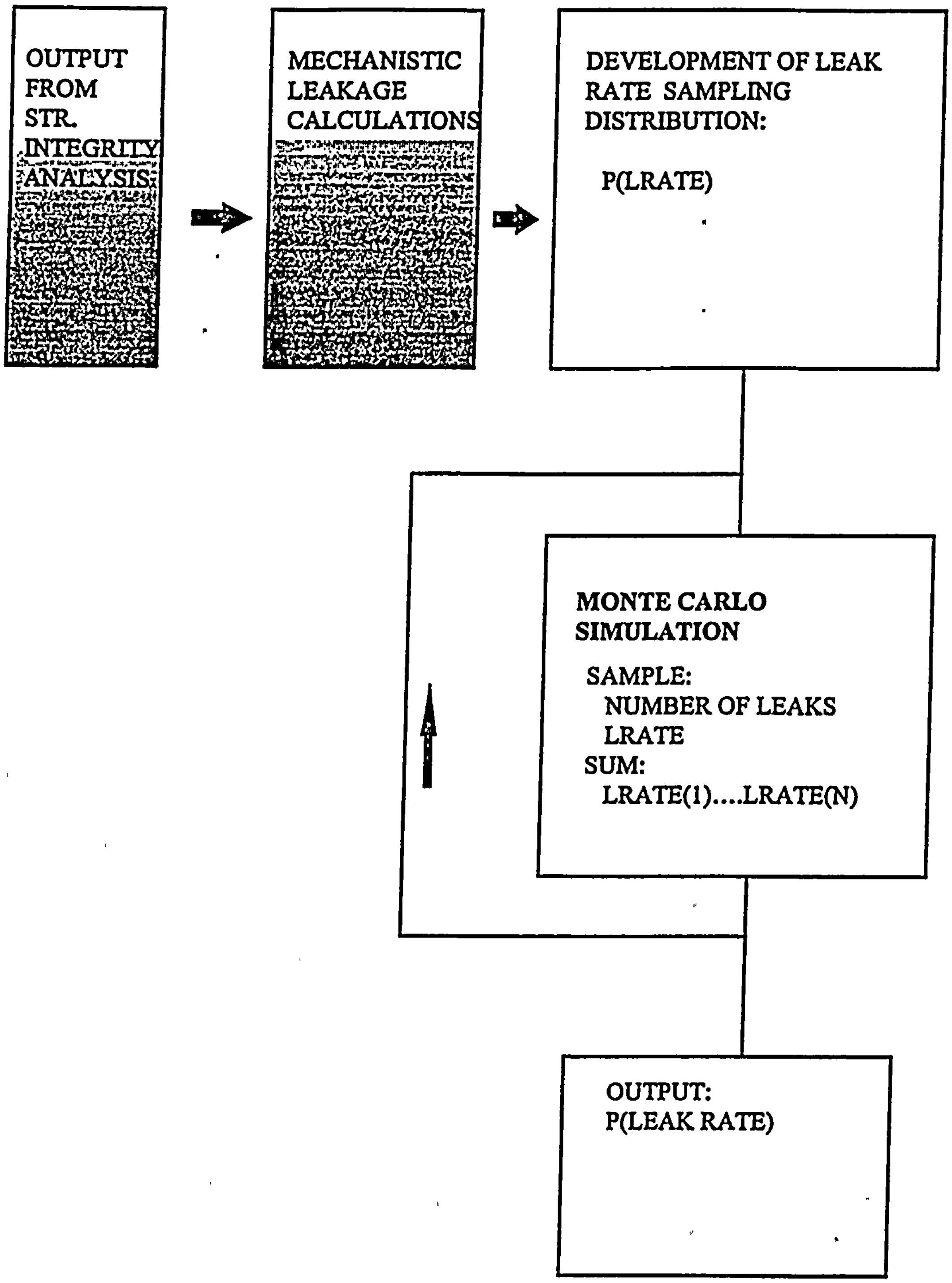


Figure 6.1 SCHEMATIC OF LEAKMC ALGORITHM

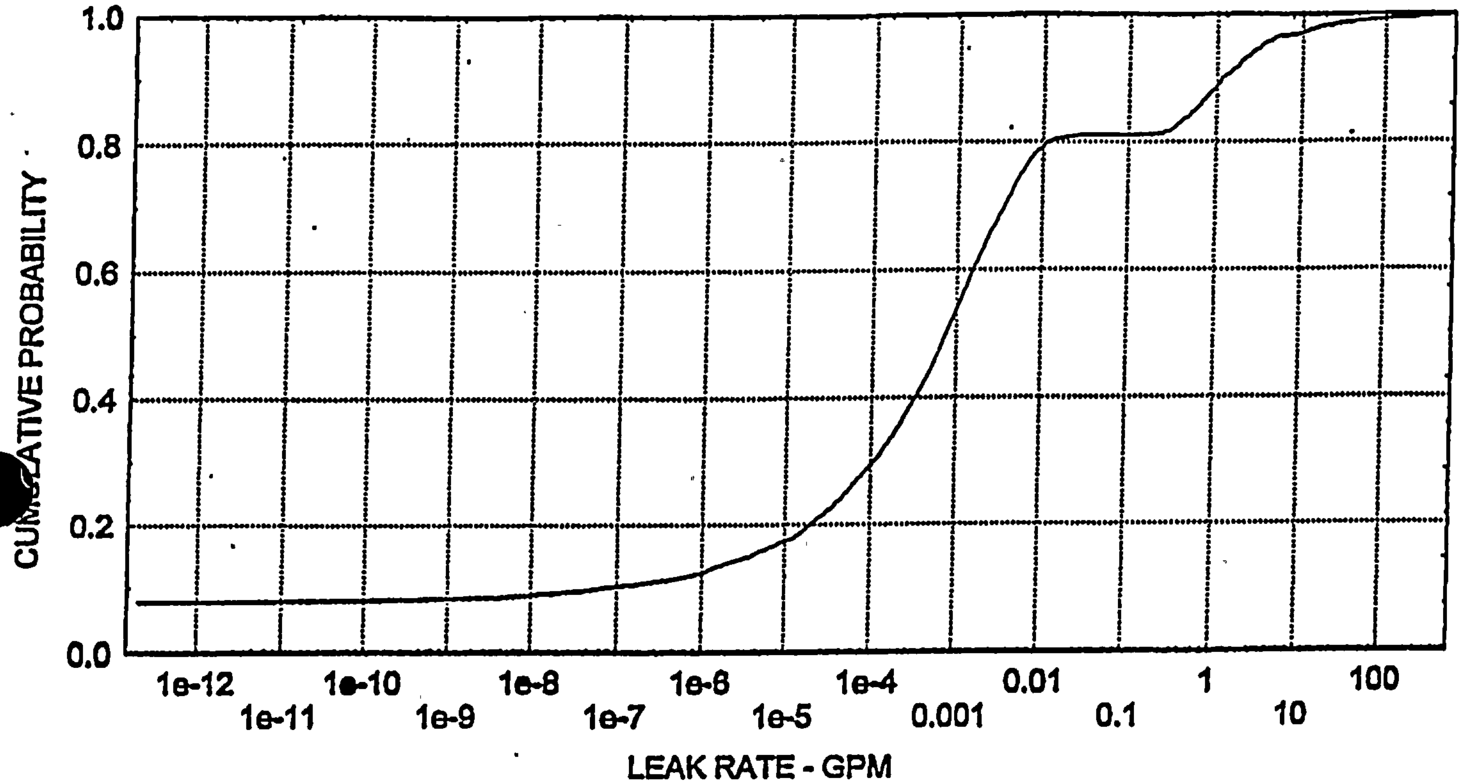


Figure 6.2 CUMULATIVE DISTRIBUTION OF LEAK RATES FOR POSTULATED STEAM LINE BREAK ACCIDENT AFTER 15 MONTHS OF OPERATION ST. LUCIE UNIT 1 STEAM GENERATOR A [FOR SLUDGE PILE AND LATTICE TYPE SUPPORTS]

SECTION 7
SUMMARY AND CONCLUSIONS

The significance of corrosion degradation to the performance of steam generator tubing at St. Lucie Unit 1 was evaluated for the final cycle of operation of the unit. Replacement of steam generators will begin in the fall of 1997. Probabilistic methods were applied to make end of cycle projections of the structural and leakage integrity of steam generator tubing experiencing corrosion degradation.

Over the past 12 years of operation, steam generator tubing at St. Lucie Unit 1 has experienced substantial corrosion degradation. Eddy current inspection data and pulled tube examinations show the degradation to be combinations of intergranular attack, IGA and stress corrosion cracking, SCC, on the outer diameter of the tubing. The five types of locations where this degradation occurs and the modes of corrosion are:

- circumferential degradation at explosive expansion transitions at the top of the tubesheet
- axial degradation at the top of the tubesheet in the sludge pile
- axial degradation at eggcrate and vertical strap tube support structures
- axial degradation at drilled tube support structures
- axial degradation at upper bundle freespan locations.

Several probabilistic run time models were employed. Modeling included scenarios of both plug on detection and plug on sizing, depending on the mode and location of degradation. Circumferential degradation at the top of the tubesheet, as well as axial degradation at freespan