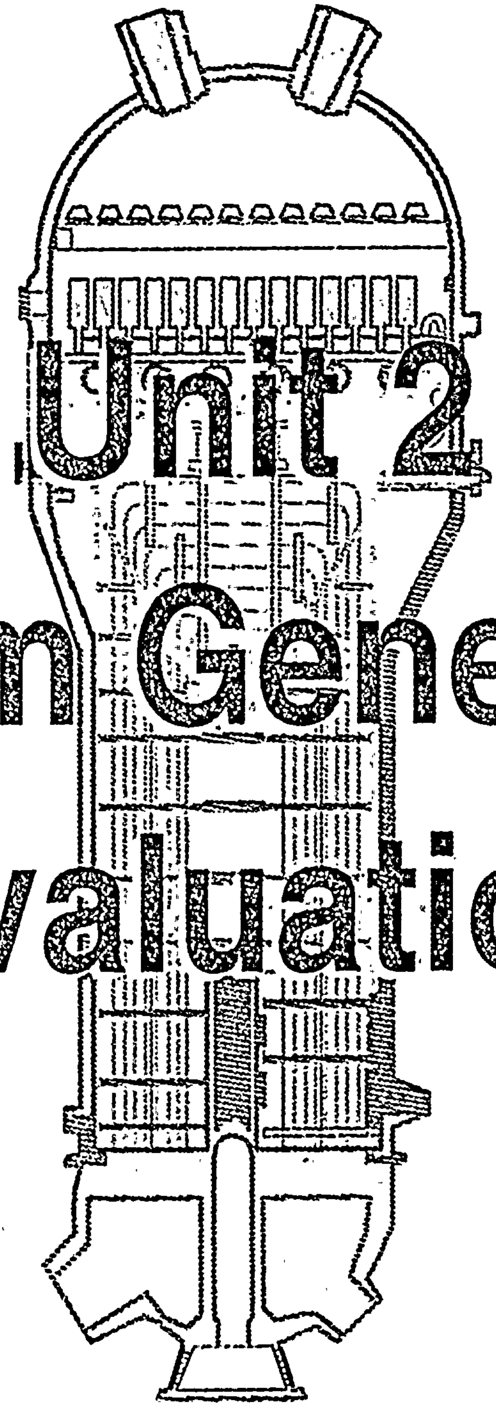
Palo Verde Nuclear Generating Station



Unit 2 Steam Generator Evaluation

August 1995

PALO VERDE NUCLEAR GENERATING STATION

UNIT 2 STEAM GENERATOR EVALUATION

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I. EXECUTIVE SUMMARY

This report describes the efforts conducted by Arizona Public Service (APS) to address ARC region Outside Diameter Stress Corrosion Cracking (ODSCC) in the Unit 2 steam generators at the Palo Verde Nuclear Generating Station (PVNGS). Other tubing degradation mechanisms found in Unit 2, were not considered in this assessment, as comprehensive eddy current testing (ECT) examinations indicate that these mechanisms exhibit slow growth and are, therefore, bounded by this report and past analyses. From an analytical perspective, Cycle 6 operation has been justified for Unit 2 based on the inspection results from plant outages U2M5-1, U2M5-2 and U2R5. The assessment contained in this report is structured to support continued operation of Unit 2 until the next refueling outage. U2R6 is currently scheduled for mid-March 1996, which represents a 12 month operating run for Cycle 6.

The steam generator structural and leakage integrity analyses are similar to the evaluations performed and presented to the USNRC Staff for Unit 1 in August of 1994 and Unit 3 in May of 1995. The analytical framework was validated by recent inspections in Unit 1 in April 1995. Based on specific issues associated with Unit 2, APS has incorporated improvements to the inspection techniques and engineering models. These improvements include:

- PVNGS use of the Plus Point probe to conduct eddy current inspections in Unit 2 during U2R5. The probe design provided field demonstrated improvements in defect detection and characterization.
- Additional review of PVNGS specific tube pull results and industry data to support the relevance of characterizing ARC region defects with MRPC signal response.
- Benchmarking of statistical model predictions with actual Unit 2 ECT inspection results from U2R4, U2M5-1, U2M5-2 and U2R5.

The report also describes the elements of the PVNGS Degradation Management Program which provides a defense-in-depth approach to preventing a challenge to nuclear safety. Program actions include preventative measures such as steam generator secondary chemistry improvements, primary temperature reductions, diagnostic equipment upgrades including the addition of N-16 monitors, comprehensive steam generator inspections and conservative plugging criteria. The PVNGS program is also prescriptive by specifying strict administrative controls on primary-to-secondary leakage and RCS activity levels, developing enhanced monitoring and emergency operating procedures, and continued operator training.

Based on the analyses and actions described in this report, APS concludes that the structural and leakage integrity of PVNGS Unit 2 steam generators will be maintained, and that Unit 2 can be safely operated until the scheduled refueling at the end of Cycle 6.

II. PROBLEM DESCRIPTION AND SAFETY ASSESSMENT

The purpose of this report is to describe the efforts conducted by APS to address the presence of ARC region[1] Outside Diameter Stress Corrosion Cracking (ODSCC) in the Unit 2 steam generators. Other degradation mechanisms found in Unit 2, such as tube support and loose part fretting wear, circumferential cracking at the tube sheet transition, and secondary side corrosion outside the ARC region were not considered in this assessment. Based on the results of comprehensive ECT examinations, these mechanisms exhibit slow growth and are, therefore, bounded by this report and past analyses performed by APS. From an analytical perspective, Cycle 6 operation is justified in Unit 2 based on the midcycle and refueling inspection results during Cycle 5. The assessment contained in this report is structured to support continued operation in Unit 2 up to 12 months following U2R5 until the next scheduled refueling outage. The refueling outage is currently scheduled for mid-March 1996 which represents a 12 month operating run for Unit 2 Cycle 6.

A. PVNGS Steam Generator Description

The PVNGS Nuclear Steam Supply System (NSSS) uses two recirculating steam generators which are vertical tube and shell heat exchangers approximately 68 feet in height with a steam drum diameter of 20 feet. The System80 steam generators were designed and fabricated by Combustion Engineering (CE), and are the only operating units of this design. Each steam generator contains 11,012 Alloy 600 tubes which are 3/4 inch OD, and have a nominal wall thickness of 0.042" with an average heated length of 57.75 feet. The tubes were explosively expanded into the tubesheet for the entire tubesheet thickness. The tubing in Unit 2 was manufactured by Noranda to the requirements of ASME SB-167 as supplemented by CE specification requirements restricting carbon content to 0.05 percent and maximum yield strength of 55,000 psi. These requirements assured a relatively high temperature final anneal of 1806 °F. The tubes are arranged in rows, with all tubes in a given row having the same length. The rows are staggered, forming a triangular pitch arrangement. The shorter tubes, which have 180° bends, are at the center of the tube bundle in the first 18 rows. All subsequent rows have double 90° bends. The horizontal supports are of eggcrate design, while the bend and horizontal regions are supported by batwing and vertical lattice supports respectively. The supports are manufactured from 409 ferritic stainless steel. Diagrams of the steam generators, including flow paths are provided in Figures II-1, and II-2.

PVNGS Unit 2 commenced operation in April 1986, and at the end of Cycle 5, the steam generators had accumulated approximately 50,500 effective full power hours.

1. For brevity, the axial free span and support defects found in the upper bundle of the Units 1, 2 and 3 steam generators at PVNGS are referred to as ARC region ODSCC. The area of interest in the tube bundle has been previously defined in References 1 and 2.

B. ARC Region ODSCC Description

The ARC region freespan ODSCC phenomenon was first recognized in PVNGS Unit 2 during the ECT inspections conducted in the Spring of 1993 during the fourth refueling outage (U2R4). This mechanism had resulted in the rupture of a tube during power operation at the end of Cycle 4 in Unit 2. This event, and the subsequent root cause of failure assessment, was discussed in depth in the "Unit 2 Steam Generator Tube Rupture Analysis Report" submitted to the NRC staff as enclosure (2) to William Conway's letter 102-02569-WFC/JRP dated July 18, 1993. Based on the results of the root cause evaluation, which included information from laboratory examinations of tubes removed from the Unit 2 steam generators, APS concluded that a unique free span axial cracking phenomenon had developed in the upper tube bundle region of the Unit 2 SGs. The defects were determined to be outside diameter Intergranular Stress Corrosion Cracking (IGSCC) which formed due to a combination of contributing factors including: a susceptible region of high quality and contaminant concentration, tube-to-tube crevice formation, bridging ridge-like deposits, increased sulfate levels, and a caustic crevice pH. Additional factors, such as, less than standard metallurgical microstructures for High Temperature Mill Annealed (HTMA) tubing and cold working at the OD tube surface from manufacturing scratches, were also observed on some of the tube samples removed from Unit 2.

Since the Reference 1 submittal, APS has continued to aggressively assess this phenomenon with respect to the affected tube population, crack growth rates, ECT techniques and defect morphology. Additional tubes were subsequently removed from Units 2 and 3, and the results are summarized in References 3-6. Thermal-hydraulic models have been developed and refined in an effort to define an empirical relationship between steam generator design and inspection results.

However, due to the complex synergy of these causal factors, APS has not determined the relative weight of each factor to the original tube failure. This issue has required that APS develop a steam generator degradation management program for this mechanism in all three PVNGS Units. Due to design and operation similarities in the PVNGS Units, APS had to consider that this accelerated corrosion mechanism might be transportable to Units 1 and 3. Consequently, the scope of ECT inspections for U1R4, U3M4 and U3R4 were adjusted to ensure that if the phenomenon was at work in Units 1 and 3, it would be discovered. As noted in Reference 2, neither bobbin nor MRPC ECT methods discovered any free span axial cracking in the Unit 1 steam generators at the end of Cycle 4. Therefore, APS concluded that significant or accelerated ARC region ODSCC was not at work in Unit 1, and no cycle length restrictions were imposed for Cycle 5.

ECT crack indications exhibiting the same characteristics of bundle location, deposition and tube-to-tube crevice (bowing) were observed in Unit 3 during the U3R4 inspection. Upon completion of the U3R4 inspection program, a total of 17 ARC region defects were identified. The defects were considered to be bounded by the analyses performed for Unit

2 in Reference 1, and APS elected to inspect the Unit 3 steam generators after six months of operation (Reference 7). The results of this inspection are summarized in Reference 35. In May 1995, APS presented to the USNRC Staff an evaluation justifying an 11 month operating run in Unit 3 (Reference 38), which when concluded, the unit will be shutdown for refueling and the steam generators re-inspected.

During inspections conducted in U1R5 in April 1995, ARC region defects were identified in both the Unit 1 steam generators. The discovery was not unexpected, and now confirms the presence of this mechanism in all six PVNGS steam generators although only Unit 2 has exhibited a significant degradation pattern. No defects found in Unit 1 exceeded Regulatory Guide 1.121 structural limits after 15 months of operation. The inspection findings were consistent with the analyses presented to the USNRC in August 1994 (Reference 2), and no cycle length restrictions were required for Unit 1 Cycle 6 operation.

C. Safety Assessment

The safety significance associated with the operation of Unit 2 until the scheduled U2R6 refueling outage has been evaluated by APS. The results of comprehensive inspection programs conducted in U2M5-1, U2M5-2 and U2R5 have been assessed statistically to determine the impact of leaving undetected ARC region defects through the remainder of Cycle 6 operation in Unit 2. The analyses concluded with high confidence that the conservative safety margins established in Regulatory Guide 1.121 are maintained. In assessing the safety significance of the current conditions in the PVNGS Unit 2 steam generators, APS has used, as guidance, the standards as defined in 10CFR 50.92 for determining whether a significant hazards consideration exists. The Code states in part that a significant hazard is not involved if the condition would not: (1) Involve a significant increase in the probability or consequences of an accident previously evaluated; or (2) Create the possibility of a new or different kind of accident from any accident previously evaluated; or (3) Involve a significant reduction in the margin of safety. A discussion of these standards as they relate to Unit 2 operation until U2R6 follows:

<u>Standard 1</u> -- **Does the Unit 2 steam generator operation involve a significant increase in the probability or consequences of an accident previously evaluated?**

APS has determined via the analyses presented in this report, that operation of the Unit 2 steam generators does not represent a significant increase in the probability or consequences of an accident previously evaluated in the PVNGS UFSAR. APS has determined that there is a low probability (less than 0.01) of generating a defect in excess of the structural margins specified in Regulatory Guide 1.121. The probability of tube rupture at normal operating conditions has been calculated to be 2.7E-3. This value is within the acceptance criteria used by the USNRC for PVNGS Unit 2 in Reference 39. The conditional probability for tube rupture given a MSLB was calculated to be 1.8E-2

which meets the criteria set forth in NUREG-0844. APS has also assessed leakage potential, and the impact of operation with ARC region defects on core damage probability. Tube leakage can occur when the maximum crack depth reaches 100% through-wall with structural integrity maintained. The analyses contained in this report indicate that there is low probability that tube leakage and consequential off-site doses, given a main steam line break (MSLB), will exceed 10CFR100 limits. Analysis performed by APS also indicates that the core damage probability (CDP) is negligibly increased by the propagation of axial cracks predicted for Unit 2. PVNGS PRA results also indicate that higher core damage risk would be incurred due to midcycle shutdown operations required to support the steam generator inspections. Based on the low CDP, it is clear that continued operation of Unit 2 to the end-of-cycle (EOC) is preferable, from a risk perspective, to performing another midcycle shutdown and inspection.

Since probabilistic models contain a degree of uncertainty associated with the upper tail of the crack growth rate distribution, additional actions have been taken by APS to assure safe plant operation. An improved leak rate monitoring program and administrative limits on primary-to-secondary leakage as described in Section VII provide additional assurance that an orderly shutdown would be conducted prior to a through-wall leak propagating to a rupture.

The consequences of accidents previously analyzed are not increased as a result of operation with existing steam generator tubing conditions. To minimize the consequences of currently analyzed accidents, APS has taken measures to provide operations personnel with improved diagnostic tools and training. These measures include: event specific training of operations personnel for tube rupture events; improvements in leakage diagnostics via equipment upgrades including the implementation of N-16 monitors; and protocol upgrades to the Emergency Operating Procedures. These actions permit faster identification and isolation of the affected steam generator given an SGTR event.

Finally, an analysis was performed by APS in Reference 9 to demonstrate that in the unlikely event of a main steam line break with consequential multiple tube ruptures, with the current administrative limits on reactor coolant system dose equivalent iodine, the resulting offsite doses are less than 10CFR100 limits.

These actions assure that the expected end-of-cycle steam generator condition will not significantly increase the probability or consequence of a previously analyzed accident.

<u>Standard 2</u> -- **Does the proposed operating interval for the Unit 2 steam generators create the possibility of a new or different kind of accident from any accident previously analyzed?**

The analyses contained in this report demonstrate with high probability that steam generator tubing structural integrity is maintained for the proposed operating interval. An analysis was performed by APS in Reference 9, which demonstrates that in the unlikely

event of a main steam line break with consequential multiple tube ruptures, with current administrative limits on reactor coolant system dose equivalent iodine, the resulting offsite doses are less than 10CFR100 limits. The analyses conducted by Packer Engineering indicate that the probability of multiple tube ruptures either as an initiating event or the consequence of a MSLB is less than 1E-5. The risk assessment performed in Section VI indicates that there is a negligible effect (1.2E-7) on the core damage probability (CDP) associated with operation of the Unit 2 steam generators until U2R6. The baseline core damage frequency is 4.74E-5 per reactor year, and therefore CDP is negligibly increased (approximately 0.4%) for consequential single and multiple tube ruptures due to the predicted propagation of ARC region axial cracks.

Additionally, APS has conducted event specific training of operations personnel for tube rupture events, incorporated improvements in diagnostics via equipment and procedure upgrades (including the implementation of N-16 monitors), and incorporated upgrades to the Emergency Operating Procedures. These measures permit faster identification and isolation of the affected steam generator given an SGTR event, and decrease the likelihood of new or unanticipated concurrent events.

Therefore, APS concludes that the possibility of a new or different kind of accident than currently analyzed in UFSAR Chapters 6 and 15 is not created for the proposed operating run.

<u>Standard 3</u> **--Does the proposed run time involve a significant reduction in the margin of safety?**

APS has developed a "defense in-depth" approach to managing steam generator tubing structural integrity. The analyses contained in this report indicate that the structural integrity margins specified in Regulatory Guide 1.121 have been satisfied to a high probability and confidence level. APS has considered that such probabilistic models contain a degree of uncertainty associated with the selected probability distributions. Therefore, additional actions have been taken by APS to assure safe plant operation. An improved leak rate monitoring program and administrative limits of 50 gpd for primary-to-secondary leakage, add significant margin over limits currently specified in both the PVNGS Technical Specifications and the recently regulated leakage limits contained in the voltage based repair criteria in Generic Letter 95-05. These conservative limits provide additional assurance that an orderly shutdown will be conducted prior to a through-wall leak propagating to a rupture.

APS concludes that these measures provide reasonable assurance that there are no reductions in the required safety margins, and that the PVNGS Unit 2 can be safely operated until the scheduled U2R6 shutdown.

III. PVNGS DEGRADATION MANAGEMENT PROGRAM

A. Background

Since the Unit 2 steam generator tube rupture in March 1993, APS has conducted four extensive ARC region inspections in Unit 2 (U2R4, U2M5-1, U2M5-2 and U2R5), two inspections in Unit 1 (U1R4 and U1R5) and three inspections in Unit 3 (U3M4, U3R4 and U3M5). These inspections have provided considerable information on the behavior of ARC region ODSCC. Additionally, APS has performed three (3) tube removal and examination activities of tubes from Units 2 and 3, ultrasonic testing (UT) in Units 1 and 2 and in-situ pressure testing in Units 1 and 2. By integrating the information obtained from activities conducted in all three PVNGS units, APS has the tools to develop the elements of a Degradation Management Program for ARC region defects. The objective of the program is reliable and safe steam generator operation. This objective is achieved through improvements in secondary chemistry, primary temperature reduction, chemical cleaning, management of ARC region degradation through an aggressive ECT and plugging program, and continually updated comparisons of inspection results to predictive models. It is APS's position, that these actions permit a return to full cycle operation for Units 2 and 3 and continued full cycle operation of Unit 1.

B. Objectives

In Reference 2, APS reviewed the expected cycle and outage durations through 1996. Figure III-1 provides an updated outage schedule through 1997. As stated in the earlier submittal, the purpose of integrating planned outages, analytical evaluations, tube inspections and remedial/repair activities is to meet the following safety and economic objectives:

- Establish cycle lengths which are dependent on demonstrating compliance with the applicable General Design Criteria (GDC) in 10CFR50, ASME Code criteria and the structural integrity margins for steam generator tubing as defined in Regulatory Guide 1.121.

- Limit the safety issues associated with equipment and personnel resources, by avoiding the performance of simultaneous outages of the PVNGS Units.

- Perform an assessment of the safety consequences of performing midcycle outages versus proposed operation to

planned refueling outages by assessing core damage risk as a function of graduated increases in inspection interval.

C. Program Plan

In order to satisfy these objectives, APS has implemented the following actions which meet or exceed similar industry and regulatory guidance for such a management program. These actions include:

- A comprehensive steam generator inspection program which significantly reduces the risk of leaving a significant defect(s) in service. Enhanced inspections (MRPC, Plus Point, UT) are conducted in the region affected by ARC degradation. The extent of MRPC and bobbin coil inspections performed by PVNGS, coupled with the use of new state of the art ECT data acquisition and analysis technology, has a significant impact in terms of preventing through-wall defects, and significantly lowers the probability of tube rupture for the specified period of operation. This position is supported by assessments performed in this report, and as well as by sensitivity studies performed by EdF in Reference 23.

- Plugging criteria more conservative than current PVNGS Technical Specifications is employed by APS. Before the steam generators are returned to service, a review by APS Engineering of all eddy current indications is conducted. Regardless of size or depth, all tubes with detected cracks, regardless of size, are removed from service. As demonstrated in Section V, and supported by data presented in Reference 23, this action also minimizes the potential for leakage and/or tube rupture, since no known crack defects are left in the steam generator at the beginning of the operating cycle.

- APS has implemented an integrated leakage detection and response program, using equipment and procedure upgrades, to permit plant operators to detect and respond to changes in steam generator primary-to-secondary leakage. The threshold for action is 10 gpd and the maximum allowable leak rate is 50 gpd. The program was established to provide reasonable assurance that the unit will be shutdown prior to a significant leak or steam generator tube rupture should tube degradation exceed expected values.

- State-of-the-art probabilistic models have been developed for assessing operating cycle lengths and calculating tube structural margins. Plant specific NDE measured parameters and unit specific material properties have been incorporated, and crack initiation and growth predictions benchmarked, to ensure that the safety margins specified in Regulatory Guide 1.121 are maintained.

- Development of a probabilistic leakage model to assess end of cycle leakage as a result of secondary overpressurization events. The model ensures that operation with ARC region degradation will not result in offsite releases in excess of 10CFR100 limits should a MSLB event occur.

- Development of a risk model to assess the impact on core damage probability for plant operation with degraded steam generator tubing. The calculation ensures that operation with ARC region degradation represents a negligible impact on core damage probability.

- Primary temperature reductions of 10°F have been implemented in all three PVNGS units to take advantage of the temperature dependence of SCC growth rates. Stress corrosion cracking is a thermally activated process, and the effects of temperature reduction can be quantified for SCC mechanisms in terms of activation energy for an Arrhenius rate equation.

- APS has removed 31 tubes from service, and has conducted extensive NDE and destructive examination in an effort to determine causal effects of corrosion damage, and to provide substantial improvements in field ECT acquisition and interpretation.

- APS has implemented the industry recommended secondary chemistry controls to mitigate the initiation and propagation of secondary side IGA/SCC. The laboratory evidence from tubes removed from Unit 2 during U2M5-1 showed a favorable change in crack crevice chemistry tending towards neutral conditions. APS has established action levels for sulfate which are more restrictive than EPRI Guidelines, and require reduced power operation for sulfate levels exceeding 20 ppb or shutdown for levels exceeding 100 ppb.

- APS has established administrative limits on dose equivalent iodine levels in the reactor coolant system. The Technical Specification limits for initial primary system activity are 1.0 μCi/gm for steady state and 60 μCi/gm for transient or spiked limits. The PVNGS Administrative limits are 0.6 μCi/gm equilibrium and 12 μCi/gm transient. Therefore even a non-isolatable main steam line break with multiple steam generator tube ruptures results in offsite doses less that 10CFR100 limits.

It is APS's position that the implementation of these elements, as further described in this report, constitutes a defense-in-depth approach which ensures that adequate structural and leakage integrity is maintained for normal operating, transient and postulated accident conditions, consistent with General Design Criteria (GDCs) 14, 15, 30, 31, and 32 of 10CFR50 Appendix A.

IV. STEAM GENERATOR INSPECTION AND REPAIR

A. Introduction

A contributor to the tube rupture in Unit 2 in March 1993, is considered to be the previously unknown limitations of bobbin coil inspection techniques used in the U2R3 steam generator inspections during the Fall of 1991. Since 1993, APS has endeavored to improve these ECT techniques via improved technology, analyst training, industry-leading use of the Plus Point[1] MRPC probe, and a large scale tube pull program which provided ECT-to-actual defect comparisons leading to the development of plant specific probability-of-detection (POD) curves. Additionally, APS has employed supplemental techniques such as ultrasonic testing (UT), and in-situ pressure testing when necessary.

The steam generator inspection programs conducted in Unit 2 during Cycle 5 were performed to assure plant safety, and to assist in understanding the initiation, progression and scope of the ARC region ODSCC phenomenon. It is recognized by APS and the NSSS manufacturer, ABB-CE, that the design of the System80 steam generators creates an environment in the upper region of the tube bundle susceptible to ODSCC if other contributing factors such as chemistry, crevice formation and material susceptibility are present. APS has continued to refine the thermal-hydraulic analyses developed and discussed in Reference 1 to assist as a self-check in defining inspection scope, and to determine the benefits of possible steam generator design modifications.

As discussed in Section V, in the development of probabilistic models of steam generator tubing degradation, it is important to incorporate normalized inspection results. During Cycle 5, three steam generator inspections were conducted with several changes in scope, technique and technology. In order to understand the impact of these changes, a summary of the inspection programs and results is provided in the following discussion. The information presented will focus on the most recent inspections conducted during U2R5, with abridged information regarding ECT, UT, in-situ pressure tests and tube pull results from the midcycle inspections. Detailed information regarding these inspections has been submitted to the USNRC Staff in References 15 and 40

1. Plus Point MRPC Probes are designed and manufactured by Zetec. The probe configuration combines the axial and circumferential coils in one gimbal-mounted surface riding coil shoe.

B. Cycle 5 Inspection Summaries

1. Unit 2R5 NDE Inspection Program - March 1995

A. Examination Scope

As in the previous midcycle inspections, the Unit 2 examination plan was developed in response to findings associated with previous eddy current examinations performed in Unit 2, as well as experience gained from recent inspections conducted in Units 1 and 3. For example, the purpose for the 100% full length bobbin coil examinations was to provide general tube condition screening. This aids in assuring that a widespread pattern of pluggable flaws including wear and loose parts was not present. If such flaws were detected and exceeded PVNGS Administrative Plugging Criteria, they would be removed from service.

MRPC testing was performed in the high risk ARC region of the steam generators in search of corrosion defects similar to that found in the previous inspections. The MRPC probe inspected, in most cases, the section of tubing from the 08H horizontal eggcrate support to the second vertical strap support that the tube is supported by (See Figure IV-1). The upper bundle MRPC testing also included a sample program of tubing between columns 40-150 and rows 90 -110 which was performed in an effort to determine if corrosion damage was occurring outside the pre-defined 2700 tube high risk ARC region.

MRPC testing at the hot leg tubesheet locations was also performed to identify any circumferential indications in the expansion transition region similar to those found in Units 1 and 3 and in other CE units. The inspection scope concentrated in the known sludge pile region. Studies conducted by APS, as well as industry information, indicate that the presence of sludge buildup combined with tube expansion at the tubesheet increases the susceptibility of circumferential cracking. Finally, based on Unit 3 experience, MRPC testing in the rows 1 and 2 short radius u-bends was conducted from 07H-07C to determine if axial cracking in this region was present. In summary, the base scope for the examination included:

- Examine 100% of Steam Generator 21 (SG 21) and Steam Generator 22 (SG 22) using bobbin coil techniques.

- Examine ~2600 tubes in SG 21 and ~2100 tubes in SG 22 from 08H-2nd vertical support (VS) using MRPC techniques. The MRPC probe included the Plus Point coil for defect detection and characterization. These tubes were selected in the area of interest for ARC region axial indications.

- Examine ~200 tubes in SG 21 and ~700 tubes in SG 22 from 08H-2nd VS using MRPC. These tubes were selected in areas between columns 40 - 150 and rows 90 - 110, and represented an additional sample based on ATHOS model results.

- Examine ~2200 tubes in SG 21 and SG 22 at the hot leg tubesheet (TSH) using MRPC. These tubes were selected in sludge pile regions where circumferential indications may be present.

- Examine ~110 tubes in SG 21 and SG 22 from 07H-07C using MRPC. This examination included all the rows 1 and 2 short radius U-Bend tubes.

The expansion criteria employed in Unit 2 included:

Axial Indications:

- Five (5) tube buffer zone in all directions using MRPC.
- MRPC of any Bobbin indications that exceed Palo Verde plugging Criteria.
- MRPC of all Bobbin I-codes including ADR's (absolute drift).
- MRPC of all wear calls above Row 90 from 06H to VS3.

Circumferential Indications:

- Any circumferential indication - expand to 100% MRPC of the hot leg tubesheet.
- If >50 circumferential indications in any steam generator then MRPC 20% cold leg tubesheet of affected steam generator.

The exam description, the extent examined and the number of tubes analyzed, including expansions, are identified in Table IV-1. Figures IV-2 to IV-5 depict the scope inspected with respect to tube location on the tubesheet.

Table IV-1 - Unit 2R5 ECT Inspection Summary

SCOPE DESCRIPTION		SG 21	SG 22
Exam Description	Extents	Analyzed	Analyzed
FULL LENGTH BOBBIN	TEC-TEH	10,716	10,115
TUBE SHEET MRPC	TSH-TSH	2220	1652
U-BEND MRPC	08H-2nd VS	2629	2065
LOW ROW U-BEND MRPC	07C-07H	113	125
RANDOM ARC MRPC	08H-2nd VS	184	632
EXPANSION 1 SPECIAL INTEREST MRPC	VARIOUS	123	195
EXPANSION 2 TUBE SHEET MRPC	TSH-TSH	8496	2107
EXPANSION 3 WEAR CALLS MRPC	VARIOUS	89	137
EXPANSION 4 SAI BOUNDING MRPC	VARIOUS	92	109
EXPANSION 5 07H MRPC	07H-07H	535	1937
EXPANSION 6 07H BOUNDING MRPC	07H-07H	--	20
EXPANSION 7 BOBBIN INDICATION MRPC	VARIOUS	480	473
EXPANSION 8 TUBE SHEET MRPC	TSC-TSC	10,710	9861

EXPANSION DESCRIPTION

EXPANSION 1 — This expansion is utilized to track the special interest MRPC performed to quantify or evaluate bobbin or previously called indications. This includes NQI, ADR, DSI, DTI, PLP[1], and other areas.

EXPANSION 2 — MRPC top of hot leg tubesheet (TSH) in search of circumferential indications. 100% of the TSH tubes were examined in Steam Generator 21 with the addition of this expansion. Approximately 37% of the TSH tubes were examined in Steam Generator 22 with

the addition of this expansion.

EXPANSION 3	MRPC of previous years wear indications >20% located with bobbin coil. This inspection was conducted to ensure that recorded bobbin wear calls did not contain axial cracks.
EXPANSION 4	MRPC examinations bounding single axial indications (SAIs) to aid in determinations of additional SAIs in general area. This expansion was triggered by SAIs found in original MRPC scope.
EXPANSION 5	MRPC examinations performed at 07H. This expansion was triggered by indications found in Expansion 3.
EXPANSION 6	MRPC examinations bounding SAIs found in Expansion 5.
EXPANSION 7	MRPC all bobbin coil wear indications. This expansion was triggered by indications found in Expansions 3 and 5.
EXPANSION 8	MRPC 100% top of cold leg tubesheet (TSC). This expansion was undertaken due to the discovery of mixed mode corrosion found in sludge pile locations near the stay cylinder. No other locations on the cold leg tubesheet indicated similar defects

Notes:

1. Non-Quantifiable Indications (NQI), Absolute Drift (ADR), Distorted Support Indication (DSI), Distorted Tubesheet Indication (DTI), Possible Loose Part (PLP).

B. Examination Results

A summary of the U2R5 examination results are summarized in Table IV-2. Additionally, ECT summary sheets for corrosion related indications are contained in Appendix C. The U2R5 inspection program resulted in the plugging of 89 tubes in SG 2-1 and 250 tubes in SG 2-2 as a result of ARC region corrosion. Figure IV-6 depicts the ECT results in the ARC region as a function of MRPC voltage and length. The treatment of these results in determining the allowable run time in Unit 2 is described in Section V and Appendix A.

Table IV-2 - U2R5 ECT Results

INDICATION CATEGORY	STEAM GENERATOR 21	STEAM GENERATOR 22
Cold Leg Corner Eggcrate Wear		
0% to 19%	5	0
20% to 29%	0	0
30% to 39%	0	0
40% to 100%	0	0
Eggcrate Wear		
0% to 19%	512	746
20% to 29%	197	300
30% to 39%	59	115
40% to 100%	2	6
Flow Dist Plate Wear		
0% to 19%	0	0
20% to 29%	0	0
30% to 39%	0	0
40% to 100%	0	0
Batwing Wear		
0% to 19%	491	690
20% to 29%	239	323
30% to 39%	85	149
40% to 100%	4	3
Vertical Strap Wear		
0% to 19%	372	437
20% to 29%	155	125
30% to 39%	86	55
40% to 100%	5	5
Possible Loose Parts		
PLI	6	0
PLP	8	3

Axial Indications	SG 21 orig	SG 21 exp2	SG 21 exp3	SG 21 exp4	SG 21 exp7	SG 22 orig	SG 22 exp1	SG 22 exp2	SG 22 exp3	SG 22 exp4	SG 22 exp5	SG 22 exp7
TEH/TSH	0	2	0	0	0	2	0	1	0	0	0	0
01H	0	0	0	0	0	0	6	0	0	0	0	0
04H-07H	1	0	1	0	0	0	0	0	3	0	6	1
08H-2nd VS	87	0	0	2	1	240	0	0	0	1	0	1

INDICATION CATEGORY	SG 21	SG 21	SG 22
Circumferential Indications	orig	exp2	orig
	1	1	2
Mixed Mode Indications	exp1	exp8	exp8
MMI	5	4	15

INDICATION CATEGORY	STEAM GENERATOR 21	STEAM GENERATOR 22
Volumetric Indications SVI/MVI	55	59

C. Examination Techniques and Equipment

The PVNGS steam generator eddy current program has continued to evolve through the use of state-of-the-art equipment and technique development which incorporate lessons learned from PVNGS exams and tube pulls, as well as industry experience. The objectives of the APS program are to acquire data in a timely fashion while maintaining and/or improving the ability to detect and characterize flaws.

The eddy current examination for U2R5 was performed by Conam Nuclear Inc. (Rockridge) using Zetec MIZ 30 digital data acquisition and analysis systems. The following frequencies were used for the tube examination(s):

Examination Frequencies	
Bobbin	MRPC
20 KHz	20 KHz
100 KHz	100 KHz
300 KHz	300 KHz
500 KHz	400 KHz

For the stated inspection scope, all tubing was examined with Zetec manufactured bobbin coil and MRPC style probes, either 0.610, 0.600, 0.590 or 0.580 inch diameter. Multiple configurations of 3-coil MRPC probes and Plus Point MRPC probes were used for the detection and characterization of axial and circumferential indications. Data acquisition was facilitated by using Zetec SM-22 manipulators with quad guide tubes and dual guide tubes in the hot leg and cold leg respectively in Steam Generators 21 and 22. A BWNT ROGER manipulator with a quad guide tube was also used in the hot legs of both of steam generators.

Fiber optic cable was used from the MIZ 30 containment location to the data acquisition room located at the PVNGS North Annex. Primary and Secondary analyses were performed remotely utilizing T-1 line technology. Primary Analysts were located in Benicia, California; Issaquah, Washington; and Lynchburg, Virginia. Secondary Analysts were located in San Clemente, California. The Primary and Secondary Resolution Analysts were located at PVNGS. Conam Nuclear Inc. provided the data acquisition and primary data analysis. Anatec International, Inc. provided the secondary data analysis.

Each Level IIA individual from Conam Nuclear Inc. and Anatec International, Inc. who performed data analysis was required to complete and pass a PVNGS site specific Eddy Current Data Analysis Course as well as an associated performance examination with at least a 80% proficiency within the last year.

Plus Point MRPC

Due to the critical nature and extent of MRPC inspections at PVNGS, the primary objective in ECT technique and analysis evolution is to improve production speed, while at the same time maintaining or improving detection capability. In meeting these objectives the Zetec Plus Point MRPC Probe was utilized for the first time at PVNGS during the U3M5 inspections and subsequently used in the U2R5 and U1R5 inspections. The Plus Point Probe was originally developed by Zetec for surface examinations of reactor vessel welds. The probe was designed to reduce geometry and permeability effects. The coils are differentially paired within the same coil shoe and surface riding to reduce the effects of geometry. The probe design utilized in Unit 2 employed a standard 0.115" diameter pancake coil, and a separate shoe contained the plus point coil (See Figure IV-7). The reasons for the use of this coil design include:

- The single Plus Point coil performs the axial/circumferential classification previously performed by two coils. This feature permits increased pull speed and longer motor life.

- For bend inspections the single coil eliminates four (4) inches of scan on each end of every examination length by combining the axial and circumferential coil in one coil shoe.

- The Plus Point coil significantly reduces the geometrical effects of the tube bends on ECT signal response.

- The Plus Point coil was designed to provide a large OD field thereby offering greater sensitivity to shallow OD flaws. The larger field also permits faster pull speeds without increasing motor speed and sample rate.

The Plus Point probe, as utilized by PVNGS, was demonstrated to meet the stated objectives of faster production rates and improved detectability in U3M5, U2R5 and U1R5. The probe has a field-demonstrated improvement over the standard three-coil MRPC, not only at PVNGS, but at other utilities as well which have used the new probe design. The probe has since been Appendix H qualified via the process described in the EPRI ISI Guidelines. In order to assess the capabilities of the Plus Point probe, several PVNGS specific qualification activities have been conducted by APS. In U3M5, all pluggable indications (all crack indications) found

were reinspected utilizing the standard three coil MRPC, which has been benchmarked via tube pulls conducted by PVNGS. Figures IV-8 and IV-9 depict a side by side comparison of pancake coil signal response to the Plus Point coil for defects and geometry signal response in the PVNGS steam generators.

APS has also conducted probe comparisons with the PVNGS Bend Mock-up Test Facility. The bend mock-up as shown in Figure IV-10 has EDM notches of various depth and location in square bends similar to the PVNGS in-plant condition. The Plus Point probe was found to provide improved signal response, and less susceptibility to bend geometry effects. When compared to the 0.115 pancake coil, a noticeable improvement in detectability was noted. Essentially, all of the EDM notches as indicated in Table IV-3 were readily evident.

Table IV-3 Square Bend Mock-up Test Results

Sample	EDM Notch	Plus Point	MRPC	Bobbin
SQ75.75	Inner Radius 90 degree Outer Radius Straight	SAI SAI SAI SAI	SAI SAI SAI SAI	NQI 55% 52% 49%
SQ50.75	Inner Radius 90 degree Outer Radius Straight	SAI SAI SAI SAI	SAI SAI SAI SAI	NQI NQI NQI NQI
SQ25.75	Inner Radius 90 degree Outer Radius Straight	SAI SAI SAI SAI	SAI NDD SAI SAI	NDD NDD NDD NQI
SQ75.50	Inner Radius 90 degree Outer Radius Straight	SAI SAI SAI SAI	SAI SAI SAI SAI	NQI NQI 59% NQI
SQ50.50	Inner Radius 90 degree Outer Radius Straight	SAI SAI SAI SAI	SAI SAI SAI SAI	NQI NQI NQI 40%
SQ25.50	Inner Radius 90 degree Outer Radius Straight	SAI SAI SAI SAI	SAI SAI SAI SAI	NDD NDD NDD NQI

Finally, POD modeling, as described in Section V and Appendix A, provides information regarding statistically validated detection improvements observed with the Plus Point probe.

Data Quality

PVNGS Station Manual Procedure 73TI-9RC01, *Steam Generator Eddy Current Examinations*, provides requirements to assure data quality for ECT inspections. The procedure requires that calibration shall be made and recorded at the beginning and end of each optical disc or every four hours whichever comes first. For bobbin coil inspections, if this time is exceeded, all tubes examined after the four hours shall be re-inspected. For MRPC, the tubes shall be reviewed by a Level III analyst to verify the data.

APS recognizes that the useful life of ECT probes has been shown to vary significantly from probe to probe and cannot be predetermined. Probe life may be fewer than five (5) tubes or greater than 1000 tubes. As a result, the analysts are required to note if undesirable variations exist during examinations or calibrations. If a probe is determined to have become defective prior to post calibration, the data analysts shall determine which tubes, if any, require re-examination. This review is documented according to procedure.

2. Unit 2M5-2 NDE Inspection Program - September 1994

A. Examination Scope

The examination plan for U2M5-2 was prepared by APS to address the major corrosion and detectability issues facing the Unit 2 steam generators. The 100% MRPC inspection scope for the ARC region was expanded from a 1800 tube ARC to a 2700 tube ARC based on inspection results from U2M5-1 and U3R4, indicating that a small number of defects exist outside the smaller ARC region. APS reviewed the previous inspection results and the ATHOS thermal hydraulic model, and redefined a larger bounding inspection zone (See Figure IV-11). The five (5) tube buffer zone expansion criteria was maintained for the larger ARC region as well. Since Unit 2 was to be operated for only 3.5 months following this inspection, APS elected to rely on the bobbin coil probe to inspect the straight section tubing in the ARC (08H-BW1). This position was based on tube pull and ultrasonic test (UT) results which indicated that the bobbin detection thresholds were sufficient to permit the limited run time with no impact on safety. Consequently, the ARC MRPC inspection extent (tube length) included the batwing support to the first vertical support. Due to the combination of pilger noise, tube ovality and bend and bend tangent geometry effects, the bobbin coil was considered to have an inadequate inspection capability for even the shorter operating period.

Although there was no evidence of an accelerated circumferential cracking mechanism in the Unit 2 steam generators, APS elected to perform an additional sludge pile MRPC exam at the tubesheet transition. Finally, based on inspection results from U3R4, APS elected to perform an MRPC inspection of the Row 1 and 2 U-bends from 07H-07C to determine if axial cracking was present. The inspection scope, including tube number count and expansions, is given in Table IV-4 and depicted in Figures IV-12 through IV-17.

Table IV-4 - U2M5-2 ECT Inspection Summary

SCOPE DESCRIPTION			SG 21	SG 22
Exam Description	ECT Method	Extents	Analyzed	Analyzed
FULL LENGTH BOBBIN	Bobbin	TEC-TEH	4285	3790
TUBESHEET MRPC	MRPC	TSH-TSH	996	528
ARC REGION MRPC	MRPC	BW1-1stVS	2849	2364
U-BEND MRPC	MRPC	07C-07H	114	125
EXPANSION 1 MRPC	MRPC	Various (I-codes)	107	206
EXPANSION 2 BUFFER ZONE MRPC	MRPC	BW1-1stVS	64	87

B. Examination Results

The U2M5-2 examination results are summarized in Table IV-5. Additionally, ECT summary sheets for corrosion related indications are contained in Appendix C. The U2M5-2 inspection program resulted in the plugging of 60 tubes in SG 2-1 and 144 tubes in SG 2-2 as a result of ARC region corrosion. Figure IV-18 depicts the ECT results in the ARC region as a function of MRPC voltage and length. The treatment of these results in determining the allowable run time in Unit 2 is described in Section V and Appendix A.

Table IV-5 - U2M5-2 ECT Results

INDICATION CATEGORY	STEAM GENERATOR 21			STEAM GENERATOR 22		
Cold Leg Corner Eggcrate Wear						
0% to 19%	0			0		
20% to 29%	0			0		
30% to 39%	0			0		
40% to 100%	0			0		
Eggcrate Wear						
0% to 19%	356			594		
20% to 29%	74			105		
30% to 39%	19			29		
40% to 100%	0			0		
Flow Dist Plate Wear						
0% to 19%	1			0		
20% to 29%	0			0		
30% to 39%	0			0		
40% to 100%	0			0		
Batwing Wear						
0% to 19%	575			661		
20% to 29%	193			270		
30% to 39%	48			107		
40% to 100%	2			1		
Vertical Strap Wear						
0% to 19%	342			336		
20% to 29%	96			59		
30% to 39%	18			17		
40% to 100%	1			1		
Possible Loose Parts						
PLI	0			0		
PLP	4			0		
Axial Indications	orig	exp1	exp2	orig	exp1	exp2
TEH/TSH	0	1	0	0	1	0
01H	0	1	0	0	4	0
08H-1st VS	59	1	2	141	2	1
Circumferential Indications	0			0		
Volumetric Indications SVI/MVI	10			7		

3. Unit 2M5-1 NDE Inspection Program - January 1994

A. Examination Scope

The examination plan for U2M5-1 was prepared and submitted to the USNRC Staff via Reference 42 to address the base scope and expansion program. The inspection took place after 4.5 months of operation following restart of Unit 2 after the U2R4 inspections. The scope included a 100% full length bobbin program of an upper bound ARC region tube population of 4000 tubes and an additional 400 random tube sample in non-ARC region areas. A 20% MRPC tubesheet transition region inspection was performed to identify possible circumferential indications and a 100% MRPC inspection was performed in the ARC region. The scope, including number count is given in Table IV-6 and depicted in Figures IV-19 through IV-24.

Table IV-6 - U2M5-1 ECT Inspection Scope Summary

SCOPE DESCRIPTION			SG 21	SG 22
Exam Description	ECT Method	Extents	Analyzed	Analyzed
FULL LENGTH BOBBIN	Bobbin	TEC-TEH	4018	3869
TUBESHEET MRPC	MRPC	TSH-TSH	2270	2245
ARC REGION MRPC	MRPC	08H-1stVS	1904	1778
CHECKERBOARD	Bobbin	TEC -TEH	400	400
EXPANSION 1 TUBE SHEET MRPC	MRPC	TSH-TSH	0	8391
EXPANSION 2 - EXPANDED ARC BOBBIN	Bobbin	TEC-TEH	0	951
EXPANSION 3 - EXPANDED ARC MRPC	MRPC	08H-1stVS	980	951
EXPANSION 4 - MRPC CHEMICAL CLEANING1	MRPC	08H-1stVS	108	1628
EXPANSION 5 - BUFFER ZONE MRPC	MRPC	08H-1stVS	0	49

Notes

1. An extensive program of re-inspection of the ARC region with MRPC was conducted to observe changes in ECT signal response following chemical cleaning. The details of the scope and basis for each expansion are provided in Reference 17

B. Examination Results

The U2M5-1 examination results are summarized in Table IV-7. Additionally, ECT summary sheets for corrosion related indications are contained in Appendix C. The U2M5-1 inspection program resulted in the plugging of 22 tubes in SG 2-1 and 306 tubes in SG 2-2 as a result of ARC region corrosion. The treatment of these results in determining the allowable run time in Unit 2 is described in Section V and Appendix A.

Ultrasonic Examinations

Ultrasonic testing was employed to augment the eddy current examinations during U2M5-1. The goal of the examinations was to provide feedback regarding depth, length, and origin of the SCC indications. A total of 38 defect locations were tested. The results of this testing were also used to assess chemical cleaning effects, and determine candidates for in-situ pressure testing. The test results appeared to provide consistent information for defects found in the tubesheet transition region. However, the UT results for defects in the ARC region were less comparative with ECT results. Table V-5 in Reference 17 provides tube number, defect location and the applicable ECT and UT results.

Table IV-7 - U2M5-1 ECT Results

INDICATION CATEGORY	STEAM GENERATOR 21	STEAM GENERATOR 22
Cold Leg Corner Eggcrate Wear		
0% to 19%	0	0
20% to 29%	1	0
30% to 39%	0	0
40% to 100%	0	0
Eggcrate Wear		
0% to 19%	381	711
20% to 29%	123	241
30% to 39%	29	65
40% to 100%	2	19
Flow Dist Plate Wear		
0% to 19%	0	0
20% to 29%	0	0
30% to 39%	0	0
40% to 100%	0	0
Batwing Wear		
0% to 19%	412	560
20% to 29%	139	287
30% to 39%	38	114
40% to 100%	10	12
Vertical Strap Wear		
0% to 19%	247	289
20% to 29%	80	80
30% to 39%	23	15
40% to 100%	2	1
Possible Loose Parts		
PLI	0	0
PLP	1	5

Axial Indications	SG 21 orig	SG 21 exp1	SG 21 exp4	SG 22 orig	SG 22 exp1	SG 22 exp4	SG 22 exp6	SG 22 exp8
TEH/TSH	0	1	0	0	0	0	0	0
01H	0	0	0	0	2	0	0	0
08H-1st VS	21	1	0	95	0	3	10	198

INDICATION CATEGORY	STEAM GENERATOR 21	STEAM GENERATOR 22
Circumferential Indications	0	4
Volumetric Indications SVI/MVI	4	44

In-situ Pressure Testing

In-situ pressure testing was conducted in U2M5-1 by APS as a means of verifying that Regulatory Guide 1.121 structural margins were maintained in tubes exhibiting large MRPC voltage calls. Based on a voltage to depth correlation observed from U2R4 tube pull results, tubes with greater than a three (3) volt MRPC response, as measured prior to chemical cleaning, were suspected to exceed Regulatory Guide 1.121 limits. Additionally, two (2) tubes with voltages exceeding two (2) volts were tested as the MRPC presentation indicated possible through-wall extents. The tube with the largest bobbin measurable corrosion defect was also tested. All tubes were pressurized to 4260 psia. The test criteria was based on three (3) times the normal operating pressure differential of 1290 psid, adjusted for room temperature and an additional 50 psi test margin. All tubes as listed in Table IV-8, were successfully pressurized thereby indicating that the required safety margins against burst were maintained. All tested tubes were subsequently re-examined with MRPC, and no change in eddy current presentation was observed.

Table IV-8 - In-situ Pressure Test Results

SG	Row	Column	Selection Criteria	Pass/Fail
2-1	118	95	> 3 Volt axial indication	Pass
2-1	99	38	SVI - 66% through-wall	Pass
2-2	149	120	> 3 Volt axial indication	Pass
2-2	146	121	> 3 Volt axial indication	Pass
2-2	105	138	> 3 Volt axial indication	Pass
2-2	144	105	>2 Volt axial - MRPC Presentations	Pass
2-2	130	95	>2 Volt axial - MRPC Presentations	Pass
2-2	110	143	SVI - 73% through-wall	Pass
2-2	117	44	61% axial indication	Pass

C. Defect Detection and Characterization

As described in Section V, the Regulatory Guide 1.121 analyses performed by Packer Engineering use MRPC signal response information to characterize defects and assess crack growth rate. As reported throughout this report, all crack indications found during the ECT examinations conducted at PVNGS are reported and removed from service. This conservative plugging philosophy makes it inherently difficult to determine growth rates on detected defects from inspection to inspection. Additionally, eddy current technique changes, probe technology improvements, improved analyst training and reduction in signal interferences can impact detection and characterization. These factors must be studied and evaluated to determine the effects of these changes, and to normalize the inspection results.

1. Probability of Detection (POD)

The analyses described in Section V are dependent on the ability to characterize the undetected defect population remaining in the steam generators upon the completion of the ECT inspections, since all detected SCC defects are removed from service. Inspection results, to date, indicate that the bobbin coil technique is not sufficiently reliable for detection of low volume SCC defects due to tube pilgering interferences and geometry effects associated with tube ovalization in the bend region. As a result, APS has relied on the use of MRPC technology to improve defect detection thresholds. Since the U2R4 inspection, APS has removed 31 tubes from the Units 2 and 3 steam generators to provide accurate comparisons of actual defect depth with MRPC detection capability. A PVNGS specific probability of detection (POD) curve has been constructed from this data and presented to the USNRC Staff in References 2 and 35. This POD curve was considered to be reasonable when compared to the typical industry MRPC pre-1993 database.

Since the U2R4 inspection and tube pulls, APS has observed three distinct inspection transients or improvements in defect detection. Most notably has been the inspection improvement observed with the use of the Plus Point MRPC probe. Similar inspection transients due to the Plus Point have been observed at other nuclear facilities. APS has characterized the inspection improvements observed during Cycle 5 by the order of their occurrence.

<u>Pancake Coil Size (0.080 vs. 0.115)</u>
NRC Information Notice 94-88 *Inservice Inspection Deficiencies Result in Severely Degraded Steam Generator Tubes* reported that Maine Yankee Atomic Power Station had observed improved signal to noise performance through the use of a larger (0.115 - inch) diameter pancake coil in lieu of the previously used 0.080 diameter coil in their July 1994 steam generator inspections. PVNGS elected to use the larger coil earlier, in the U2M5-1 inspection conducted in

January 1994. The smaller pancake coil (0.080 - inch) was primarily used in U2R4 in March 1993. As reported by ZETEC representatives to the USNRC on February 25, 1995, the 0.115 diameter pancake probe was designed to provide an improved OD field, thereby permitting better detection of shallow OD flaws. Based on the experience reported in the IEN 94-88, the USNRC Staff also requested that APS provide information comparing its ECT program with that of recent CE plant experience. In letter 102-03124-WLS/AKK/JRP dated September 22,1994, APS reported that the use of 0.115 pancake coils, low loss cables, terrain plotting and detailed analysts training had been in place since the U1R4 inspections in November 1993. The industry documented improvement of the 0.115" coil is also supported by tube pulls performed by PVNGS in U2M5-1, and a comparative review of the ECT results since U2R4.