and drilled tube support locations, was modeled using a plug on detection scenario coupled with an RPC inspection scheme. Modeling of axial degradation at other locations employed a bobbin probe inspection with a plug on sizing scenario. Probabilistic computations of the conditional probability of burst and the magnitude of leakage under accident conditions were developed. Calculational procedures were benchmarked by comparing predictions of the number and severity of eddy current indications with actual observations and by comparing predicted versus observed leakage during in situ testing.

The dominant contributor to the condition probability of burst is axial degradation in the sludge pile and at lattice type supports. This is basically due to the number of indications involved. Degradation growth rates are largely independent of location.

The projected end of cycle leak rates at postulated accident conditions were reasonably small and not markedly sensitive to run time. After 15 months of operation the total projected 95% upper bound leak rate is less than 4 gpm. Site specific analyses of dose rate consequences for various leak rates demonstrate a leakage limit far in excess of this projected value. A leak rate in excess of the charging pump capacity will not exceed 10 CFR 100 and GDC 19 accident dose limits.

The conditional probability of burst under postulated accident conditions is the limiting concern. When all corrosion mechanisms are considered, the projected end of cycle conditional probability of burst is 0.018 for a run time of 14 months. An upsweep in the conditional probability of burst is noted for longer run times. For a run time of 15 months, the calculated conditional probability of burst is 0.044.

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