Deposit Removal

As reported in Reference 17, APS noted a large change in the number of observable indications in SG 22 following chemical cleaning. In order to rule out any direct impact of the chemical cleaning process on either actual crack size or possible crack face oxidation, APS elected to conduct testing on tubes removed from the steam generator after chemical cleaning. The tests indicated that the process had no impact on the defect itself, and it was concluded that the improvement in ECT detection was related to the removal of thick deposits from the tube surface. Since SG 22 had the preponderance of indications, this transient was more pronounced in this steam generator. However, improved signal to noise performance was observed in all PVNGS steam generators following chemical cleaning. APS is continuing to monitor deposit re-formation via eddy current inspections. Although the effect of deposit interference is believed to be lessened with the use on the Plus Point MRPC.

Plus Point MRPC

As reported in NRC Generic Letter 95-03, *Circumferential Cracking of Steam Generator Tubes*, enhanced ECT techniques resulted in the detection of significantly more defects at the Maine Yankee Atomic Power Station in January 1995. This inspection transient was largely attributed to the use of the Plus Point coil. As stated previously, the Plus Point probe was originally developed by ZETEC for surface examinations of reactor vessel welds. The probe was designed to reduce geometry and permeability effects. The coils are differentially paired within the same coil shoe and surface riding to reduce the effects of geometry. The probe design utilized in Unit 2 employed a standard 0.115" diameter pancake coil, and a separate shoe contained the plus point coil.

As stated previously, the Plus Point probe has been Appendix H qualified via the process described in the EPRI ISI Guidelines. In order to further assess the capabilities of the Plus Point probe, several PVNGS specific qualification activities have been conducted by APS. In U3M5, all pluggable indications (all crack

indications) found were reinspected utilizing the standard three coil MRPC, which has been benchmarked via tube pulls conducted by PVNGS. APS has also conducted probe comparisons with the PVNGS Bend Mock-up Test Facility. APS, Packer Engineering and APTECH have used these one-to-one comparisons to assess the overall detection improvement of the Plus Point MRPC. A plant specific POD curve has been developed by Packer Engineering in the analyses presented in Appendix A.

Assessment

Several means, deterministically and statistically, have been used to characterize the change in POD resulting from all of these inspection improvements. The analyses performed by Packer Engineering in Section V have only credited the effect of the Plus Point probe in shifting the POD function. It should be noted that the Plus Point probe design contains a 0.115 pancake coil, and therefore an on-line comparison of the coil differences can be observed and characterized by the eddy current analyst. The overall impact of these improvements can be shown graphically using the life prediction techniques in the APTECH BALIFE Code. Figure IV-25a provides an outage prediction of actual detection versus a predicted value had the Plus Point MRPC probe been available since U2R3. Figure IV-25b provides additional information regarding the need to account for inspection transients in predicting future defect rates. Without such accounting for the effects of improving technology, an absurdly high Weibull shape parameter (β) would be estimated. This not only projects unreasonably high future plugging rates, but also fails benchmarking standards for past inspections.

Section V provides the results of a sensitivity studies performed by APTECH and APS on the impact of avoiding structural limit exceedances given changes or improvements in ECT detection. A similar sensitivity analysis was performed by EdF in Reference 23. EdF established that substantial reduction in tube rupture risk could be achieved via better inspections.

2. Defect Characterization

As stated previously, the conservative plugging philosophy employed by APS makes it inherently difficult to determine growth rates on detected defects from inspection to inspection. However, as part of the analysis process of ARC region crack growth rate, historical information was reviewed by APS and Conam to determine if certain precursor signals from previous inspection data could be identified and sized.

Since analyst variability exists with the selection of peak MRPC voltage, APS has strived to provide consistent measurements for the purpose of determining the voltage change for a particular flaw. Upon conclusion of the U2R5 inspections, a select group of resolution analysts were retained to independently rereview the

current inspection results and compare those results to the ECT data from previous inspections. Special care was taken to assess the effects of geometry, interfering signals and overall data quality. A lissajous graphic and C-scan hardcopy of each defect was generated and a final review of critical calls for the Unit 2 data was conducted by the APS Level III analyst. Review of critical flaws was also conducted by Steve Brown of Packer Engineering. The results of this review are summarized in Appendix C.

D. Metallurgical Examinations

Since the Unit 2 tube rupture event, APS has removed 31 tube sections from both the Unit 2 and Unit 3 steam generators. Laboratory examinations of these tubes have been conducted at Combustion Engineering, Babcock and Wilcock (B&W) and Westinghouse. The purpose of these examinations included:

- Evaluation of field eddy current testing (ECT) results against actual defect size and location
- Validation of ECT detectability thresholds
- Characterization of various ECT probe detection capabilities in the bend section tubing
- Burst test data correlation for structural integrity analysis
- Probability of detection (POD) database development
- Identification of mode of degradation

The testing conducted on these tubes included:

- Receipt Inspections
- Visual Inspection and photography
- NonDestructive testing (Bobbin and MRPC, ultrasonic (UT) characterization)
- Dimensional Measurements (bend section radius, tube ovality)
- Deposit chemical analysis
- Swell testing of tubes without ECT corrosion indications
- Burst testing
- Scanning electron microscopy (SEM) of burst and crack extension areas
- Low Optical Microscopy of material cross sections
- Radial metallography to characterize surface intergranular corrosion
- Auger electron spectroscopy (AES) to determine crack tip chemistry

- X-Ray photoelectron microscopy to determine crack tip chemistry
- Dual etch metallography to characterize tube microstructures
- Modified Huey testing to determine degree of tube sensitization
- Mechanical testing for tensile and yield strength properties and base metal chemical analysis

A detailed description of the test results has been provided to the USNRC Staff in References 1 and 2. The complete results of each exam are documented in References 3-6. A summary of the critical results are provided below.

1. **U2R4 Tube Pull Program**

During U2R4, eight (8) tubes were removed from the Steam Generator 22 after extensive ECT examinations identified tube candidates deemed most representative of the ODSCC indications at free span, eggcrate, batwing and flow distribution plate locations. A portion of the ruptured tube (R117C144) was also removed. A tubesheet map depicting the location of these tubes is provided in Figure IV-26.

The examinations conducted by CE and B&W under the supervision of APS Metallurgists resulted in the following conclusions/findings:

1. The examination concluded that the ruptured tube, R117C144, failed as a result of IGA/IGSCC attack in an alkaline to caustic with sulfate environment associated with free span deposits formed at a tube-to-tube crevice due to tube bowing. The detection of cold working due to scratches on this tube and on the largest defects suggested that the presence of deposits combined with long linear scratches led to preferred IGA corrosion sites and early crack initiation.

2. The detailed exam led to a further conclusion that the tubing examined had microstructures which were not consistent with industry expectations for High Temperature Mill Annealed (HTMA) Alloy 600 tubing. The requirements of ASME SB-167 were supplemented by CE specification requirements restricting carbon content to 0.05 percent and a maximum yield strength of 55,000 psi. These requirements assured a relatively high temperature final anneal of 1806 °F. The microstructural characterization of Tube R117C144 indicated a microstructure absent of intragranular carbide precipitation, with slight intergranular carbide precipitation. This microstructure was not expected for HTMA Alloy 600, which would normally be expected to have a semi-continuous grain boundary, thus providing more IGSCC resistance in caustic environments. It should be

noted that a microstructure acceptance criteria, in terms of grain boundary carbide precipitation requirements, was not contained in the tubing specification when it was developed. The tubes did meet specification requirements with regard to carbon content and maximum yield strength.

3. A critical objective in performing tube pulls in Unit 2 was eddy current validation and structural margin assessment of freespan IGA/IGSCC. Difficulties associated with bobbin coil detection of these flaws during U2R3 contributed to the presence of several cracks which were structurally deficient at normal operating pressures at the end of Cycle 4. APS found during U2R4 inspection, that MRPC examination could be used to detect and characterize ARC region flaws. Table IV-9 provides a summary of the key results of this evaluation, which was incorporated into the Regulatory Guide 1.121 assessment described in Section IV and Appendix A.

2. U2M5-1 Tube Pull Program

Based on results of eddy current testing following chemical cleaning the Unit 2 steam generators, APS elected to remove additional tubes for metallurgical examination. Since many of the ARC defects exist above the batwing support location at the bend tangents or within the bends, the tube removal effort consisted of removing bend sections from the secondary side of the steam generator from above the tube bundle. This technique, also referred to as "tube harvesting" removed 21 tube sections from the periphery of the tube bundle. Of the 21 sections, 13 contained eddy current indications, while the eight (8) remaining sections were removed to provide access to tubes with indications. A sketch of the removed sections is provided in Figure IV-27.

All tube sections were examined by ABB-Combustion Engineering in accordance with a detailed APS tube examination plan as described in Reference 6. Independent laboratory microstructure examinations of all 21 sections and a corrosion examination of one crack indication were conducted by Westinghouse. Burst testing procedure review and test oversight was provided by Dr. Jim Begley of Packer Engineering. All laboratory work was performed under the direction of APS Metallurgists.

Since the previous tube pull during U2R4 did not remove bend sections, APS was interested in determining if causal similarities existed for bend region defects. No evidence of bowing (free span crevice formation) or ridge deposits were identified during examination of the bend region. The results of the U2M5-1 tube examinations did support previous conclusions that defects in the ARC region tubing are due to contaminants present as either general deposits, support deposits or ridge deposits. Corrosion attack in freespan locations below the batwing was still associated with long narrow ridge-like deposits, which act as

preferential crevice sites. Although some differences were identified, APS concluded that the overall findings were consistent with the 1993 tube pull metallurgical examinations.

The investigation results indicated a potential favorable change in crack crevice chemistry tending towards neutral-alkaline and in some places neutral-acidic. This crevice chemistry was considered to be improved over the more alkaline-caustic crevices observed during the 1993 Unit 2 steam generator tube metallurgical analysis. The increased IGA character of the tube degradation indicated a slower growth factor which is further supported by the thin oxide thickness layers found on the crack surfaces. Studies published by EPRI (Reference 13) have shown that under the same stress IGSCC propagation is approximately 10 times faster than the IGA propagation rate.

The presence of sulfates and reduced sulfide species were again concluded to be an important factor in the tube degradation. Sulfur was detected in all areas examined on crack surfaces, and therefore, is still suspected to be aggravating the IGA and SCC in the tubing. However, the amount of sulfates deposited, and subsequently detected on the crack faces, may have been influenced by the chemical cleaning corrosion inhibitor. Sulfur-bearing residues as a result of chemical cleaning had been observed during EPRI qualification testing (Reference 14). EPRI has assessed this condition with respect to additional degradation and concluded that there was no contribution to degradation, that residues were essentially removed during normal operation, and that the amount of sulfur that remained in the metal oxide layer was negligible compared to the amount carried into the generator during normal operation.

As was observed in the U2R4 examination, scratches and wear scars under concentrating ridge deposits were present and were often identified as preferential sites for IGA and SCC. Additionally, tubing microstructures were found to contain random carbides with discontinuous or some semi-continuous grain boundary carbides, indicating less than optimum resistance to stress corrosion cracking.

Tube burst testing was performed on tubing with ECT detected defects per a quality controlled procedure under supervision by APS and its consultant. A similar procedure was applied to the swell testing of tubes with no reported field eddy current signals. Burst opening average and maximum depths were measured using SEM montages of the burst face with depth measurements every 0.025 inches. The data indicated that all tube burst pressures were significantly above 3ΔP (three times normal operating differential pressure) and 1.4 times main steam line break pressures as required by Regulatory Guide 1.121. The information from this testing and subsequent examination serves as input to the plant specific run time analyses performed in Appendix A. Table IV-9 provides a summary of the burst test results.

TABLE IV-9 SUMMARY OF UNIT 2 TUBE PULL RESULTS

Tube No	Defect Location	Actual Depth (max)	Actual Depth (Ave)	Burst Length (in)	MRPC Length (in)	Burst Pressure (psig)	Yield Strength (ksi)	Ultimate Strength (ksi)
R105C156	08H+26.5	98%	77%	1.38	1.6	3200	47.8	102.9
R103C156	08H+21.5	57%	45%	0.325	0.29	6968	48.7	101.6
R127C140	08H	89%	58%	1.0	0.4	6119	50.9	112.1
R127C140	07H	100%	40%	0.58	0.3	5330	50.9	112.1
R117C40	08H+40.89	61%	27%	N/A	0.21	N/A	47.8	105.6
R22C13	01H	56%	31%	0.325	0.25	8948	N/A	N/A
R29C24	01H	40%	21%	0.275	0.33	9662	N/A	N/A
R133C134	BW1+3.95	73%	51%	1.44	1.38	7320	43.6	101.4
R135C134	BW1+2.79	73%	51%	1.25	N/A	7820	N/A	N/A
R137C134	BW1+16.0	41%	32%	1.3	2.03	8500	N/A	N/A
R140C135	BW1+16.4	66%	47%	1.15	3.73	7540	45.4	106.3
R133C136	09H+16.6	85%	45%	1.5	1.91	6020	N/A	N/A
R137C136	BW1+17.45	53%	38%	1.3	2.53	8860	53.7	104.6
R139C136	BW1+18.03	84%	51%	0.95	2.35	6860	55.3	105.3
R134C137	BW1+16.2	60%	41%	1.3	1.12	8640	46.3	102.3
R136C137	BW1+16.6	45%	32%	1.24	0.94	9180	50.1	106.7
R138C137	BW1+16.3	55%	39%	1.25	2.67	8020	49.4	105.7
R140C137	BW1+17.37	48%	31%	1.36	2.35	8960	46.4	105.0
R135C138	BW1+1.51	59%	38%	1.25	1.01	8520	55.3	105.3

3. Unit 3R4 Tube Pull Program

The scope and process description of the metallurgical examination and subsequent evaluation of tubes removed from Unit 3, SG 32, ARC region during U3R4 are discussed in detail in Reference 3. Two (2) Unit 3 tube bend sections, tubes R152C73 and R154C73, were removed and delivered to ABB-CE for laboratory examination. Tube R152C73 contained a suspected volumetric indication (SVI) on the intrados of the tube just above the batwing support contact area, but below the bend tangent point. Tube R154C73 did not have an eddy current indication, but was removed to allow access to the tube of interest. As discussed in Reference 2, the results of the examination found that:

- There was no IGA or IGSCC in tube R152C73 which was called SVI by field ECT
- The SVI was approximately $2^{3}/_{16}$ inches long and 1/4 inch wide and had a depth of approximately 26%
- The SVI exhibited a general corrosion process (micro-pitting) under a ridge-like deposit which concentrated impurities in the bulk water
- There was no evidence of active wear caused by repeated tube-to-tube contact
- As observed in the Unit 2 tube pull programs, the micro-structures of the tubes examined were not typical of HTMA Alloy 600 with good resistance to stress corrosion cracking

4. Conclusions

To date, APS has performed extensive steam generator tube removal and examination work. Data gained from the detailed examinations has provided valuable input towards assessing eddy current capabilities, structural testing and analyses, and understanding the challenging ARC region degradation mechanism. The benefits of this effort have provided APS with a strong database of plant specific information. When supplemented by industry data and experience, it permits APS to implement the appropriate steam generator inspection and mitigation programs aimed at ensuring safe and reliable plant operation.

E. ATHOS Thermal-Hydraulic Modeling

APS has continued to assess the thermal-hydraulic conditions, which are believed to resulted in a region of increased susceptibility to ODSCC in the PVNGS steam generators. As reported in Reference 1, APS has developed empirical relationships for predicting dryout in the vertical and square bend sections of the tubes in the upper bundle of the steam generator based on calculated steam quality and mass flux. Using these relationships, thresholds for dryout in the vertical section of the tubes and in the bend/horizontal section have been established. For the vertical sections of tubes, the dryout region represents a departure from nucleate boiling, and has been defined empirically by APS as a "deposit parameter" with a threshold value of $\rho V/1\text{-}X = 180$ lbm/sq ft•s. As part of an ongoing investigation, APS has found that the deposit parameter does not correlate for the cracks initiating in the bend or horizontal regions. APS and ABB-CE believe that contaminant concentration and the corresponding initiation of cracks are related to a critical quality parameter. By empirically correlating the location of the bend/horizontal defect, it has been determined that the threshold value for critical steam quality is 65%. APS and ABB-CE believes that further correlation is provided by reviewing previous steam generator designs. Other than the System80 design, all other ABB-CE designs have maximum bundle exit qualities of less than 60% and have not experienced similar corrosion after longer operating histories than PVNGS.

APS has also performed an additional assessment of an experimental correlation referred to as the Zuber correlation (Reference 41) which relates the critical heat flux to quality (or void fraction) for low flow conditions. As shown in Figure IV-28, the bend and horizontal defects are located in a region of high void fraction with heat flux values in excess of the Zuber critical heat flux. This correlation supports the empirically determined threshold of 65% quality for the upper bundle region of the PVNGS steam generators. Figures IV-29 and IV-30 provide iso-surface contour plots for both the deposit parameter and critical quality parameter for the PVNGS steam generators.

With these criteria established, the number of tubes subject to dryout for various modifications, operational changes, or combinations thereof, can be predicted and appropriate changes in ECT scope can be assessed. Based on further analyses performed by APS and ABB-CE, two (2) major modifications have been selected for implementation in Unit 2 during U2R6. The modifications are described as follows:

Downcomer Feedwater on Hot Leg Side

The System80 steam generators were designed to introduce 10% of the feedwater flow to the cold side recirculating fluid. This feature maximizes the temperature difference between the cold leg sides of the primary and secondary fluids, thereby improving the thermal efficiency of the generators.

The proposed modification shown in Figure IV-31, involves replacement of the existing ring with a new ring designed to deliver the downcomer feedwater flow to the hot side downcomer annulus. With the modification, maximum bundle exit quality and deposit parameter decrease and hot side circulation ratio is increased with a negligible decrease on thermal efficiency. The ARC region affected tube population is reduced by approximately 15%. The new feedring would be constructed of materials resistant to erosion/corrosion as an added benefit.

Downcomer Shroud Modification.
The System80 steam generators are designed with a flow distribution plate (FDP) on the hot leg side. The baffle is located 16" above the tubesheet, and helps to distribute the incoming recirculating fluid more uniformly as it flows upward in the bundle. The FDP, contributes to the ARC region phenomena as it produces additional flow resistance in the hot side recirculating loop, thus reducing recirculation. The new System80+ design eliminated this feature, however, removal of the FDP at PVNGS would be an unrealistic field modification. As an alternative option, the FDP could be bypassed by cutting holes in the downcomer shroud above the flow distribution plate (See Figure IV-32).

Once again this modification reduces steam quality and hence the dry-out region. ATHOS modeling predicts a 39% reduction in affected tube population. For both modifications the reduction in ARC region size is estimated at 45%.

These modifications improve the thermal-hydraulics in the tube bundle by reducing the maximum quality from 73.67% to 56.10%. This quality is more comparable to the earlier 3410 MWT CE plants and the newer Korean System80-modified steam generators. The number of tubes in the dry-out region decreases from approximately 2700 tube to 1600 tubes. The analyses performed by APS and ABB-CE also indicate that the modifications do not have any significant impact on flow induced tube vibration, the structural integrity of the shroud, tubesheet sludge deposition and feedring water hammer susceptibility.

An additional measure currently under review and consideration involves the reduction in feedwater inlet temperature. ATHOS analyses indicate that additional reductions in ARC region population may be accomplished via this operational change. Feedwater temperature reduction can be achieved by either isolating flow to the #7 feedwater heaters or by rerouting a portion of the feedwater flow around the #5, 6 and 7 heaters. The method chosen would depend upon an evaluation of the economical and technical trade-offs associated with each change.

V. STRUCTURAL AND LEAKAGE INTEGRITY ANALYSIS

A. Description of Structural Integrity Model

The PVNGS Degradation Management Program uses two (2) independent methods and sources to assess structural integrity of steam generator tubing. The primary model for assessing structural margins, in accordance with the guidance given in Regulatory Guide 1.121, was developed by Packer Engineering with input and review by APS. The method of analysis, including results, are described in detail in Appendix A. The calculational framework is essentially the same as that presented to the USNRC Staff in References 2 and 35. The model is considered to be a mechanistic model as it addresses the historical development of cracks, including, crack initiation, crack growth, detection of cracks and removal from service. Initiation and growth of new cracks during a given cycle of operation is included as is the population of defects which have not been detected by eddy current inspections.

The model framework, as first presented for Unit 1 in Reference 2 in August 1994, has been validated for Unit 1 in the U1R5 inspections conducted in April 1995. The model predicted with high confidence that structural margins would not be exceeded for either circumferential cracks in the tubesheet transition or ARC region axial cracks. The inspection confirmed this result, and the number of observable defects when adjusted for the Plus Point MRPC indicated good correlation with model predictions. However, based on discussions between USNRC, APS, Packer Engineering and an independent consultant, refinements to the models have been incorporated to address items identified in References 8 and 16. The critical features of the model, as well as recent refinements, include:

1. APS and Packer Engineering have continued to review PVNGS specific tube pull results and industry data to support the relevance of characterizing ARC region defects with MRPC signal response. The length and depth profiles of cracks in tubes pulled from Unit 2 have been analyzed to identify the critical regions of these profiles relative to burst pressures. Structurally significant crack lengths and depths have been defined. The structurally significant crack lengths have been correlated to crack lengths observed from the eddy current MRPC data. Average crack depths over the structurally significant crack lengths have been determined and correlated with MRPC eddy current probe voltage readings.

2. Computer modeling of the signal response of eddy current pancake coil probes to cracks in thin plates has shown the practicality of estimating crack depths from voltage readings in limited but useful circumstances.

3. MRPC voltage changes have been analyzed to estimate crack growth rate distributions. Variations in the correlation of voltage with structurally significant depth have been included to reflect the effects of variable crack morphology.

4. For Unit 2, crack initiation parameters have been optimized relative to the observations of eddy current indications throughout the history of Unit 2. Sensitivity studies have shown that it is possible to determine reasonably constant crack initiation parameters from the statistics of eddy current indications.

5. Three (3) different statistical procedures have been used to determine degradation growth rate parameters. Agreement was found to be excellent. By assessing these approaches, crack morphology effects, uncertainty in voltage measurements and extreme values in voltage growth have been included.

6. A probability of detection (POD) curve has been calculated for the Plus Point MRPC eddy current probe from the observed inspection transient resulting from its use in the U2R5 steam generator inspections.

7. Mechanical break-through effects have been specifically treated in the calculations of through-wall crack lengths for input to the probability of leakage model.

8. The ability to benchmark the model output with past inspections was presented for Unit 3 in Reference 35. In addition to benchmarking of the simulation model relative to the Unit 2 history of the number and severity of eddy current indications, the probability of tube burst during normal operation at the end of Cycle 4 was examined. In agreement with actual experience, the model correctly predicts a high probability of tube burst at normal operating pressures, as well as the presence of several severely degraded tubes. This correlates well with the actual end of Cycle 4 inspection results presented in Reference 1.

A complete description of the analysis conducted by Packer Engineering is provided in Appendix A. The following is a discussion of the fundamental components of the model including a summary and results.

1. **Structural Assessment**

The length and depth profiles of all cracks in tubes removed from Unit 2 have been analyzed and the critical regions of these profiles relative to burst pressures have been identified. As found in many industry examples, APS utilized MRPC detected crack length to assess structural margins. However, tube pull results consistently indicate that actual crack length, whether the defect is axial or circumferential, can be substantially longer than the MRPC detected length. This difference is not considered to be of issue since laboratory examination of PVNGS tubing removed from Unit 2 indicates that the shallow cracking at the ends of the crack profile is not a consequential factor in burst pressure. The Unit 2 tube pull data show that the MRPC results provide an excellent indication of structurally significant length. Although there are individual instances where the MRPC crack length is slightly less than the directly corresponding structurally significant crack length, Packer Engineering performed sampling of the MRPC crack length distribution. This approach provides a conservative estimate of the crack lengths in service. Since no known cracks are left in service, there is no need to adjust an individual crack length to cover the possibility that it may be undersized. An additional element of conservatism, which is to be more significant, is the fact that the crack length distribution used in the Packer Engineering Monte-Carlo calculations is based on the crack length distribution obtained from U2R5 eddy current inspection data. This crack length data is substantially influenced by the detection improvements expected from the use of the Plus Point probe. Hence, it is biased toward longer crack lengths.

Through the Unit 2 tube pull results, Packer has also correlated the depth profiles of the cracks evaluated with a structurally significant crack depth. If a chosen profile is symmetric, then the minimum burst pressure can be defined as a function of increasing lengths of the central section of the crack. When crack profiles are not symmetric relative to their axial midpoint, the selection of a critical section or even the point to begin calculations is not at all obvious. Packer used short computer program to find the minimum calculated burst pressure and the critical section of the crack profile. It was found that when this structural minimum method is applied to actual crack profiles, the Framatome burst equation is a very conservative predictor of the burst pressure.

The field determination of structurally significant depth has been more difficult due to a number of plant specific differences at PVNGS versus more traditional industry experience. As reported in Reference 1, the PVNGS steam generator tubing was manufactured via a pilger process. The signal to noise ratio associated with the PVNGS tubing, combined with an IGA influenced morphology, and geometry variations associated with the tubing bends, has made the process of bobbin detectability and depth sizing of these defects virtually nonexistent. As a result, MRPC techniques have been utilized as the primary defect assessment technology.

APS, Conam (Rockridge) and Packer Engineering have considered several approaches for characterizing MRPC signal response. In principal, the phase angle of the impedance plane lissajous figure formed as the MRPC probe passes over the crack should provide a good correlation with crack depth. However, based on early field experience and tube pull results, significant difficulty had been encountered in attempting to characterize defect depth via phase angle measurements. APS and Packer are continuing to develop the ability to dimensionally profile discontinuities by capturing the in-phase and quadrature signal components of the MRPC probe. Additional information concerning this effort is contained in Appendix A, and this work corresponds with recent industry programs for circumferential crack sizing.

Until this work is completed, an empirical correlation of MRPC voltage with crack depth has been used to assess significant crack size. This correlation, as reported in References 2 and 17, has proved to be reasonable in calculating crack depth, assessing crack propagation and determining structural integrity. However, a number of questions have been raised by the USNRC Staff regarding the physical basis of this correlation. The work conducted and presented in Appendix A attempts to address these issues. Packer Engineering reported that computer modeling of the response of eddy current pancake probes to cracks in thin Alloy 600 plates supported the practicality of estimating crack depths from voltage readings in limited but useful circumstances. The data indicated that systematic impedance changes with crack depth occur in the range of interest, 40-80% through-wall.

It is important to note that the objective at PVNGS is not to accurately size all indications, since no detected cracks are left in service either as a function of measured depth or voltage. Instead, the MRPC voltage correlation was developed as a vehicle for assessing inspection data to arrive at a reasonable distribution of crack growth rates. As indicated in Section IV, APS has minimized the variability associated with field MRPC voltage values by conducting a thorough post inspection review of all the ECT crack indication data.

2. Growth Rates

Eddy current records of tubes found to contain MRPC indications during the U2R5 inspection were revisited to determine if precursor signals were present at the time of the previous U2M5-1 and U2M5-2 inspections. The review indicated that precursor signals could be found and that a plot of voltage change versus initial voltage could be generated. The results of the review are summarized in Appendix C and Figure 4.1 of Appendix A. The review revealed growth in signal amplitude combined with significant scatter. The presence of more than a few negative voltage changes points to a non-trivial uncertainty in voltage measurement compared to voltage growth. Overall, the voltage growth points to an increase in

the severity of corrosion degradation relative to structural requirements. The challenge is to separate voltage measurement uncertainties from real voltage growth and then quantitatively relate voltage growth to reduction in structural margins. As noted previously, the chosen approach is to relate MRPC voltage to structurally significant depth.

Given the presence of confounding variables and a correlation of MRPC voltage with structurally significant crack depth with considerable scatter, three different statistical approaches were developed by Packer Engineering to use the distribution of voltage changes to arrive at a distribution of degradation growth rates. These methods are described in detail in Appendix A. As a further check, this calculated growth rate distribution was compared to data in the literature. Data in the literature permitted a check of both the mean and variance of the calculated lognormal growth rate distribution. The degradation morphology of Unit 2 pulled tubes also helped to benchmark the calculated growth rate distribution.

3. Probabilistic Model

As indicated previously, the probabilistic model used for Unit 2 is similar to the models described in References 2 and 35, and is designed to simulate four basic processes:

Upper bundle crack initiation
Crack Growth
MRPC Inspection
Removal and repair of degraded tubes

The crack initiation model relies on defining appropriate Weibull parameters for Unit 2 ARC region degradation rates. Since Unit 2 has experienced much more extensive upper bundle cracking, the simple time-delay approach to developing an initiation model as used for Units 1 and 3 in References 2 and 35, proved far too conservative. The behavior of the initiation model developed in this manner resulted in consistent under-prediction of early inspection results (U2R4, U2M5-1) and over-prediction of later inspection results(U2M5-2, U2R5). This behavior suggested a systematic effect caused by an overestimate of the Weibull shape parameter (N) from the observed data.

A more sophisticated approach to the development of a crack initiation function was, therefore, developed by Packer Engineering. This methodology used a simplified version of the RG 1.121 simulator in conjunction with an optimization module to evaluate the best-fit Weibull initiation model parameters including the time-delay value. The approach is described in detail in Appendix A. It should be noted that the Weibull shape and scale parameters were not treated as independent in the analysis. In the mathematical sense, this can be viewed as forcing the results through a specific observed point, in this case, the observed U2R5 cumulative

results. It should also be noted that the Weibull parameters were in excellent agreement with results generated independently by the APTECH BALIFE model. As described previously, crack growth rate is determined by assessing voltage changes as changes in structurally significant crack depth. The Monte Carlo analysis samples the log-normal crack growth distribution to obtain growth rates for each crack, and this rate is assumed to be constant throughout the propagation process.

Since the inspection and repair model is dependent on the capabilities of the inspection process, an MRPC POD function was developed from PVNGS specific tube pull data. This POD function, described in Reference 35 was modified to permit the incorporation of a simulated Plus Point probe POD function for the U2R5 inspection. As detailed in Section IV, several means of assessing the benefits of improved detection have been examined. The appropriate POD function is applied to all of the predicted active cracks. All detected cracks are removed from service, and are therefore not subjected to the subsequent inspection. Consequently, only non-detected defects (in essence, MRPC NDD indications) remain and are projected for the remainder of the operating cycle. As indicated previously, Figures 5.4 and 5.7 of Appendix A compare simulated observed cracks with actual observed cracks, and the actual inspection results compared favorably with the mean values. The overall process is therefore considered conservative based on the described distribution function.

The model also includes a material property and crack length distributions. The material property effects are included by obtaining randomized flow stress values for actual Unit 2 Certified Material Test Reports (CMTR) data. The crack length effects are simulated by sampling from Unit 2 MRPC measurements. For U2R5, these measurements are considered additionally conservative, as the detected lengths are biased compared to earlier inspections due to the detection improvements realized by the Plus Point probe. The distributions for flow stress and crack length are used in defining structural margins in distributional terms for the implementation of Regulatory Guide 1.121 limits for free span axial cracks.

4. Summary

The Packer Engineering approach, endorsed by APS, characterizes the structural integrity of steam generator tubing by performing a Monte Carlo simulation of the physical processes of crack initiation, growth, eddy current detection and removal of all detected cracks from service. This approach, which is supported by a large plant specific database of pulled tubes, provides a reasonable physical characterization of critical cracks and crack growth. This characterization is key to the overall success of managing ARC region degradation and demonstrates that the proposed operational run times provide adequate safety margins. Obviously, other voltage based approaches are available, and for the most part form the basis of the Generic Letter 95-05. APS and Packer Engineering have reviewed the

industry data and have determined that either insufficient data exists for an adequate comparison due to the nature of ARC region free span defects, or if similar industry methods are used, one is basically trading less uncertainty in one area for more uncertainty in another. For example, in correlating structural margins to MRPC voltage, the past history of EOC voltage observations leads to confidence in the prediction of future EOC distributions of voltages. While this process provides a reasonable measure of the physical process of crack initiation and growth, the benefit is offset by a high degree of uncertainty in the correlation of voltage with burst pressure. This approach is further confounded by an industry database which supports the use of a voltage based criteria that is mainly developed for crack lengths up to 0.75 inches long. Therefore, its applicability is considered limited to longer freespan crack conditions.

5. Results

As stated in References 2 and 35, APS established a reasonable probability criteria for meeting Regulatory Guide 1.121 structural margins for Unit 1. This criteria was:

> *There must be a 90% probability that one or fewer tubes will be expected to violate Regulatory Guide 1.121 limits for axial cracks during the specified operating period.*

The model as described above was exercised using Monte Carlo simulation techniques as shown schematically in Figures 5.1, 5.10 and 5.11 of Appendix A. The probability of exceeding Regulatory Guide 1.121 structural margins has been computed by Packer Engineering as a function of run time in Cycle 6. After 12 months of operation the probability of more than one exceedance would be less than 0.01. At this same point in time, the conditional probability of tube burst given the occurrence of a main steam line break is 0.018. With regard to leakage, there is less than a 10% chance of wall penetration if a steam line break occurs after 12 months of operation. These results exceed the acceptance criteria established by APS in Reference 2, and demonstrate with high confidence that steam generator tube integrity in Unit 2 can be maintained until end of cycle.

6. Benchmarking

As a further measure of assuring that this modeling approach addresses the issues associated with crack growth and inspection uncertainties, the USNRC staff has requested during a public meeting, that statistical models for predicting steam generator tube integrity be benchmarked against previous inspection findings. The Packer Engineering probabilistic model has a significant amount of internal benchmarking, particularly with respect to the combined effects of crack initiation, growth, and detection. The modeling of four previous inspections

provides a robust basis for the comparison of simulated and actual crack evolution in the Palo Verde Unit 2 steam generators, giving confidence in the U2R6 projections. As can be seen from Figures 5.4 and 5.7 in Appendix A, the comparison between simulated numbers of cracks and observed values is nearly exact.

Other benchmarks are facilitated by the mechanistic nature of the model in which critical elements such as crack growth rate, crack length, material property and probability of detection (POD) distributions are each individually benchmarked from plant specific tube pull data, NDE results including UT and in-situ pressure data and industry documented corrosion and burst test data.

Perhaps the most important benchmark for the Unit 2 probabilistic model is contained in the prediction of tube rupture for normal operating conditions as described in Appendix A. This case is calculated in support of the Risk model presented in Section VI. The first inspection modeled for this case is U2R4 which is coincidentally the inspection immediately following the Unit 2 tube rupture during normal operation. The model predicts a "best estimate" of between 2 and 3 tubes degraded to the point of burst at normal operating pressure for the U2R4 inspection and greater than 10 Regulatory Guide 1.121 exceedances. As shown in Figure IV-11, reprinted from Reference 1, this result is in excellent agreement with actual U2R4 results. This particular benchmark lends credence to the combined effects of growth rate and initiation models in terms of resulting in accurate estimates of historical risk. These elements of the Unit 2 probabilistic model were never calibrated with this benchmark in mind.

It can therefore be concluded that the Unit 2 probabilistic model is thoroughly benchmarked in terms of:

Individual model components

- crack growth rate
- burst pressure
- crack length
- material properties

Combinational effects

- observable crack evolution

Tube Rupture Risk

- normal operating conditions

B. Independent Assessment

In accordance with the guidance given in 10CFR50 Appendix B, APS has employed the use of an independent alternative calculational method as a means of performing a check of the results generated from the primary structural model developed by Packer Engineering. APTECH Engineering Services has been retained by APS to perform this independent assessment. These independent assessments have been performed for the Unit 1 and 3 steam generator evaluations presented in References 2 and 35 with excellent agreement. This section provides a discussion of the modeling assumptions and results for the APTECH evaluation.

1. Model Description

Currently, APS utilizes the BALIFE computer code (Reference 29) developed by APTECH to perform long term statistical analyses for evaluating the effects of repair and remedial measures on steam generator life. The BALIFE code applies rigorous Bayesian reliability estimation methods to the prediction of failure frequencies from life- or age-to-failure data. The code allows the user to develop a "prior" distribution such as a set of Weibull curves and slopes to establish a baseline for a typical industry damage mechanism. Plant specific data can then be used to calculate a "likelihood" function which allows APS to estimate the probability of specific values of the Weibull slope in light of PVNGS specific failure data. Finally, a "posterior" distribution is calculated as the product of the "prior" and "likelihood" functions. The code has been verified by APTECH by comparing the BALIFE and exact solutions for several "textbook" classical and Bayesian problems, and by constant benchmarking against service failure and cracking data.

The BALIFE code has also been utilized by APS for assessing the probability of Regulatory Guide exceedances (RGEs) as a self-check of more detailed analyses, as in the case of Units 1 and 3, in References 2 and 35 respectively. The same calculational framework was employed by APTECH for ARC region ODSCC in Unit 2. The key assumptions, inputs and model improvements developed for this analysis are summarized below.

2. BALIFE Model Assumptions and Input

A. The BALIFE Code, Version 5.051 has improved a "Nuclear Inspection Option" which permits the user to assess varying inspection samples on the tube population of interest. This is useful when considering random, subsequent or repeat sample ECT inspections for the specific steam generators or the input of industry trends where different inspection samples are routine. This computer program has been benchmarked against the last five Unit 2 inspections with reasonably accurate results for the subject ARC region cracks and other tube crack modes.

B. In Reference 35, a separate MRPC probability of detection (POD) analysis was performed by APTECH, independent of the Packer Engineering POD curve, from the PVNGS plant specific tube pull data. The best estimate POD curve from Reference 35 is used in the APTECH baseline analysis. The effects of various possible inspection improvements were then calculated by altering the best-estimate POD values.

C. Results from previous BALIFE predictions for Unit 2 show that ARC region ODSCC has a Weibull slope or β value of between three and five. The most recent BALIFE predictions for PVNGS Unit 2 steam generator strategic models approximates the Weibull slope to be 3.176. This value is in excellent agreement with the Packer Engineering Weibull function which estimates the β value to be 3.2. Different scale parameters (θ, the age at which 63.2% of the affected population has failed) were calculated directly from inspection data. These calibrated θ values were based on damage categories related to ECT detection levels, as defined below. For example, different categories were established for MRPC, Bobbin "I" codes and bobbin depth calls as a means for tracking crack growth and θ values.

3. Inspection Model Assumptions and Input

The BALIFE modeling approach employed by APTECH was supplemented to include an inspection/repair capability for ARC region defects. The following assumptions were used in the simulation:

A. Tube Population

- At the start of operation for each steam generator, each of the 2700 unplugged tubes was susceptible to the subject arc region cracks. Only eventual plugging can immunize a tube against this failure mode.

- The 2700 tubes are assumed to come from the same statistical population. This is done in spite of much evidence of preferred cracking sites within the ARC region, especially in SG 22. The use of only one tube population is very conservative in that it exaggerates the calculated probability of an RGE. The single-population model ignores the fact that all or most tubes in the worst ARC population subsets have already been plugged.

B. Damage Classification for Each Tube

- At any stage in the life of an unplugged tube, its worst crack belongs to one of five damage categories:

  a. Nonexistent and waiting to be initiated. Conservatively, the chance of plugging such a tube is assumed to be zero (i.e., no false calls).

  b. MRPC-size. These cracks are defined to be so small as to be possibly detected only by MRPC. The probability of a miss is quantified below and defined as POM(MRPC)=1-POD(MRPC).

  c. Bobbin-size. These cracks are defined to be large enough to be possibly detected by *either* MRPC *or* Bobbin or both. This probability of a miss by *both* inspections is quantified below and defined as POM(Bobbin)=1-POD(Bobbin).

  d. RGE-size. These cracks are defined to exceed the size defined in Regulatory Guide 1.121. They are large enough to be possibly detected by *either* MRPC *or* Bobbin or both. This probability of a miss by *both* inspections is quantified below and defined as POM(RGE)=1-POD(RGE).

  e. Leak or burst. The crack penetrates through the tube wall.

- As any tube ages, its worst crack moves from category one toward category five and plugging is the only way to halt this process.

- Any tube found to be damaged is immediately plugged.

C. Inspection Simulation

- From the POD curve (Figure V-12), a given MRPC inspection has a probability, POM(RGE) = 6% of missing a crack (conversely a 94% probability of detection) which exceeds Regulatory Guide 1.121 based on the POD curve.

- Each single inspection has a probability POM(Bobbin) = 15% assigned for missing a crack that is "normally" detectable by Bobbin inspection.

- Each single inspection has a probability POM(MRPC) = 40% of missing damage that is normally detectable by MRPC inspection (35-40% through-wall).

- The last three assumptions are combined as a best-estimate baseline inspection model, and labeled as ***6-15-40***.

- The effects of improved inspections were studied with five hypothetical, but realistic, combinations of these POM values: 4-10-25, 2-5-15, 6-15-25, 6-10-40, and 4-15-40. These cases were run to assess the benefits of improved technology, such as use of the Plus Point probe, on the probability of Regulatory Guide exceedance.

- For the 6-15-40 model baseline, the time to the next planned inspection in 4/96 is taken as 13 months. For sensitivity cases, APTECH also examined 6, 9, 12, and 15 month inspection intervals.

- The baseline case was first run for the actual past schedule and includes the two midcycle inspections. Then as a sensitivity case, it was run with an original plant schedule, which would have included no midcycle inspections. This case was evaluated to assess the impact of performing midcycle inspections on reducing the probability of Regulatory Guide exceedances.

- The effect of limiting *only* the MRPC baseline inspection's sample size was studied by running two other POM combinations: 6-15-98.2 and 6-15-88. These two are simplified representations of a baseline MRPC inspection sample of 3% and 20%, respectively. (That is, 98.2% = 100% - [1-0.4]*3% and 88% = 100% - [1-0.4]*20%.). These cases were run to assess the overall sensitivity of the results to a Technical Specification inspection sample (3%), and EPRI recommended sample (20%) and a 100% inspection scope as has been performed by APS for ARC region inspections.

D. Crack Growth

- Within any inspection interval, the average number of tubes which move from a damage category (e.g., MRPC size) to the next higher damage category (Bobbin size) is directly proportional to the number of tubes within the lower damage category at the start of the interval.

E. Unit 2 Forecast from Statistical Combination of SG 21 and SG 22 Forecasts

- The RGE analysis was first run for each steam generator. To make the calculations for RGEs in Unit 2, it is assumed that the number of RGEs in SGs 21 and 22 are independent Poisson-distributed variables. So steam generator "failure" rates were added to obtain best estimates for Unit 2. To calculate confidence bounds for Unit 2, the variances associated with the steam generator RGE confidence interval ranges were also added. (In statistics, the variance is defined as the standard deviation squared.)

F Future EFPY Buildup and Damage Exposure

- *No credit* was taken for primary temperature reduction or chemical cleaning. Damage is assumed to correlate with EFPY through the Bayesian Weibull model. EFPY is assumed to increase with future calendar time at past rates.

4. Results

As stated in References 2 and 35, APS established a reasonable probability criteria for meeting Regulatory Guide 1.121 structural margins for PVNGS. This criteria was

> *There must be a 90% probability that one or fewer tubes will be expected to violate Regulatory Guide 1.121 limits for axial cracks during the specified operating period.*

Eighteen different cases were run by APTECH and the estimates are summarized in Table V-1. Based on the results, the probability of one (1) or fewer RGEs after 13 months of operation is 5.9E-3 or a 99.41% chance of no more than 1 tube exceeding Regulatory Guide 1.121 structural limits. The confidence level associated with this upper bound forecast is 90%. The best-estimate forecast shows a 99.74% chance of one or less RGE in Unit 2. It was also calculated that there is a 89 to 95% chance of absolutely zero RGEs in Unit 2 for a 13-month operating interval following U2R5.

5. Comparison with Packer Engineering Results

The results of the APTECH Regulatory Guide 1.121 evaluation compare well with the Packer Engineering analyses for the operating run proposed in this evaluation. The results from both models are depicted as a function of run time in Figure V-1. The objective of an independent check has been satisfied for the Unit 2 evaluation.

Table V-1 - APTECH Independent Assessment Results

Analysis	% Chance of 0,1,or more than one RGE crack		
Type of BALIFE Analysis	**Zero RGEs**	**Exactly one RGE**	**More than 1 RGE**
Best Estimate of SG 21	99.49	0.51	0.00
90% High Bound of SG 21	97.64	2.34	0.03
10% Low Bound of SG 21	99.78	0.22	0.00
Best Estimate of SG 22	93.78	6.41	0.23
90% High Bound of SG 22	90.25	9.26	0.49
10% Low Bound of SG 22	95.74	4.17	0.09
Best Estimate of BOTH SGs of Unit 2	92.88	6.86	0.26
90% High Bound of Unit 2	89.35	10.06	0.59
10% Low Bound of Unit 2	95.26	4.62	0.11

6. Sensitivity Studies

APS and APTECH, using the Unit 2 ARC region model conducted several sensitivity assessments to determine the impact/benefit of certain aspects of the APS Degradation Management Program. The parameters evaluated included inspection improvements, sampling size and inspection frequency. Changes in these parameters were related to their impact on the probability of RGE. Similar sensitivity assessments have been performed by EdF in Reference 23 and were used for comparison purposes. The results of these studies confirm the strengths of the APS program in reducing the potential of exceeding tubing structural margins for a proposed operating run.

Effect of Inspection Improvements

The baseline (Reference 35) POD values are believed to be conservative in the current analysis. They discount the evolution of all inspections. Also, they do not account for enhancements to POD of using several inspection procedures the Plus Point probe and of "learning where to look." Figure V-2, illustrates five realistic combinations of POM values to see how they would affect P0RGE, the estimated chance of zero RGEs, in Unit 2 through 4/96. The effects are predictable. Lowering all POMs in all inspections by about a third (from 6-15-40 to 4-10-25) raises the chance of zero RGEs from 93% to 98%. An additional halving of POM levels to 2-5-15 raises P0RGE above 99%.

The last three cases in Figure V-2 each lower only one POM value by a third. Lowering the past and future POM values for finding smaller cracks (MRPC- or Bobbin-size) is more important than similar improvements in detecting RGE-size cracks. The case which lowers POM(MRPC) from 40% to 25% is indicative of the effects of plugging all MRPC calls including Plus Point ones as well as conventional 0.115 MRPC.

Effect of sharply limiting MRPC sampling

Figure V-3 shows how important the cumulative effects of repeated MRPC inspections are. In these simplified cases, we used an artificially high MRPC POM value to simulate a much-less-than 100% coverage of *all* past MRPC surveys. If all past MRPC inspections had covered only 20% of the ARC region population, P0RGE would be dramatically reduced from 93% to about 50%. If past coverage was only 3% for all MRPC surveys, one or more RGEs would be virtually certain in Unit 2 during the upcoming 4/96 inspection. The 100% sampling strategy employed by APS for the ARC region in all three units is supported by these results.

Effect of the Midcycle Inspections

Figures V-4 and V-5 compare the average number of RGEs before and after inspections of SG 22 for three cases. In each plot, the upper curve assumes no inspections or tube plugging and shows how annual RGEs would increase dramatically with age.

The two lower curves show the classical sawtooth shape associated with the competing effects of component degradation and periodic inspections or repairs. The sawtooth curves are so much lower than the no-plug curve that the linear scale in Figure V-4 can't properly distinguish them. The log scale in Figure V-5 separates these two sawtooth curves.

The solid sawtooth curve is the baseline case which results in a 6.6% chance of RGE(s) on 4/96 for SG 22. The dashed sawtooth curve predicts what "would have happened" using the original inspection schedule. With no midcycle inspections, the chance of one or more RGEs on 4/96 would increase markedly to about 25% in SG 22.

C. Leakage Model

1. Introduction

The leakage model for PVNGS Unit 2 was developed by APTECH and APS. The model predicts end of cycle (EOC) primary to secondary leakage under faulted loads by probabilistic methods using a Monte Carlo numerical simulation of deterministic models for crack opening area, and statistical distributions for material strength and through-wall crack lengths. The analysis follows a mechanistic approach whereby the beginning of cycle (BOC) flaw distributions of undetected defects were projected over the remainder of Cycle 6 to give the EOC probability distribution for through-wall cracks (leakers) should a main steam line break (MSLB) occur. The probability distribution function (PDF) was developed from an evaluation of the progression of ARC region ODSCC during the remainder of Unit 2 Cycle 6, and an analysis of ligament integrity under MSLB loads to establish the number and through-wall extent of leaking defects at EOC. The PDF was provided by Packer Engineering. A deterministic model for leakage from an axial through-wall crack with variable crack aspect ratio formed the basis of the Monte Carlo model. The leakage model is based on the same fluid mechanics model developed for Unit 3 and presented to the USNRC Staff in Reference 35.

2. Acceptance Criteria

The MSLB analysis and associated assumptions are addressed in Section 15.1.5 of the PVNGS UFSAR. Based upon the review of these assumptions it has been determined that a primary-to-secondary leak rate could increase to 6 gpm without the associated radiological consequences exceeding 10CFR100 limits. The APS probability of leakage model acceptance criteria shall be the demonstration of a 95% probability that leakage from EOC tubing conditions with consequential MSLB will remain below the 6 gpm.

3. Model Description

The deterministic leakage model for MSLB conditions was developed from the PICEP computer code (Reference 19). The PICEP program was developed by EPRI for performing leak before break evaluations for reactor piping and steam generator tubing. The leakage algorithm in PICEP is based on two-phase flow for subcooled and saturated liquid discharge through a crack. A schematic illustration of the two-phase flow model used in PICEP to represent the flow through a cracked tube is shown in Figure V-6. The critical flow equations are based on a modified Henry's homogeneous non-equilibrium critical flow model. Non-equilibrium "flashing" mass transfer between liquid and vapor phases, fluid friction due to surface roughness, and convergent flow paths are modeled. The model for the leak before break analysis was validated with data discussed in References 20, 21, and 22.

The leak rate will depend on several parameters including flaw length, crack opening area, tube differential pressure and fluid properties. Other parameters that affect flow rate, such as surface roughness and irregular or nonplanar crack surfaces are conservatively accounted for in the leak rate model. The model will determine the flow through a freespan crack under MSLB conditions as a function of crack length, crack opening displacement, and crack aspect ratio as defined by the ratio of exit to inlet crack lengths (ie. l_{OD}/l_{ID}).

To allow leak rate calculations to be solved rapidly in the Monte Carlo simulations, key PICEP output was fitted with regression equations. PICEP leak rates were calculated for many combinations, covering all crack opening areas and aspect ratios of interest. The crack opening area varied from zero to 0.1 square-inch and the aspect ratio was varied between 1 and 20. The regression equations selected for Monte Carlo modeling fit these computed leak rate values with an average error of less than 2%. The regression fit was conservatively biased so as not to underestimate a PICEP leak rate by more than 3%. Details of the leakage model development and the regression equations model are given in Reference 43. To ensure a conservative leakage model, assumptions were made that are reasonable and conservative for predicting flow through a crack that will exaggerate the rate of flow. These include:

- Maximum MSLB primary differential pressure was assumed.
- A nominal crack surface roughness of 2E-4 inch is assumed for SCC surfaces per the PICEP manual.
- The crack faces are conservatively taken as flat (i.e. Nonzig-zag).
- The crack opening area in the model development is conservatively based on a rectangular opening equal to the crack opening displacement times the crack length.

To verify the behavior of the leakage model (i.e., flow assumptions and regression fit), a comparison was made between the PICEP/APS model developed by APTECH for Palo Verde, and the Hernalsteen (LABOLEAK) model which is based on a single-phase flow approximation as discussed in Reference 27. This comparison is shown in Figure V-7 where the leak rate Q is plotted as a function of crack opening area (A_c). The PICEP/APS model is observed to be conservative over the range of interest in A_c.

4. Fluid Conditions

For the design basis accident conditions, the largest ΔP in the tube will occur during a postulated main steam line break. Per PVNGS UFSAR Section 15.1.5, the maximum primary pressure following a main steam line break is 2400 psia. This peak pressure occurs at the start of the event at 100% power with a concurrent loss of offsite power. The secondary side pressure is conservatively assumed to be at vacuum conditions

caused by the instantaneous loss in secondary pressure during the event. This combination of high peak primary pressures with vacuum conditions on the secondary side yield the largest possible ΔP across the tube wall, and therefore, the highest hoop stress and flow conditions, for design basis or faulted events. The fluid conditions used in the leakage model are therefore:

$p_i = 2400$ psia
$p_o = 0$ psia
$T = 593\ ^{\circ}F$

Where T is based on the average of the hot leg (inlet) and cold leg (outlet) temperatures.

5. Crack Opening Area

The crack opening area (A_c) calculational method was conservatively selected from a comparison of three crack opening displacement models; namely, Erdogan solution (Reference 19), Tada/Kumar solution (Reference 22) and the Hernalsteen model (Reference 27). A plot of these three crack opening area models is shown in Figure V-8. The Erdogan model, which is contained in PICEP, is too limited and produces smaller A_c values at larger crack lengths (Reference 22). The Tada/Kumar and Hernalsteen models give similar results for A_c, with the latter being slightly more conservative at the crack lengths of interest. The Hernalsteen model was therefore used for computing A_c in the probabilistic analysis.

6. Crack Distributions

As in Reference 35, the distributions for through-wall crack ID and OD lengths are calculated from the crack growth simulation data from the Packer Engineering model. During a meeting with the USNRC Staff on July 12, 1995, APS indicated that the possibility of mechanical breakthrough without burst was being included in the Unit 2 leakage model. In the Packer Engineering model, the assumption of maintaining a semi-elliptical crack shape but constant crack length as growth occurs in the depth direction is reasonable and consistent with the Packer Monte-Carlo simulation model. Hence, following maximum crack depths in excess of the wall thickness permits calculation of the through-wall crack lengths. There is some population of crack geometries where mechanical breakthrough may occur during a MSLB without leading to a full tube burst. That is the case for deep cracks whose total length is less than the critical through-wall crack length for burst. The Framatome burst equation does not extrapolate to the true burst pressure for a through-wall crack. This burst pressure is given by the EPRI equation given in Reference 36, which has received a full industry review. For very deep cracks, the Framatome equation does correlate with the onset of local but not necessarily global fracture. Figure V-9 shows a plot of

burst pressure versus relative crack depth for steam generator tubes containing stress corrosion cracks approximately 1.1 inches in length. The data is taken from NUREG/CR-2336. The test was terminated upon loss of the pressurizing medium. A full tube burst was not required to terminate the test. The Framatome equation together with the EPRI equation for burst pressure for through-wall cracks provide a good definition of the combinations of crack lengths and depths where local breakthrough, but not full burst will occur. At breakthrough, the through-wall crack length is taken as equal to the total crack length and this is input to leak rate calculations.

7. **Probabilistic Method**

The preliminary probabilistic calculation for EOC leakage has been completed for this report, however the final calculation results will be presented to the USNRC Staff in September 1995. The analysis technique as described in Reference 28, is based on a Monte Carlo numerical solution of the deterministic models for crack opening area and corresponding leakage employing statistical distributions as input for material strength (σ_y and σ_u) and through-wall crack lengths (l_{OD} and l_{ID}). The distributions for strength are Weibull representations developed from tube strength properties based on CMTR data for the Unit 2 steam generator tubing. The distributions for through-wall crack ID and OD lengths are calculated from the crack growth simulation data from the Packer Engineering model. APTECH has conservatively fitted the Packer Engineering model output in order to bound all through-wall length estimates.

The Monte Carlo evaluation for leakage rate is based on 20 million unit simulations of combinations of conservatively simulated OD and ID through-wall crack lengths and material strengths. The leak rates for any and all simulated cracks in both steam generators is combined to give the total leakage for Unit 2. The cumulative distribution for Unit 2 leak rate has been computed to establish the mean and 95% upper bound leak rates for Unit 2. Leak rates for any other probability level of interest can be obtained from the computed cumulative density function (CDF).

8. **Leakage Analysis Results**

Packer Engineering has utilized the Appendix A, Monte Carlo model to estimate the probability of tube leak from undetected defects under worst case, main steam line break conditions. Based on 5,000 simulations for 12 months of Unit 2 operation, a total of 475 simulations yielded through-wall crack. Therefore, a point estimate of the chance of a through-wall crack in the Unit 2 steam generators for a MSLB failure mode is approximately 0.095 or 9.5%. Assuming a "Poisson process" for the leak occurrence, the chance of 2 such cracks in Unit 2 is low, with a point estimate of about 0.004 or 0.4%. Under these assumptions, the chance of more than 2 through-wall cracks is very low (0.015%).

By applying the APS/PICEP leakage model to the entire distribution of crack lengths from the Packer Engineering model, it is estimated that the average leak rate from through-wall crack, which maintain structural integrity, will be approximately 7.2

gallons per minute (gpm) with a median leak rate of 0.75 gpm. Although this conditional leakage probability analysis indicates that the expected leak rate for a given crack is just above the acceptance criteria of 6 gpm, the median leak rate is well below this limit with a conditional probability of exceedance computed at 0.24. So in the unlikely event of a through-wall crack developing at EOC, the leak rate will be acceptable to plant accident limits with a probability of approximately 76%.

Taking into account the actual probability of having a leaker given MSLB conditions after 12 months of operation, the resulting CDF distribution for total leakage probability is shown in Figure V-9. Both best estimate and upper bound probability curves are given. From the upper bound analysis, the chance of exceeding the 6 gpm limit for through-wall cracks, which maintain structural integrity under MSLB conditions, is less than 0.016 or 1.6%. Thus, it is highly likely (i.e., greater that 98% probability) that the maximum leakage computed at EOC under worst case MSLB conditions will remain below the applicable 10CFR100 limits for off-site doses.

VI. RISK ASSESSMENT

APS has evaluated the risk of operating Unit 2 until shutdown for refueling at the end of Cycle 6 in March 1996. The objective of this assessment is to calculate the incremental core damage probability that may result from operating the Unit 2 steam generators with the existence of ARC region degradation. The results of the assessment performed by Packer Engineering in Appendix A serves as the primary input for the risk assessment performed by APS.

A. Evaluation Methodology

An evaluation was performed by the APS Probabilistic Risk Assessment Group (PRA) to evaluate the probability that core damage occurs as a result of the tube degradation predicted by Packer Engineering in Appendix A. The evaluation utilizes data and core damage estimation methodologies which had previously been developed to evaluate the risk associated with axial crack growth rate. The methodologies employed are similar to the methods described in Reference 9 with the exception that the prediction of the number of degraded tubes is based upon the input provided by Packer Engineering. The evaluation considers the following core damage scenarios:

1) ARC region crack growth propagation results in failure of a Unit 2 steam generator tube, and the steam generator tube failure is not successfully mitigated.

2) A plant transient occurs which significantly increases the differential pressure between the primary and secondary sides of the steam generator resulting in the failure of one or more tubes in the affected steam generator (or steam generators). Plant transient conditions which were considered included secondary depressurization events (such as a main steam line break or a stuck open unisolable secondary valve), and events which result in rapid primary side pressure increases, such as, a loss of condenser vacuum with failure of the Steam Bypass Control System to provide secondary heat removal.

The risk associated with steam generator tube failure events, including multiple tube rupture events, which could reasonably be postulated to occur as the result of a plant transient (other than an unisolable MSLB or SOSV which are considered separately) is shown in Table VI-1. The risk values associated with (single or multiple) tube ruptures that result as a consequence of unisolable MSLB or SOSV are summarized in Tables VI-2, VI-3, VI-4 and VI-5.

Summing the results from these tables, the total core damage probability due to the

propagation of ARC region axial cracks between now and U2R6 is estimated to be approximately 1.2 E-7.

TABLE VI-1 - SGTR Core Damage Probability (SGTR Initiating Events)

Event Scenario	SGTR Initiating Event Frequency(1)	Event Mitigation Failure Probability(2)	Core Damage Probability
Single SG tube rupture occurs (as initiating event) and the event is not mitigated	1.4E-3 (single tube ruptures)	7.7E-5	1.1E-7
Single SG tube leak occurs(as initiating event) and event is not mitigated	1.4E-3 (single tube leaks)	2.9E-6	4E-09
Multiple (2-10) SG tube ruptures occur as initiating event and event is not mitigated	3.7E-7 (2-10 tube ruptures)	7.4E-4	3E-10
Multiple (>10) SG tube ruptures occur as initiating event and event is not mitigated	1.5E-9 (>10 tube ruptures)	7.1E-3	1E-11
Total CDP for SGTR events due to propagation of ARC region cracks prior to EOC			1.1E-7

Notes:

1. The single SGTR probability and the probability of tube failure resulting in leakage were estimated from data provided by Packer Engineering. The multiple tube rupture frequencies were estimated based on the probability that a plant transient occurs (other than MSLB/SOSV) resulting in significantly increased differential pressure resulting in a multiple tube failure.

2. Failure to mitigate event probabilities were taken from Reference 25, which are based on results from the PVNGS PRA and NUREG-0844.

Table VI-2 - Consequential SGTR Core Damage Probability (EOC-30 days to EOC)

Event Scenario	MSLB/SOSV Event Probability(1)	Consequential Tube Rupture Probability(2)	Event Mitigation Failure Probability(3)	Core Damage Probability
Single SG tube rupture due to MSLB/SOSV and the event is not mitigated	3.1E-4	1.8E-2 (one tube)	1E-3	6E-9
Multiple (2-10) SG tube ruptures due to MSLB/SOSV and event is not mitigated	3.1E-4	1.8E-4 (2-10 tubes)	1E-2	6E-10
Multiple (>10) SG tube rupture due to MSLB/SOSV and event is not mitigated	3.1E-4	7E-7 (> 10 tubes)	0.5	1E-10
Total CDP due to consequential tube ruptures as a result of propagation of ARC region cracks prior to EOC				7E-9

Table VI-3 - Consequential SGTR Core Damage Probability (EOC- 60 days to EOC-30)

Event Scenario	MSLB/SOSV Event Probability(1)	Consequential Tube Rupture Probability(2)	Event Mitigation Failure Probability(3)	Core Damage Probability
Single SG tube rupture due to MSLB/SOSV and the event is not mitigated	3.1E-4	8.8E-3 (one tube)	1E-3	3E-9
Multiple (2-10) SG tube ruptures due to MSLB/SOSV and event is not mitigated	3.1E-4	4E-5 (2-10 tubes)	1E-2	1E-10
Multiple (>10) SG tube rupture due to MSLB/SOSV and event is not mitigated	3.1E-4	2E-7 (>10 tubes)	0.5	3E-11
Total CDP due to consequential tube ruptures as a result of propagation of ARC region cracks prior to EOC				3E-9

Table VI-4 - Consequential SGTR Core Damage Probability (EOC- 90 days to EOC-60)

Event Scenario	MSLB/SOSV Event Probability(1)	Consequential Tube Rupture Probability(2)	Event Mitigation Failure Probability(3)	Core Damage Probability
Single SG tube rupture due to MSLB/SOSV and the event is not mitigated	3.1E-4	4.5E-3 (one tube)	1E-3	1E-9
Multiple (2-10) SG tube ruptures due to MSLB/SOSV and event is not mitigated	3.1E-4	1E-5 (2-10 tubes)	1E-2	3E-11
Multiple (>10) SG tube rupture due to MSLB/SOSV and event is not mitigated	3.1E-4	4E-8 (>10 tubes)	0.5	6E-12
Total CDP due to consequential tube ruptures as a result of propagation of ARC region cracks prior to EOC				1E-9

Table VI-5 - Consequential SGTR Core Damage Probability (EOC- 180 days to EOC-90)

Event Scenario	MSLB/SOSV Event Probability(1)	Consequential Tube Rupture Probability(2)	Event Mitigation Failure Probability(3)	Core Damage Probability
Single SG tube rupture due to MSLB/SOSV and the event is not mitigated	9.3E-4	1.8E-3 (one tube)	1E-3	2E-9
Multiple (2-10) SG tube ruptures due to MSLB/SOSV and event is not mitigated	9.3E-4	1E-5 (2-10 tubes)	1E-2	9E-11
Multiple (>10) SG tube rupture due to MSLB/SOSV and event is not mitigated	9.3E-4	4E-8 (>10 tubes)	0.5	2E-11
Total CDP due to consequential tube ruptures as a result of propagation of ARC region cracks prior to EOC				2E-9

Notes

1. The MSLB/SOSV event probability is 3.78E-3 per year (3.1E-4 per 30 days)

2. The consequential tube rupture probability was estimated based on information provided by Packer Engineering. Table VI-2 uses data from EOC, Table VI-3 uses data from EOC minus 30 days, Table VI-4 uses data from EOC minus 60 days and Table VI-5 uses data from EOC minus 90 days.

3. Failure to mitigate event probabilities were taken from Reference 25 which based its estimates upon results from the PVNGS PRA and NUREG-0844.

B. Summary

The core damage probability due to propagation of ARC region axial cracks between now and the end of the current operating cycle (March 1996) has been estimated as 1.2E-7. The baseline core damage frequency is 4.74E-5 per reactor year (approximately 2.5E-5 for Unit 2 between now and U2R6). Therefore, core damage probability (CDP) is negligibly increased (approximately 0.4%) by the predicted propagation of axial cracks predicted in Appendix A. Based on the low CDP which was calculated, it is clear that continued operation of Unit 2 to EOC is preferable from a risk perspective to performing another midcycle shutdown and inspection. PVNGS PRA results indicate a controlled shutdown core damage probability on the order of 1E-6 per shutdown, and additional core damage risk would be incurred due to shutdown operations required to support the steam generator inspections.

APS has determined that the large early release frequency as defined by Reference 37 is not significantly affected by the predicted propagation of ARC region degradation. Only a fraction of the tube rupture events would result in large early releases (if feedwater to the steam generators fails or if operators fail to maintain secondary inventory above the break location). Based on PVNGS PRA results, the Large Early Release Probability (LERP) is 2.1E-6 per year. The PRA also indicates that 24% of the Level 1 steam generator tube rupture core damage events result in large early releases. Therefore, of the calculated 1.2E-7 core damage probability, it is judged that approximately one-fourth (3E-8) would result in large early releases. Therefore, it is evident from this analysis that the increase in LERP is also tolerable (approximately a 3% increase over the last six (6) months of operation from 1.1E-6 to 1.13E-6).

VII. OPERATIONAL RESPONSE

A. Background

APS has implemented an integrated leakage detection and response program, using equipment and procedure upgrades, to permit plant operators to detect and respond to changes in steam generator primary-to-secondary leakage. The program was established to provide reasonable assurance that the unit will be shutdown prior to a significant leak or steam generator tube rupture should tube degradation exceed expected values. The program is designed to provide clear and unequivocal plant management support to commence orderly shutdown should leakage exceed very stringent administrative limits. APS has also endeavored to ensure that adequate staff, equipment and organizational resources are in place to implement this program, using a combination of radiation monitors and laboratory radiochemical analyses. The integrated leakage program at PVNGS is not only prescriptive, but preventative as well, as the program is supported by extensive steam generator inspections and conservative plugging criteria which ensure that all detected SCC defects are removed from service. A description of how PVNGS operational response is supported by integrating inspection, repair, leakage monitoring, and operator training is provided below.

B. Inspection and Repair

The objective of the inspection and repair program at PVNGS is to support structural and leakage integrity. Industry studies and observations indicate that the use of enhanced NDE techniques and conservative plugging criteria can reduce the likelihood of forced shutdown due to primary-to-secondary leakage.

Inspection Program
A comprehensive steam generator inspection program reduces the risk of leaving a significant defect(s) in service. Enhanced inspections (MRPC, Plus Point, UT) as summarized in Section IV were conducted in the region affected by ARC degradation. As demonstrated by assessments performed in this report, and as indicated by sensitivity studies performed by EdF in Reference 23, the level of MRPC and bobbin coil inspections and industry leading use of new ECT data acquisition and analysis technology is statistically significant in terms of preventing through-wall defects and significantly lowers the probability of tube rupture for the specified period of operation.

Plugging Criteria
APS employs an administrative plugging criteria which is significantly more restrictive than required in the PVNGS Technical Specifications. The current plugging criteria is given in Table VII-1. Before the steam generators are returned

to service, a review is conducted by APS Engineering of all eddy current indications. Regardless of flaw size or depth, all tubes with detected cracks are removed from service. As demonstrated in Section V, and supported by data presented by EdF in Reference 23, this action also reduces the potential for leakage and/or tube rupture, since no known crack defects are left in the steam generator.

Table VII-1 - PVNGS Administrative Plugging Criteria

Mechanism	Plugging Criteria	Basis
Stay Cylinder Batwing Wear	≥ 20% wear	Rapid wear for these supports has been observed at several CE plants
Cold Leg Corner Wear	≥ 20% wear	Rapid wear has led to inservice leaks at PVNGS
Support Wear	≥ 35% wear for tubes previously examined with no indications detected	Per PVNGS fretting wear curves, tubes exhibiting this wear rate could exceed structural margins in following operating cycle
Support Wear	≥ 40% wear for tubes which had previous indications of > 10%	Technical Specification 4.4.4.4.a.6
Axial Cracks	All detected/suspected cracks	Conservative criteria based on NDE capabilities
Circumferential Cracks	All detected/suspected cracks	Conservative criteria based on NDE capabilities. All tubes removed from service are stabilized
Volumetric Indications	Engineering and ISI evaluation for ≤ 40% through-wall	Possible corrosion growth is monitored and defects exhibiting noticeable change are removed from service
Loose Part Wear	All locations with detectable wear for unretrievable parts	APS Loose Part Study - All tubes removed from service for loose part wear are stabilized

C. Leakage Monitoring and Procedural Control

Monitoring Equipment Upgrades

As reported in References 2 and 17, APS has implemented upgrades in leakage monitoring equipment to provide plant operators with enhanced diagnostic tools. These upgrades have now been implemented in all three PVNGS Units. The specific upgrades include:

Steam Generator Blowdown Radiation Monitors (RU-4 & RU-5)
The blowdown monitors currently monitor the downcomer flowstreams rather than hot leg blowdown to provide greater sensitivity for detection and response to primary to secondary leakage.

Condenser Vacuum Exhaust Monitor (RU-141)
The CVE Monitor has been changed to an in-line monitor, and a graph of monitor reading verses leak rate is trended.The alert setpoints for the CVE Monitor were decreased to four (4) times background to provide earlier alarms to plant operators in the event of increasing primary leakage.

N-16 Monitors
N-16 monitoring systems have been permanently installed in all three units to provide an additional diagnostic tool for primary-to-secondary leakage detection. The design incorporates sodium iodide crystal detectors connected to the existing radiation monitoring system. The detectors are located on the main steam lines (4 per unit) in the Turbine Building and are connected to the condenser exhaust high-range effluent monitor (RU-142), which had been abandoned in place when the condenser vacuum exhaust was routed to the plant vent. Existing control room alarm and indication capabilities were utilized. Addition information regarding recent changes in procedures, training and use of the N-16 monitors are described later.

Procedural Upgrades
The current leak rate limits at PVNGS were developed in response to the Unit 2 tube rupture event in March 1993. An administrative maximum shutdown limit was set at 50 gpd, well below the Technical Specification limit of 720 gpd. It should be noted, that a review of the available data prior to the tube rupture event determined that the new administrative limits would have resulted in an orderly shutdown prior to the Unit 2 tube rupture at the end of Cycle 4.

The administrative limits, as well as, a leak rate hierarchy are proceduralized in PVNGS Station Manual Procedure 74DP-9ZZ05, Abnormal Occurrence Checklist. The hierarchy includes:

1. Leak Rate < 10 GPD: Monitor and perform accurate leak determinations shiftly. Inform the Control Room of all leak rate calculation results. Additionally, the CVE Monitor is trended shiftly. If an increase of three-fold is observed, Step 2 is entered. Finally, alarm setpoints for RU-141, as well as RU-4

and -5 are evaluated daily.

2. Leak Rate 10-50 GPD: Monitor and perform accurate leak determinations shiftly. Inform the Control Room of all leak rate calculation results. Additionally, if a increase in leak rate by 50% is observed within a 24 hour period or less, or the leak rate is greater than 25 GPD, formation of an evaluation team is required to address continued operation. Additional monitoring of RU-141, RU-4 and RU-5 is also required.

3. Leak Rate > 50 GPD: Following verification of the calculated leak rate by the most readily available method outlined in 74DP-9ZZ05, the Shift Supervisor initiates a plant shutdown, and then informs plant management.

N-16 Monitor Enhancements
As a result of an INPO audit regarding the use of N-16 monitors, significant changes have been incorporated in PVNGS procedures, training and setpoints regarding the use of N-16 monitors. These changes include:

- Changes to the PVNGS Station Manual Procedure 74DP-9ZZ05, *Abnormal Occurrence Checklist*, to monitor N-16 trends with a steam generator leak < 50 gallons per day, as well as to evaluate indication and alarm setpoints for the N-16 monitors.

- Changes to PVNGS Station Manual Procedure 43AO-3ZZ08, *Steam Generator Tube Leak*, to include the N-16 monitors as a means of identifying the affected steam generator. Cautions and classroom and simulator training have been incorporated to alert operators to the possible effects of "shine" from the affected steam lines to monitors on the unaffected steam lines.

- Changes to PVNGS Station Manual Procedure 74RM-9EF41, *Radiation Monitoring System Alarm Response*, to include a cross check of the N-16 monitors when alarms are received on the blowdown radiation monitors. Cautions have also been added to this procedure to alert personnel to the effects of "shine".

- Calculations have been performed using the ATHOS thermal-hydraulic model to assess N-16 monitor response to varying leak rates at various leak locations (See Figure VII-1) as well as different reactor power levels (Reference 24).

- An engineering/chemistry evaluation has been completed to determine optimum setpoints for the N-16 monitors.

APS believes the enhancements to the leak rate program provide the operators with information and direction to recognize a leak prior to break, regardless of whether the defect is axial or circumferential. In June 1995, APS representatives met with EdF officials in an effort to establish a technology transfer program. Based on these discussion APS believes that the overall PVNGS steam generator program to be comparative to the programs instituted by EdF. The defect management program at EdF of comprehensive eddy current inspections, preventative plugging criteria and strict leakage limits (≅ 32 GPD) has resulted in 600 reactor years without tube rupture. Based on a 10^{-2} frequencies, six (6) significant leakage events could have occurred within this operational time frame. As stated previously, an added conservatism is provided with the PVNGS philosophy, that all detected cracks are removed from service, whereas EdF plants are permitted to operate with known SCC defects in service.

D. Operator Training

As stated in Reference 2, extensive simulator training of operations personnel for tube rupture events as well as upgrades to the Emergency Operating Procedures permit faster identification and isolation of the affected steam generator. Improvements in operator response assure that in the unlikely event of a main steam line break with consequential multiple tube ruptures, the resulting offsite doses are maintained less than 10CFR100 limits.

Since the March 1993 Unit 2 tube rupture, PVNGS has developed the following operator training material. Industry Events Training provided to operations personnel details the Unit 2 SGTR event itself. This training was followed by three (3) simulator scenarios.

NUS08 Re-creation of the Unit 2 SGTR event with an emphasis on procedure changes implemented since March 1993, including N-16 monitor response to a SGTR (pre and post trip). Additional emphasis is placed on event impacts to the Auxiliary Steam System.

NUS22 Simulates a SGTR with a stuck open Main Steam Safety Valve. Similar to NUS08, emphasis was placed on functional changes to the plant procedures. Event impact on N-16 monitor response, square root extractor and low flow cutouts on the HPSI flow indicators were emphasized.

NUS28 Simulates a SGTR with a Loss of Offsite Power. In this scenario the ability to recognize an SGTR without the use of radiation monitors

was emphasized. As with the other simulator scenarios, procedure changes were reviewed as well as discussions regarding HPSI low flow cutouts.

The training program changes have been in place since the third quarter of 1993. Upon implementation of the training in the new simulator, APS identified a previously unknown transient effect. The new simulator model for the SGTR event indicated that steam generator pressure increased during refill, with the auxiliary feed and MSIV's isolated. This phenomenon was categorized as a compression effect, and unexpected transient resulted in four crew failures. Based on the discovery of this condition, APS implemented additional training to provide operators with the approaches to adjust for the compression effect. Since the second quarter of 1994 no additional crew failures have occurred. As stated previously, additional training was also provided on the radiation shine effects associated with N-16 monitors. This updated training was provided in both the classroom and the simulator. Figure VII-2 depicts crew results during the past 16 months.

VIII. SUMMARY

The analyses and evaluations contained in this report demonstrate that the operating, inspection and repair program for the Unit 2 steam generators permit safe operation of Unit 2 for the remainder of Cycle 6. The progression of ARC region degradation in Unit 2 is such, that a further midcycle inspection are not required. The ability to manage the corrosion mechanisms in the PVNGS steam generators is a primary safety and strategic objective. The comprehensive actions completed by APS to achieve these objectives are summarized below:

- Primary temperature reductions of 10°F have been implemented in all three PVNGS units to take advantage of the temperature dependence of SCC growth rates. Stress corrosion cracking is a thermally activated process, and the effects of temperature reduction can be quantified for SCC mechanisms in terms of activation energy for an Arrhenius rate equation.

- APS has removed 31 tubes from service, and has conducted extensive NDE and destructive examination in an effort to determine casual effects of corrosion damage, and to provide substantial improvements in field ECT acquisition and interpretation.

- APS has implemented the industry recommended secondary chemistry controls to mitigate the initiation and propagation of secondary side IGA/SCC. The laboratory evidence from tubes removed from Unit 2 during U2M5-1 show a favorable change in crack crevice chemistry tending towards neutral conditions. APS has exceeded EPRI action levels for sulfate by requiring reduced power operation or shutdown for sulfate levels as low as 20 ppb. The discussion provided in Appendix B indicates improvements have been attained in the current operating cycle in Unit 2.

- APS has incorporated an integrated operational response program, utilizing equipment and procedure upgrades, to provide plant operators the ability to detect and respond to changes in steam generator primary-to-secondary leakage, and shutdown the unit prior to a significant leak or steam generator tube rupture should unexpected tube degradation exceed expected values. A number of improvements to the N-

16 monitors and their use have been implemented during 1994-1995. The integrated leakage program at PVNGS is considered prescriptive, as well as preventative, as the program is supported by extensive steam generator inspections and conservative plugging criteria.

- APS with support from Packer Engineering and APTECH has developed state-of-the-art probabilistic models for assessing operating cycle lengths which maintain the safety margins specified in Regulatory Guide 1.121.

- APS has developed a probabilistic leakage model to assess EOC leakage as a result of secondary overpressurization events. The model demonstrates that operation with ARC region degradation will not result in offsite releases in excess of 10CFR100 limits should a MSLB event occur during Cycle 6.

- APS has developed a risk model to assess the impact on core damage probability for plant operation with degraded steam generator tubing. The calculation indicates that operation with ARC region degradation in Unit 2 represents a negligible impact on core damage probability. The impact is in fact lower in risk than the performance of an additional midcycle outage in Unit 2.

These actions are all part of a defense in depth approach employed by APS, to provide reasonable assurance that PVNGS Unit 2 can be safely operated until the next scheduled refueling shutdown for further steam generator inspections. This approach incorporates additional analyses performed and submitted to the USNRC in Reference 9, which demonstrate that in the unlikely event of a main steam line break without or with consequential single or multiple tube ruptures, with the current administrative limits on reactor coolant system dose equivalent iodine, the resulting offsite doses are less than 10CFR100 limits. Additionally, APS has continued to update training and conduct simulator testing of operations personnel for tube rupture events and has developed upgrades to the Emergency Operating Procedures which permit faster identification and isolation of the affected steam generator.

It is APS's position that the implementation of the elements of the PVNGS Degradation Management Program, as described in this report, constitutes a conservative and comprehensive approach which ensures that adequate structural and leakage integrity is maintained for normal operating, transient and postulated accident conditions for Unit 2 Cycle 6, consistent with General Design Criteria (GDCs) 14, 15, 30, 31, and 32 of 10CFR50 Appendix A.

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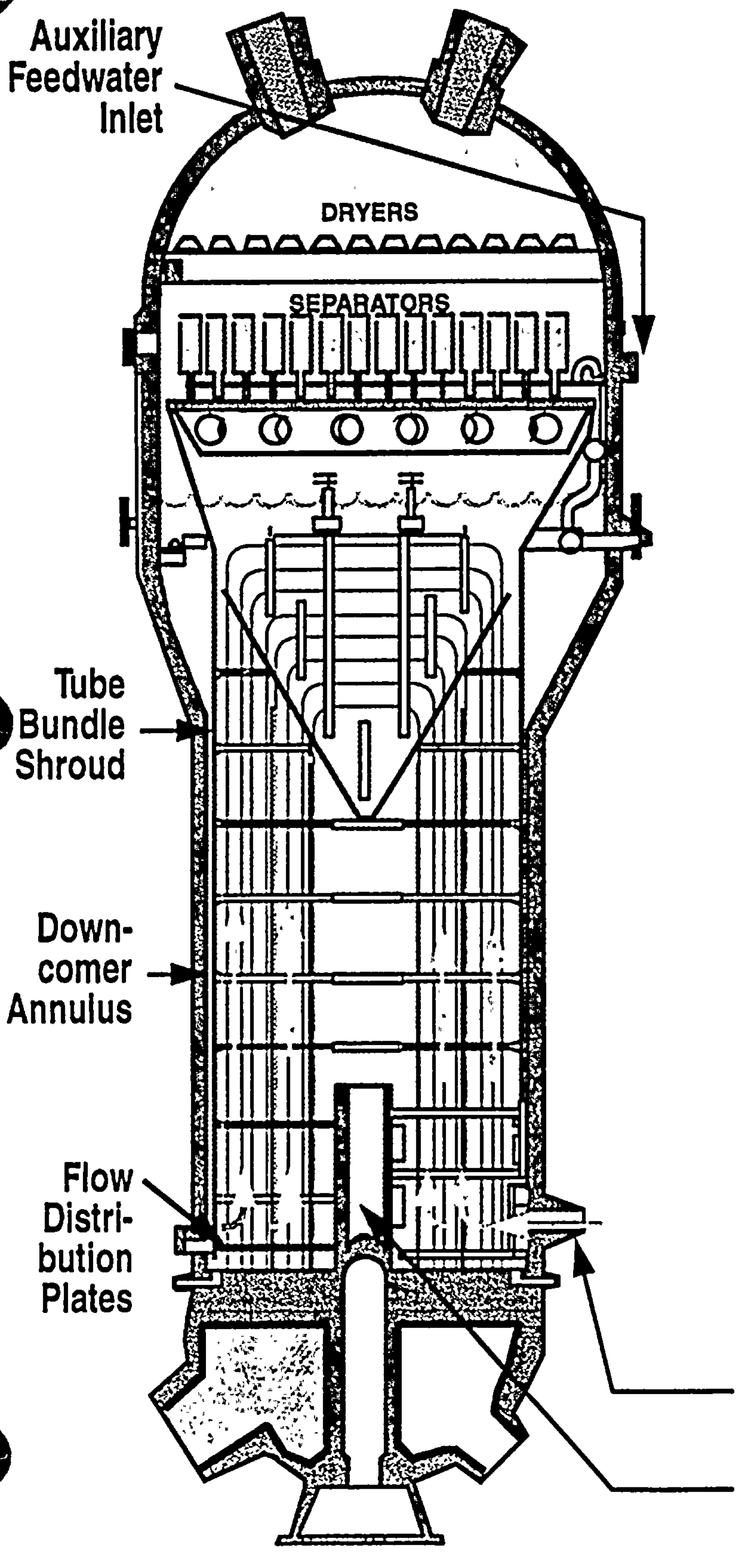
X. FIGURES

Integral Economizer Steam Generator Axial Flow

Side Elevation



System 80 Steam Generator Design and Operating Parameters

Plant rating	3817 MWt
Primary inlet temp:	
Original	621.2 F°
Current	611.0 F°
Primary outlet temp.	564.5 F°
Primary pressure	2250 Psia
Primary flow rate (per SG)	82×10^6 lb/hr.
Steam pressure	1070 Psia
Steam flow rate (per SG)	8.59×10^6 lb/hr.
Feedwater temp.	450 F°
Number of tubes	11,000
Tube diameter	0.750 inches
Tube wall thickness	0.042 inches
Tube material	Inconel 600 (Ni-Cr-Fe)
Overall length	67 feet
Steam drum diameter	247 inches
Evaporator shell diameter	189.5 inches
Weight (dry)	1,585,000 lbs.

FIGURE II-1

SG-3B

Secondary Fluid Flowpaths of CE System 80 Steam Generator

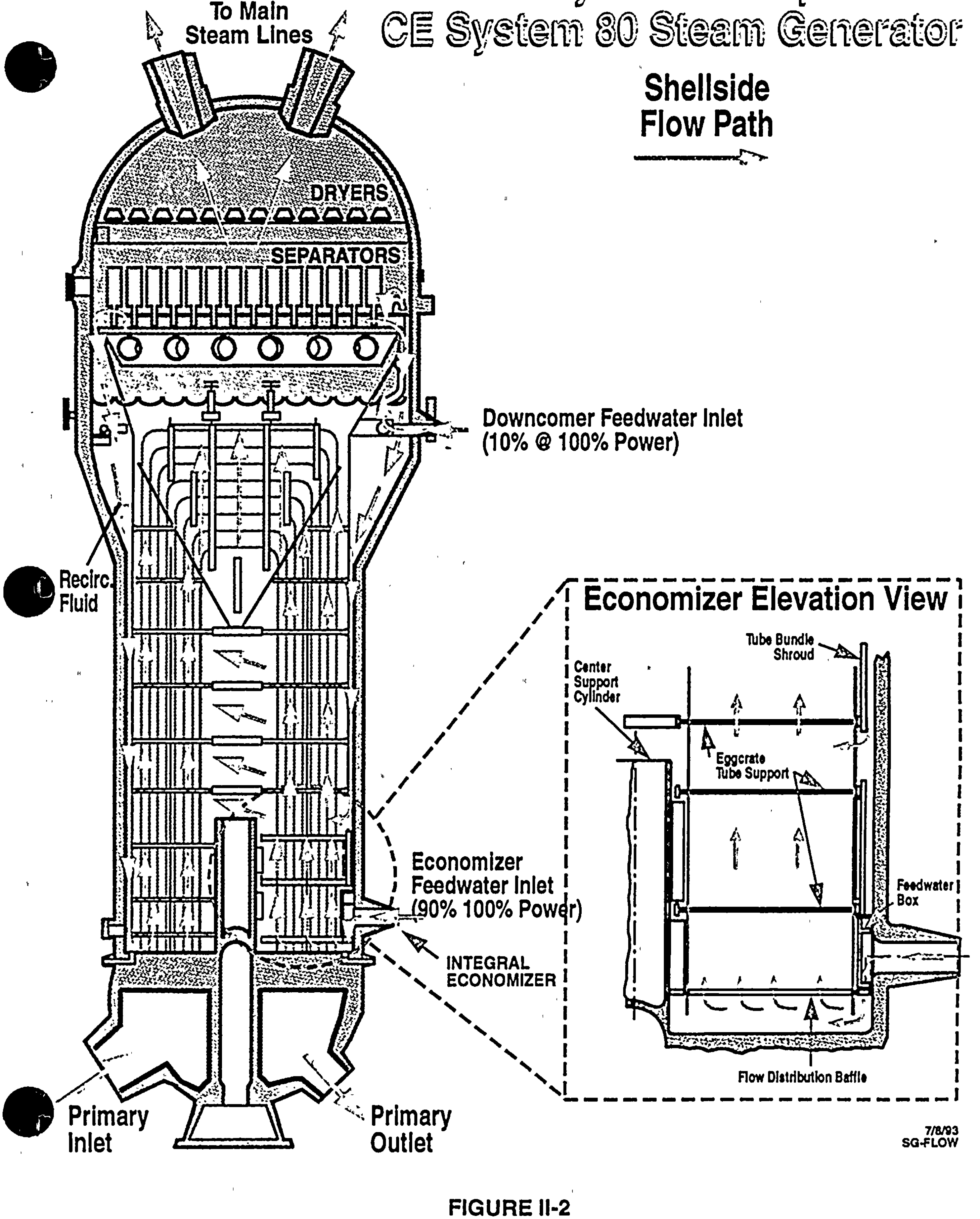


FIGURE II-2

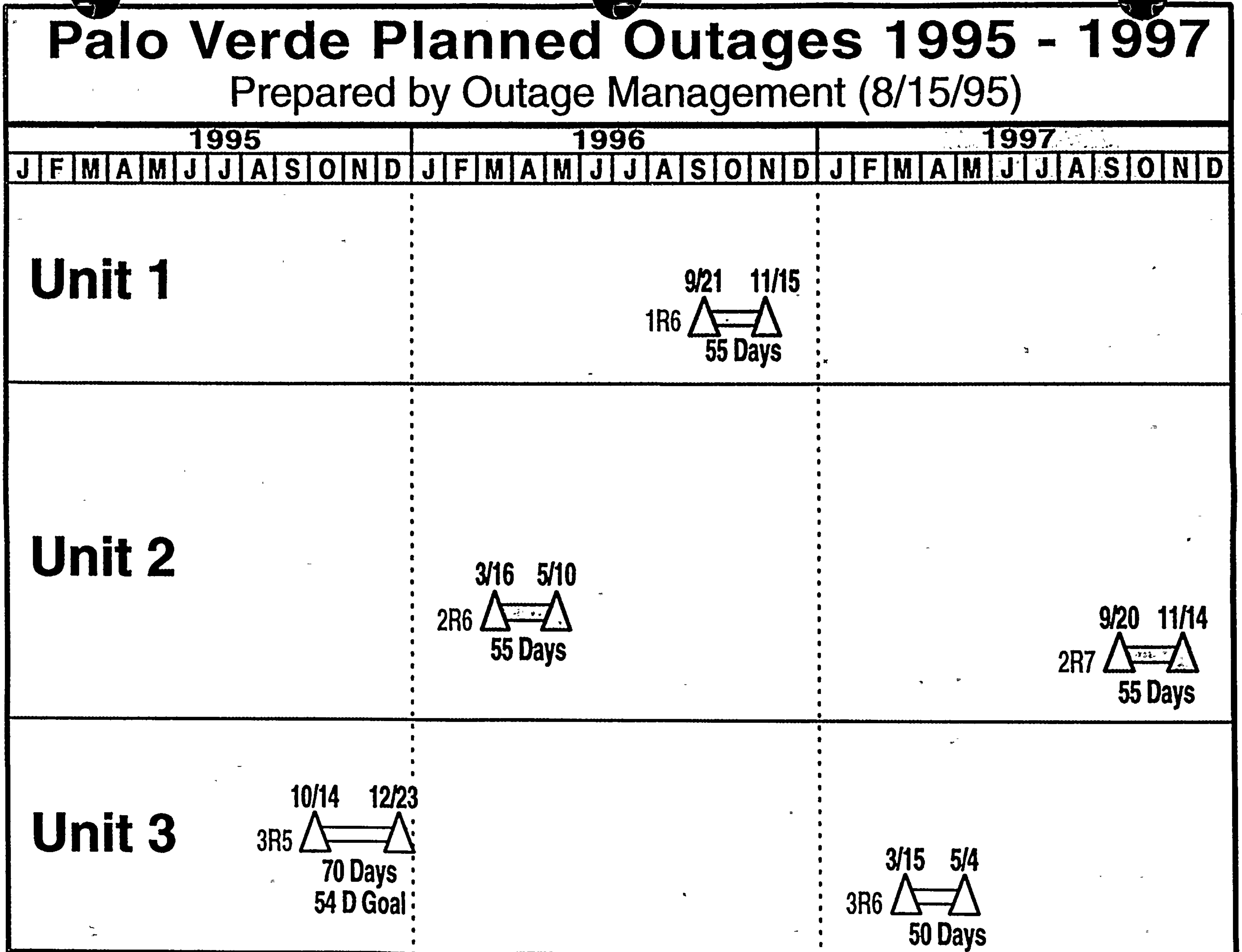

Palo Verde Planned Outages 1995 - 1997
Prepared by Outage Management (8/15/95)
1995
1996
1997
J F M A M J J A S O N D
Unit 1
9/21
11/15
1R6
55 Days
Unit 2
3/16
5/10
2R6
55 Days
9/20
11/14
2R7
55 Days
Unit 3
10/14
12/23
3R5
70 Days
54 D Goal
3/15
5/4
3R6
50 Days

Figure III-1

Location of Unit 2 Axial Cracks

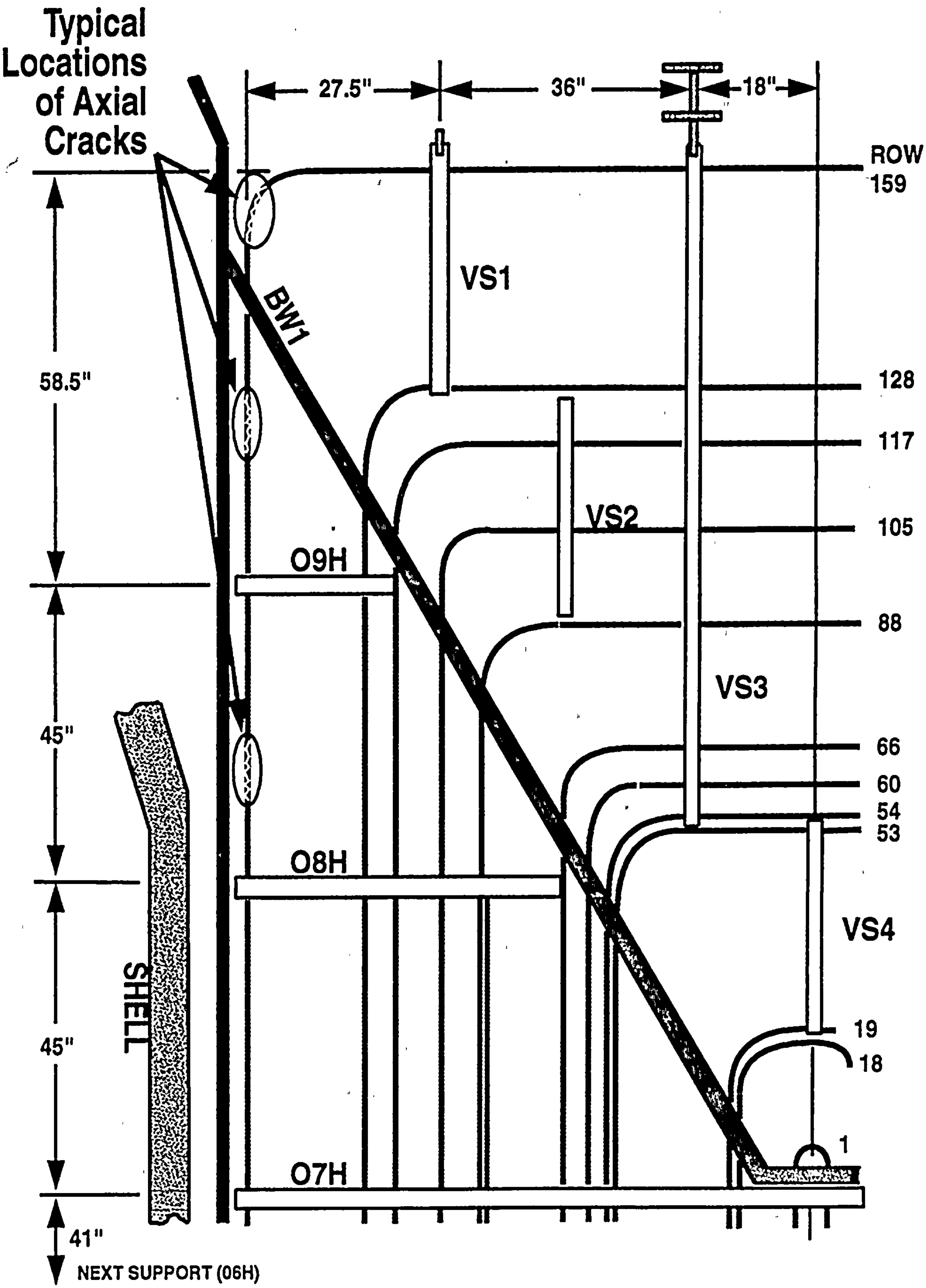


FIGURE IV-1

SO_14.IMA

02/95, ARIZONA PUBLIC SERVICE, PALO VERDE, UNIT 2

STEAM GENERATOR: 21 DATE: 08/16/95
MRPC U-BEND (ARC REGION and RANDOM LINES) TIME: 16:30:10
Area of Generator: Include ARC REGION , AND Probe: AND Exam Extent: Tubes Examined to STAYS
Any Extent Between 07H and VS5

PLUGGED 296 X 08H VS3 2604 ◆ 07H-VS3 47 ◆ 08H-VS6 2 ◆ 08H-VS2 134 ◆
07H VS[illegible] [illegible] ◆ 08H-VS7 1 X

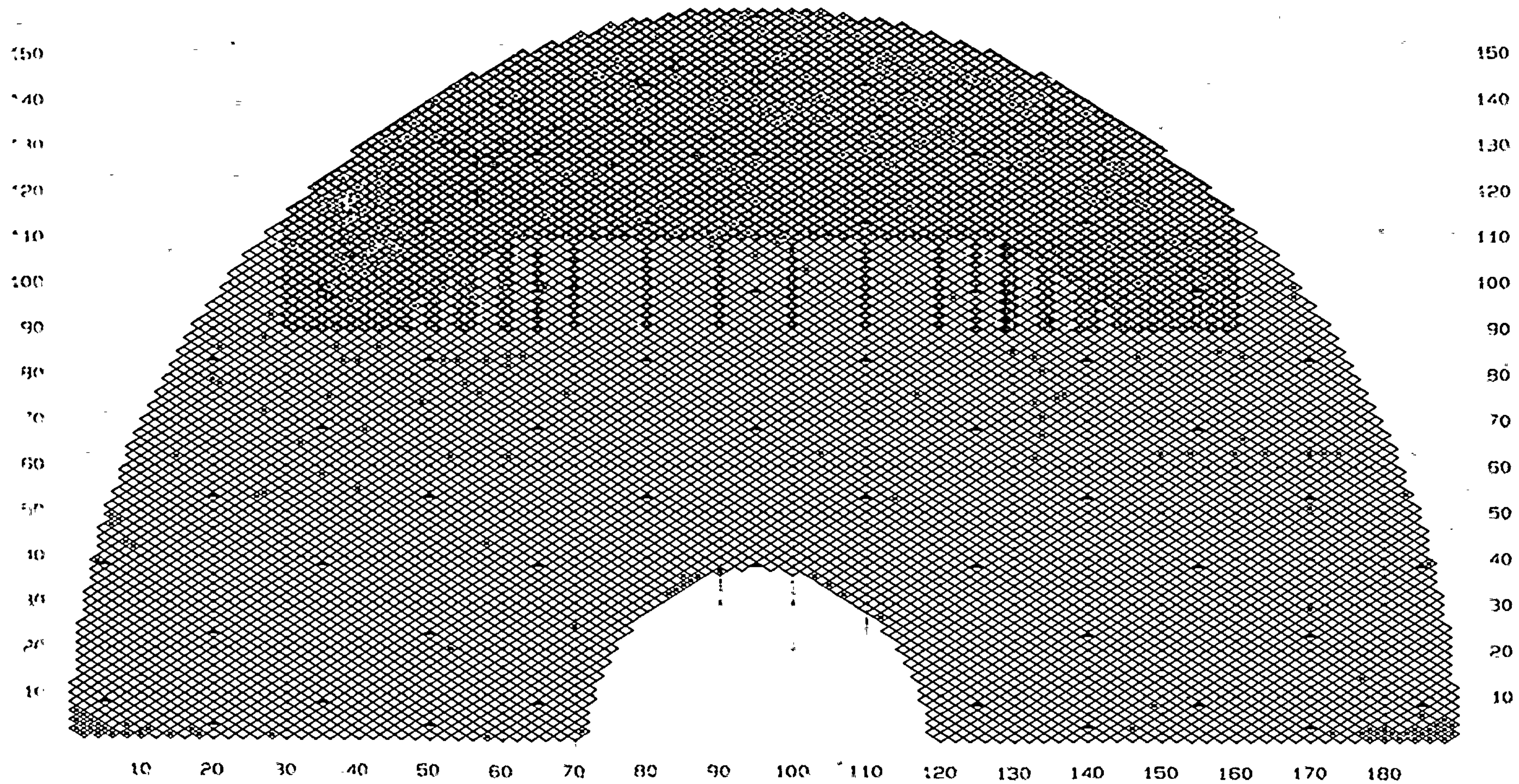


Figure IV-2
SG 21 ARC Region and Random
Sample - U2R5

ROCKRIDGE TECHNOLOGIES

02/95, ARIZONA PUBLIC SERVICE, PALO VERDE, UNIT 2

STEAM GENERATOR: 21
OUTAGE DATA SET : CURRENT
Percent: MAI, SAI AND Area of Generator: Include ARC REGION

DATE: 08/16/95
TIME: 12: 29: 07

STAYS ▲

PLUGGED 296 X MAI 12 ◆ SAI 77 ◆

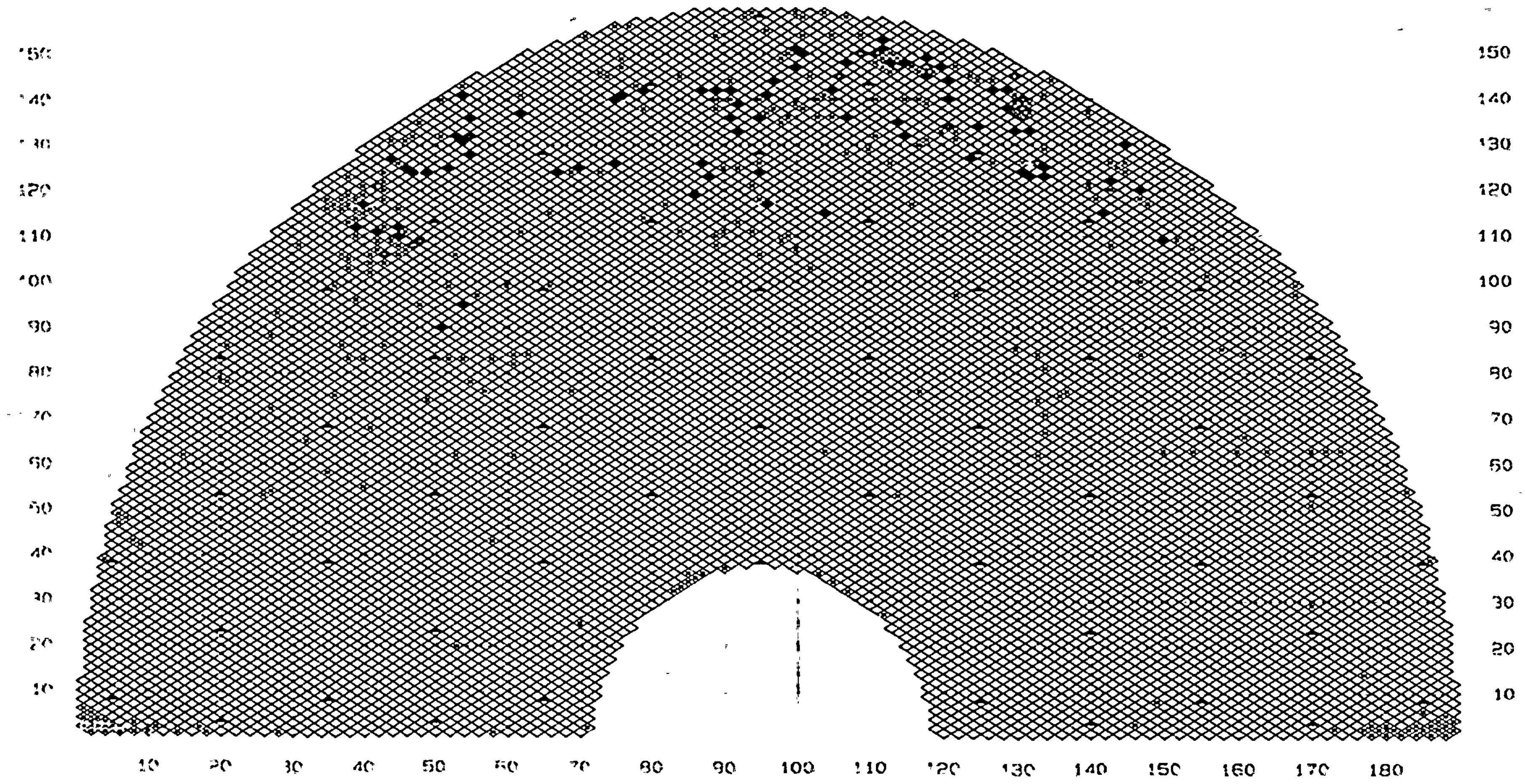


Figure IV-3
SG 21 ARC Region Defects U2R5

ROCKRIDGE TECHNOLOGIES

02/95, ARIZONA PUBLIC SERVICE, PALO VERDE, UNIT 2

STEAM GENERATOR: 22
MRPC U-BEND (ARC REGION and RANDOM LINES)
Area of Generator: Include U-BEND ARC , AND Probe: AND Exam Extent: Tubes Examined to STAYS
Any Extent Between 07H and VS3

DATE: 08/17/95
TIME: 09: 27: 45

PLUGGED 897 ✕ 08H VS3 2529 ◆ 08H-VS5 29 ◆ 06H-VS3 1 ◆ 07H-VS5 1 ◆
06H VS5 3 ◆ 07H-VS2 2 ◆

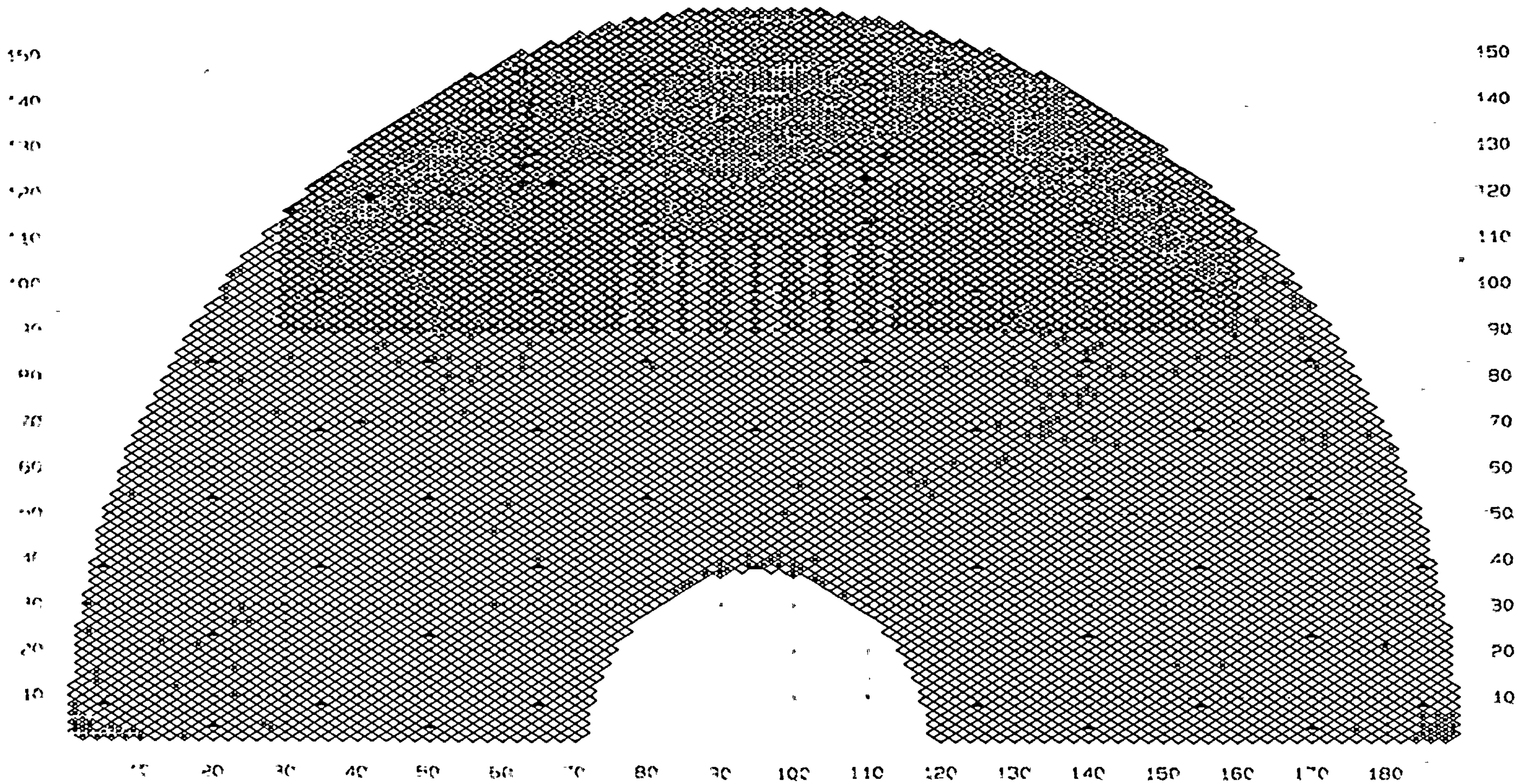


Figure IV-4
SG 22 ARC Region and Random Sample - U2R5

ROCKRIDGE TECHNOLOGIES

02/95, ARIZONA PUBLIC SERVICE, PALO VERDE, UNIT 2

STEAM GENERATOR: 22
OUTAGE DATA SET : CURRENT
Percent: MAI, SAI AND Area of Generator: Include U-BEND ARC , AND Probe:

DATE: 08/17/95
TIME: 09: 40: 38

STAYS ▲

PLUGGED 897 × MAI 82 ◆ SAI 168 ◆

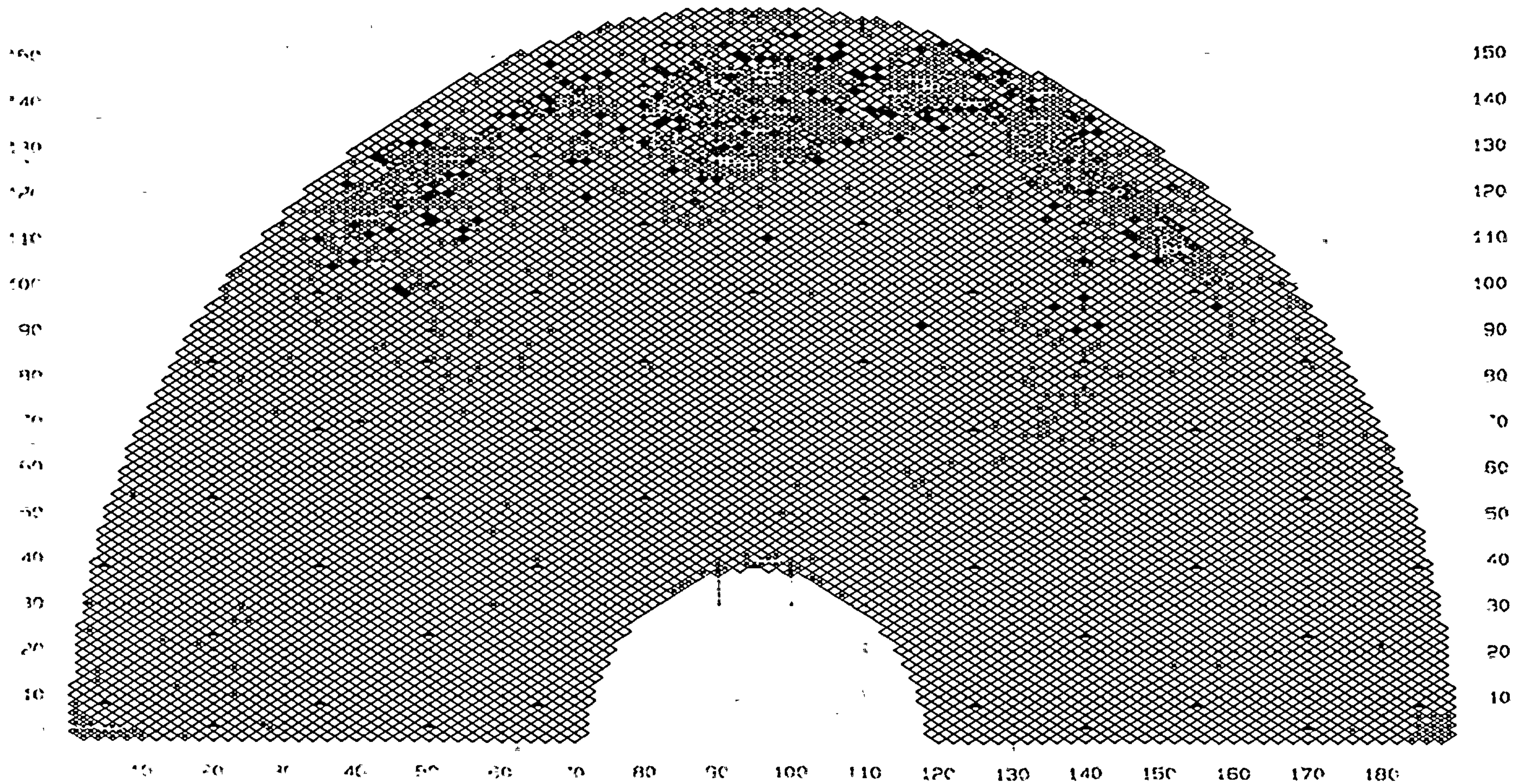


Figure IV-5
SG 22 ARC Region Defects U2R5

ROCKRIDGE TECHNOLOGIES

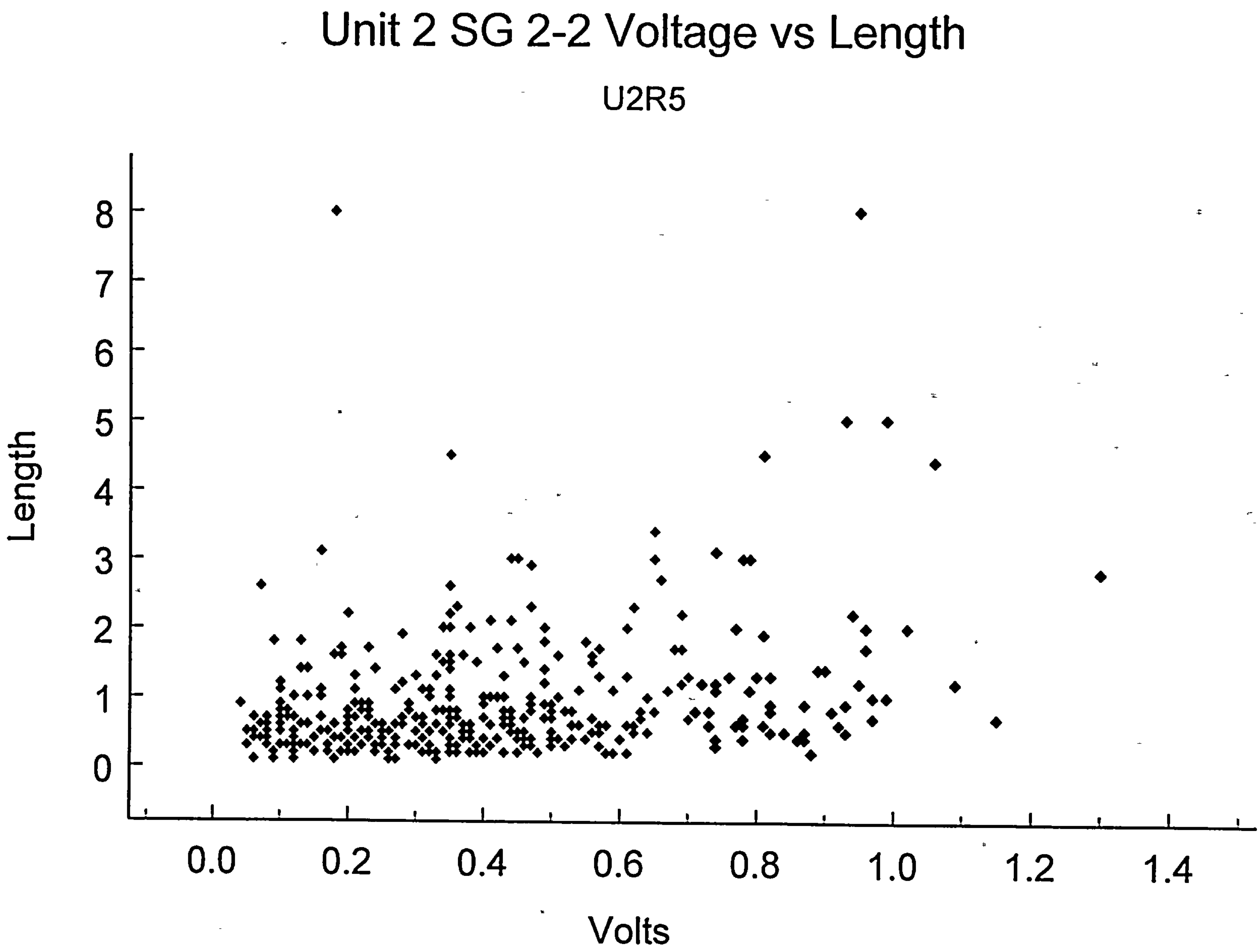
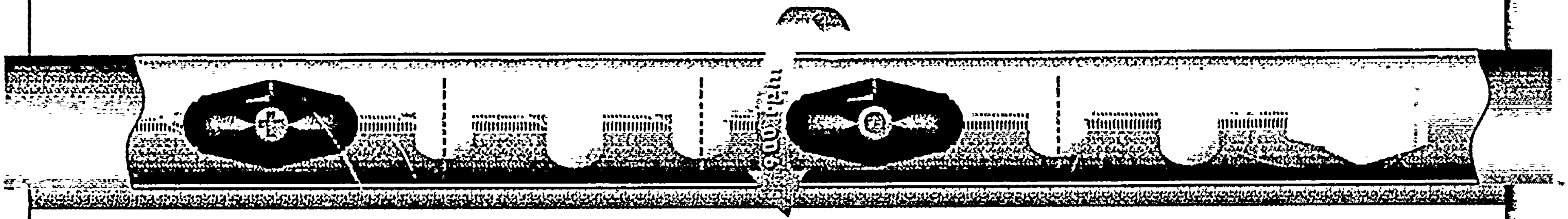

Unit 2 SG 2-2 Voltage vs Length
U2R5
Length
8
7
6
5
4
3
2
1
0
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Volts

FIGURE IV-6

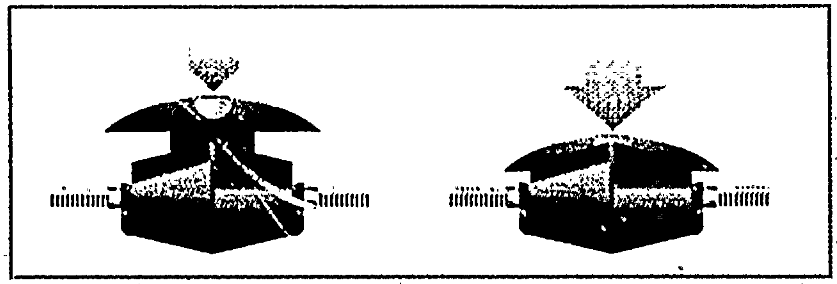
EDDY CURRENT PROBE TYPES

Plus Point



PLUS POINT FLEX-HINGE PROBE

Pancake and Plus Point coils.



A probe design with differentially wound axial and circumferential coils in the same coil cup.

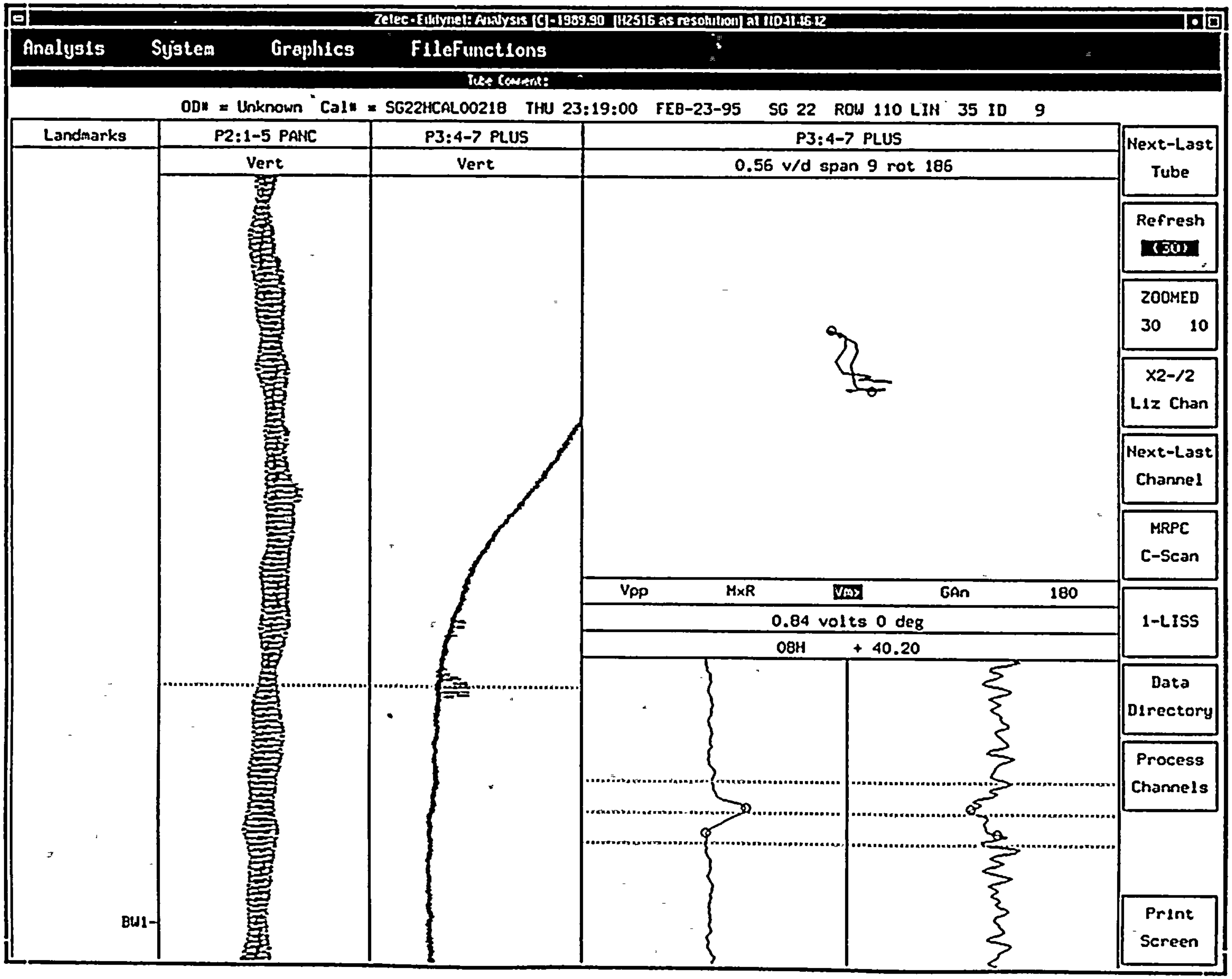
A new technology which replaces 3 coil MRPC, offers reduced scan times and increased sensitivity while being less sensitive to changes in tube geometry.

CONAM NUCLEAR, INC.

B&W NUCLEAR TECHNOLOGIES

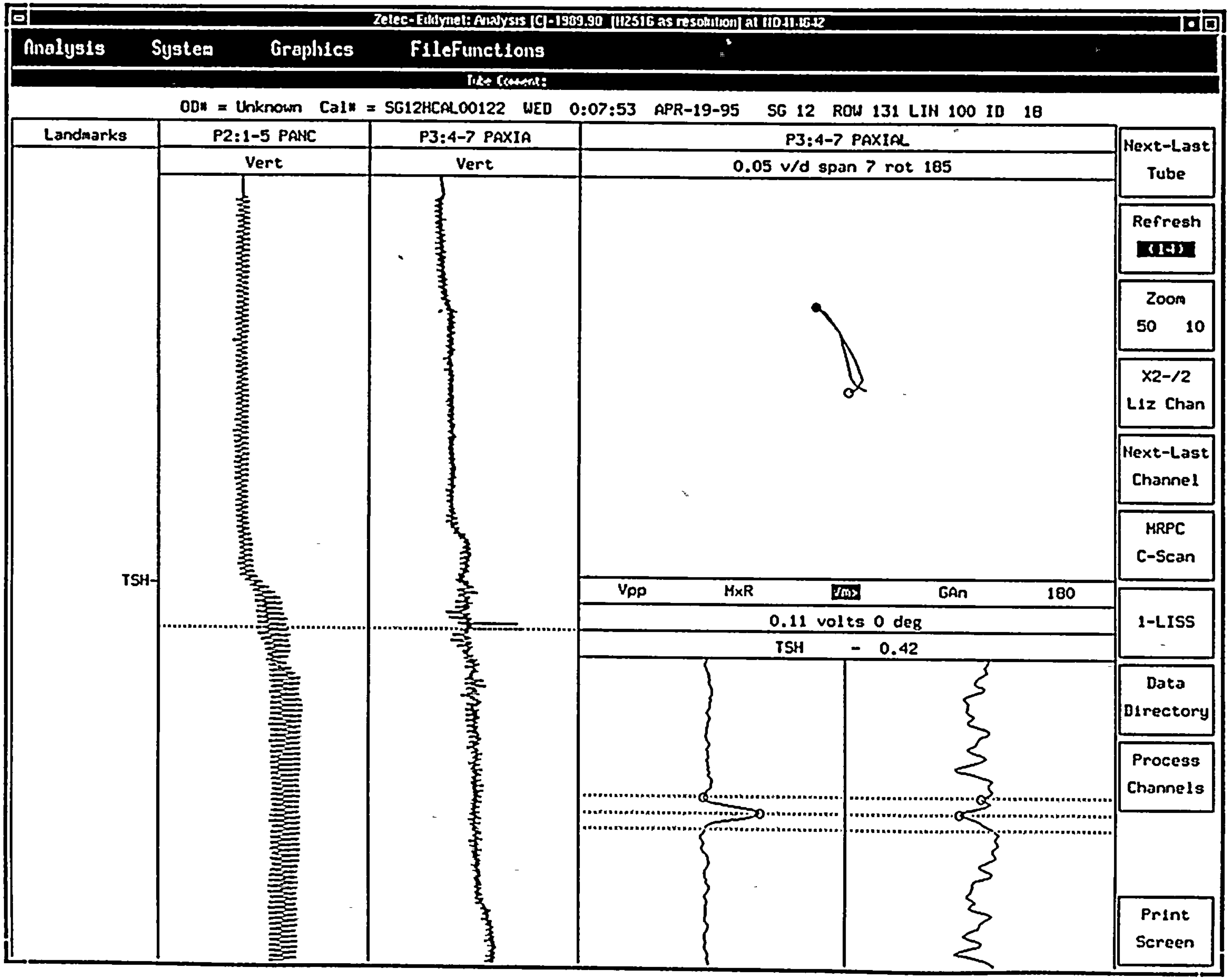
Graphic by Jim Piro for CONAM NUCLEAR, INC.

Figure IV-7



PLUS POINT STRIP CHART ANALYSIS

Figure IV-8



PLUS POINT AT HOTLEG TUBESHEET

Figure IV-9

PVNGS SQUARE BEND MOCKUP

SAMPLE NO	EDM LENGTH	DEPTH
SQ75.5	.50"	75%
SQ50.5	.50"	50%
SQ25.5	.50"	25%
SQ75.75	.75"	75%
SQ50.75	.75"	50%
SQ25.75	.75"	25%

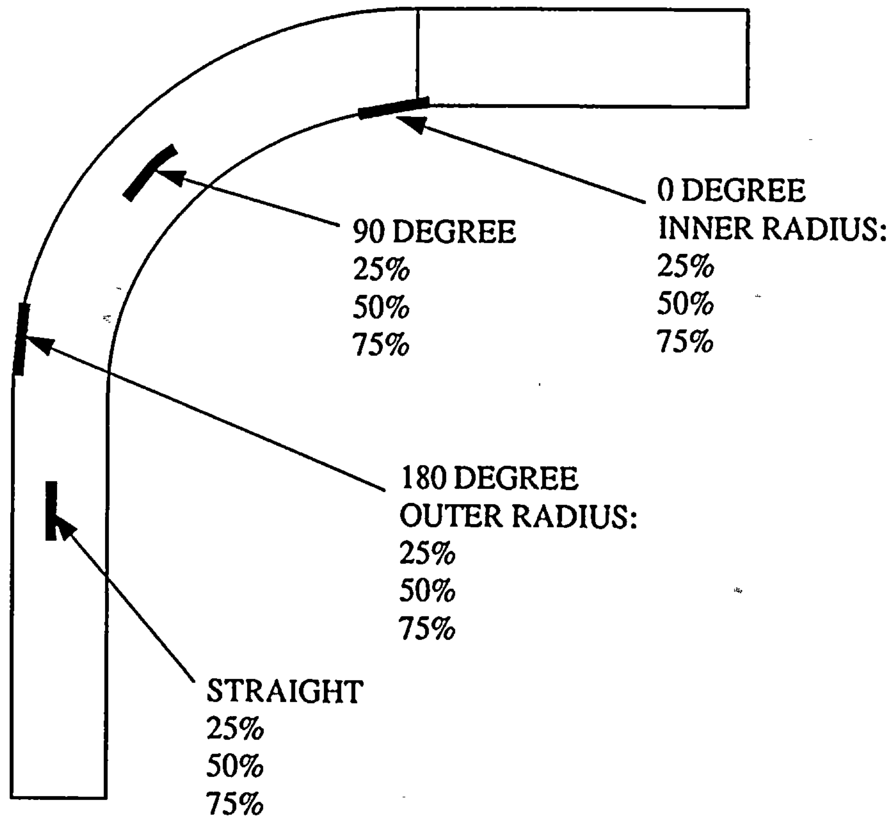


FIGURE IV-10

01/94, ARIZONA PUBLIC SERVICE, PALO VERDE, UNIT 2

STEAM GENERATOR: 22

DATE: 05/04/94
TIME: 17:23:05

CRITERIA: TUBES TO BE EXAMINED IN GROUP(S) 63, 64, 65, 66, 67, 68, 69, 70

STAYS ▲

PLUGGED 371 X Group63 111 ◆ Group64 16[illegible] ◆ Group65 11[illegible] ◆ Group66 89 ◆ Group67 80 ◆ Group68 173 ◆ Group69 113 ◆
Group70 106 ◆

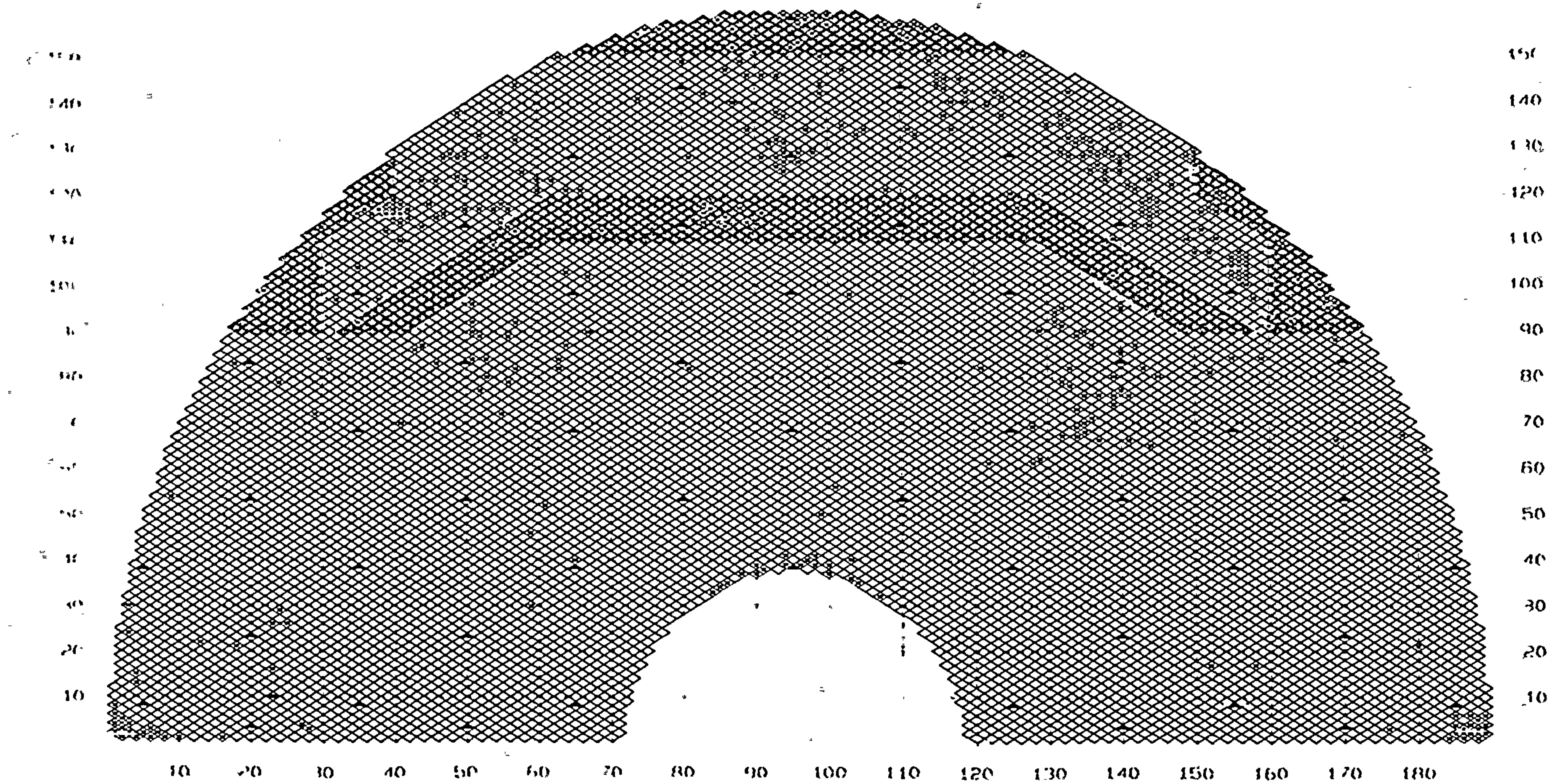


Figure IV-11
Additional Tubes for 2700 Tube Arc

CONAM NUCLEAR, INC. BW

09/94, ARIZONA PUBLIC SERVICE, PALO VERDE, UNIT 2

STEAM GENERATOR: 21
MRPC U-BEND (ARC REGION)
Area of Generator: Include MRPC UBEND - GROUPS 12-19. AND Probe: AND Exam Extent: Tubes Examined to Any Extent Between 07H and VS3

DATE: 08/17/95
TIME: 10:44:55

STAYS ▲

PLUGGED 226 X
8H1-VS2 1294 ◆
09H-VS1 12 ◆
09H-VS2 16 ◆
8H1-VS1 1504 ◆
08H-VS2 3 ◆
OTHER 4 Δ

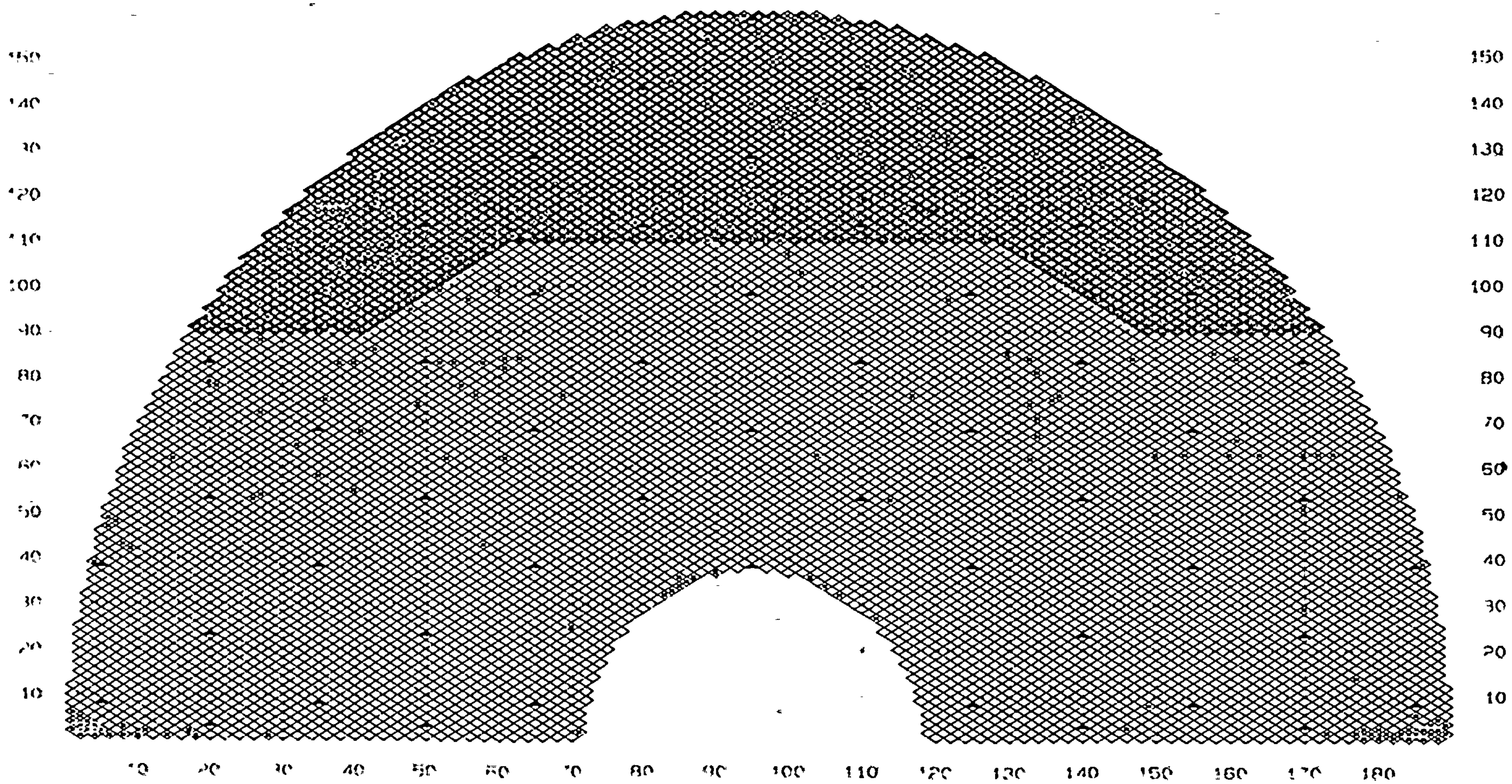


Figure IV-12
SG 21 ARC Region MRPC U2M5-2

ROCKRIDGE TECHNOLOGIES

09/94, ARIZONA PUBLIC SERVICE, PALO VERDE, UNIT 2

STEAM GENERATOR: 21
BOBBIN SCOPE
Probe AND Exam Extent: Tubes Examined to Any Extent Between TEH and TEC

DATE: 08/17/95
TIME: 10:56:58

STAYS ▲

PLUGGED 226 X TEH TEC 4287 ◆ 07H-TEC 1 ◆

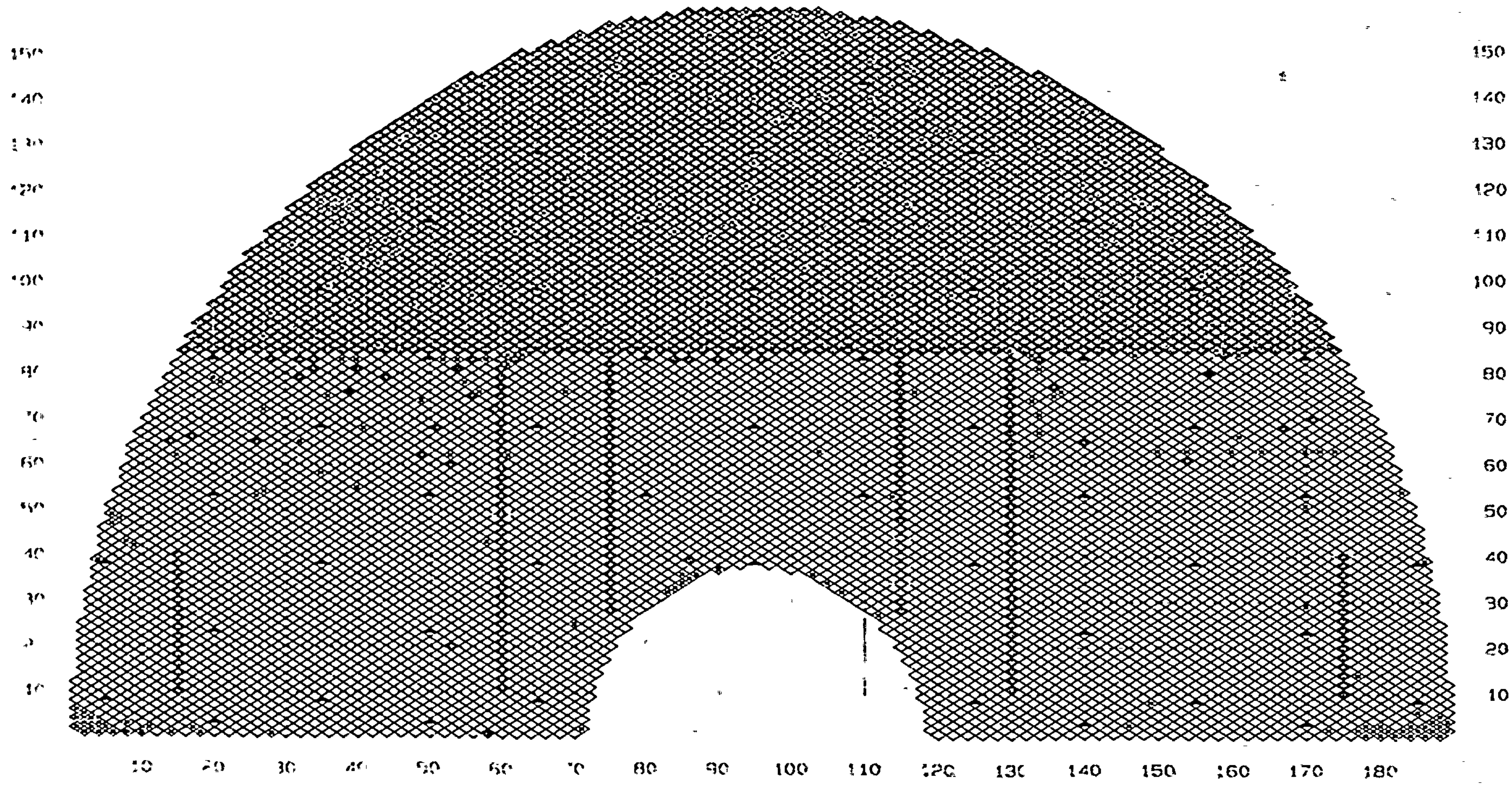


Figure IV-13
SG 21 Bobbin Coil Scope U2M5-1

ROCKRIDGE TECHNOLOGIES

09/94, ARIZONA PUBLIC SERVICE, PALO VERDE, UNIT 2

STEAM GENERATOR: 21
OUTAGE DATA SET · CURRENT
Percent: MAI, SAI AND Area of Generator: Include MRPC UBEND - GROUPS 12-19.

DATE: 08/17/95
TIME: 11: 35: 23

STAYS ▲

PLUGGED 226 X MAI 12 ◆ SAI 48 ◆

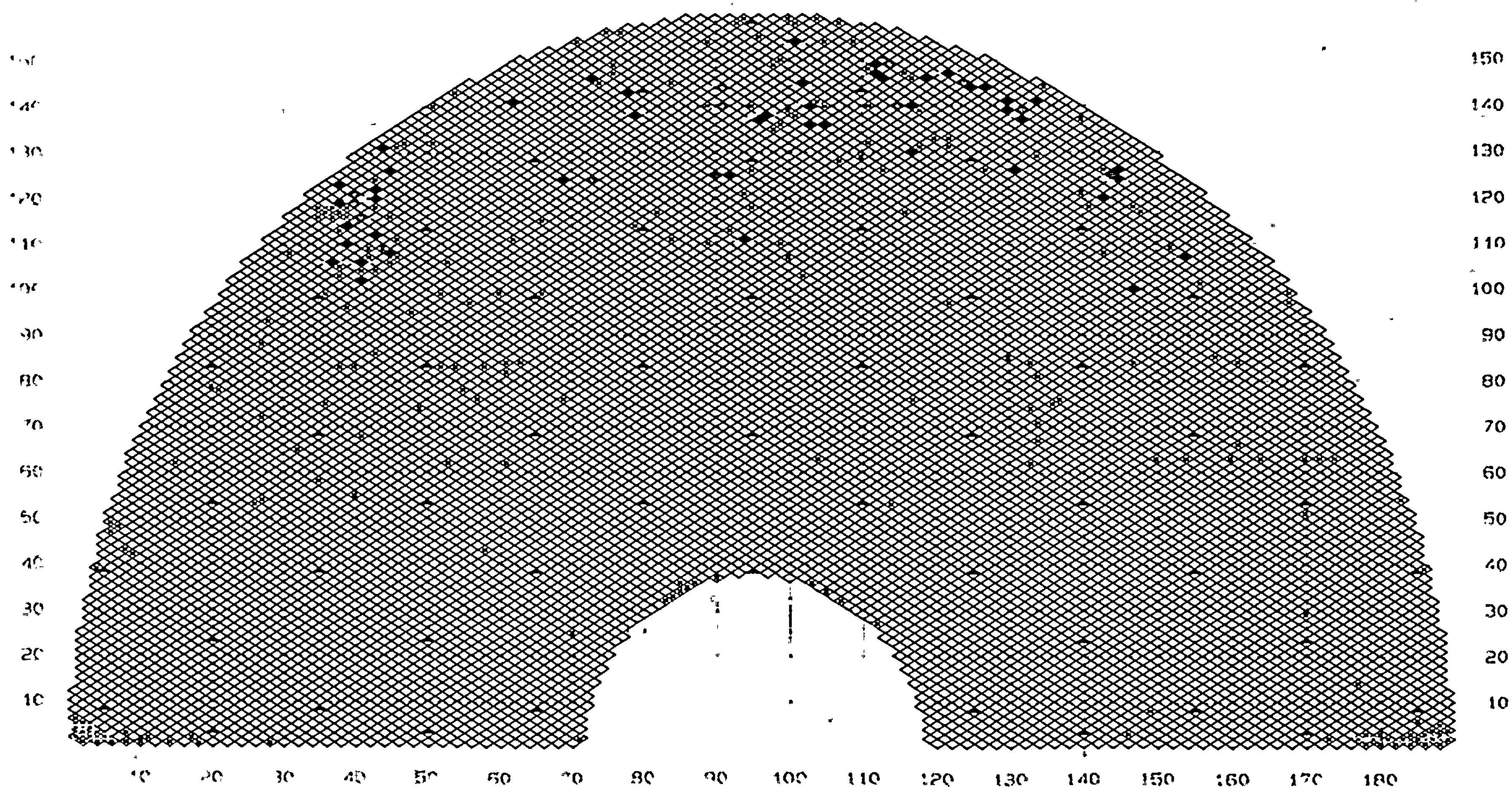


Figure IV-14
SG 21 ARC Region Defects
U2M5.4

ROCKRIDGE TECHNOLOGIES

09/94, ARIZONA PUBLIC SERVICE, PALO VERDE, UNIT 2

STEAM GENERATOR: 22
MRPC U-BEND (ARC REGION)
Area of Generator: Include MRPC U-BEND ARC REGION , AND Probe: AND Exam Extent: Tubes Examined to STAYS
Any Extent Between 07H and VS3

DATE: 08/17/95
TIME: 15:14:42

PLUGGED 741 X BH1-VS[illegible] 1138 ◆ 09H-VS2 7 ◆ [illegible] ◆ BH1-VS1 1147 ◆ 08H-VS2 22 ◆
08[illegible] [illegible] ◆ BH1-VS5 [illegible] O 08H-VS1 1 O
OTHER 19 O

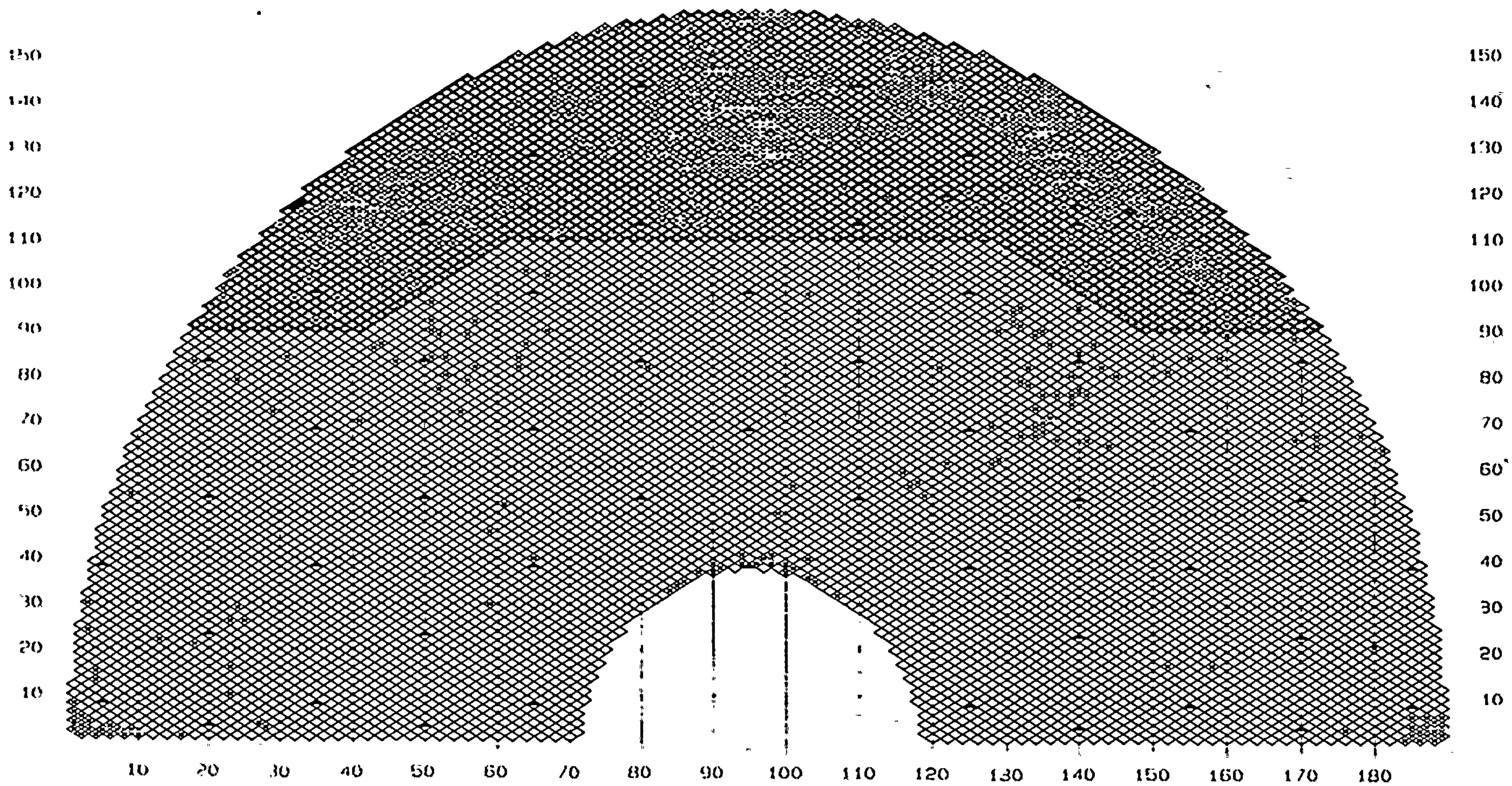


Figure IV-15
SG 22 ARC Region MRPC
U2M5-2

ROCKRIDGE TECHNOLOGIES

09/94, ARIZONA PUBLIC SERVICE, PALO VERDE, UNIT 2

STEAM GENERATOR: 22
BOBBIN SCOPE
Probe' AND Exam Extent: Tubes Examined to Any Extent Between TEH and TEC

DATE: 08/17/95
TIME: 15:02:41

STAYS ▲

PLUGGED 741 X TEH-TEC 3784 ◆ TSH-TEC 10 ◆

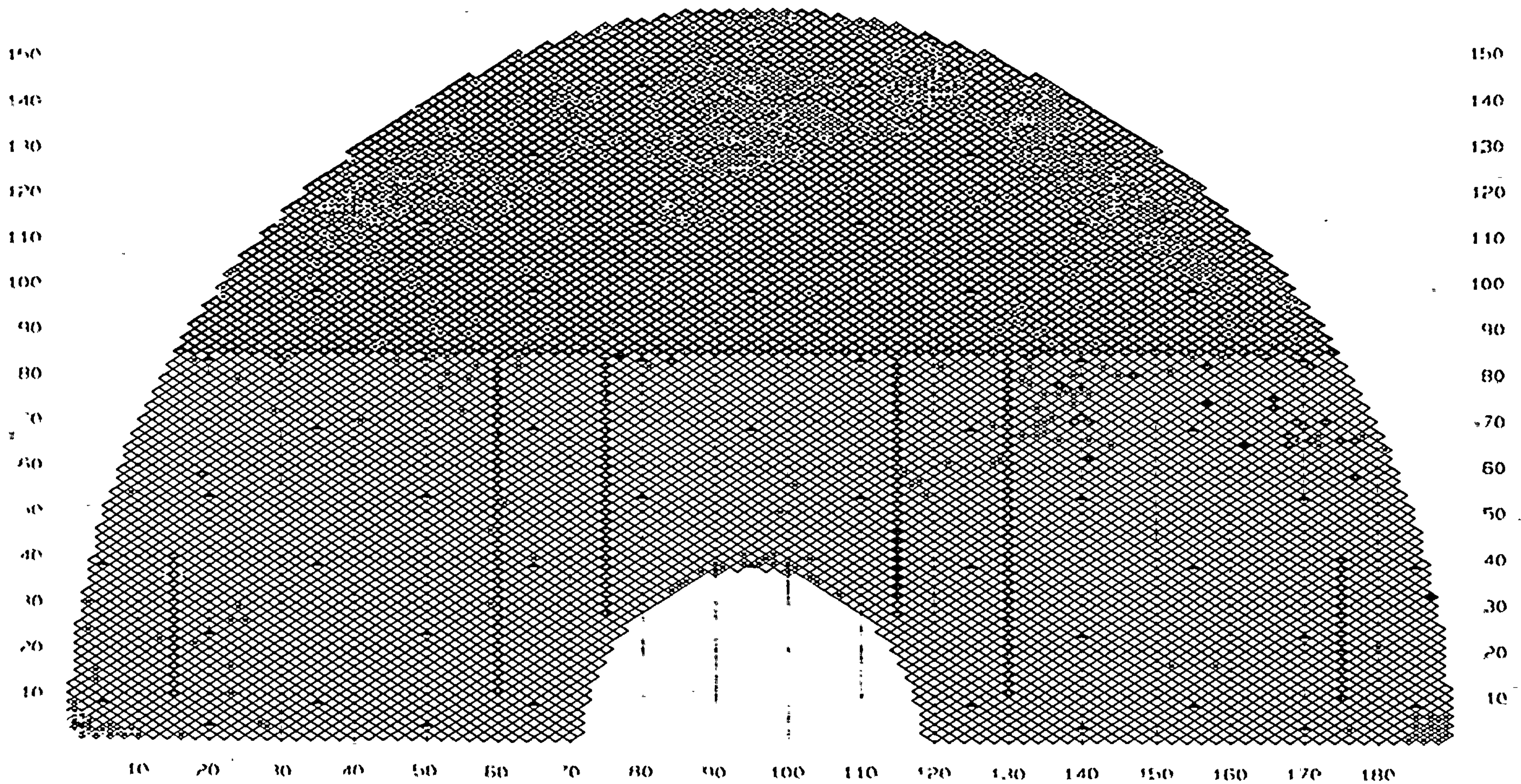


Figure IV-16
SG 22 Bobbin Coil Scope U2M5-2

ROCKRIDGE TECHNOLOGIES

09/94, ARIZONA PUBLIC SERVICE, PALO VERDE, UNIT 2

STEAM GENERATOR: 22
OUTAGE DATA SET : CURRENT
Percent: MAI,SAI AND Area of Generator: Include MRPC U-BEND ARC REGION

DATE: 08/17/95
TIME: 15:36:16

STAYS ▲

PLUGGED 741 X   BW1 VS2 25 ◆   BW1-VS1 113 ◆   01H-01H 3 ◆   09H BW1 1 ◆
09H VS2 1 ◆
OTHER 1 C

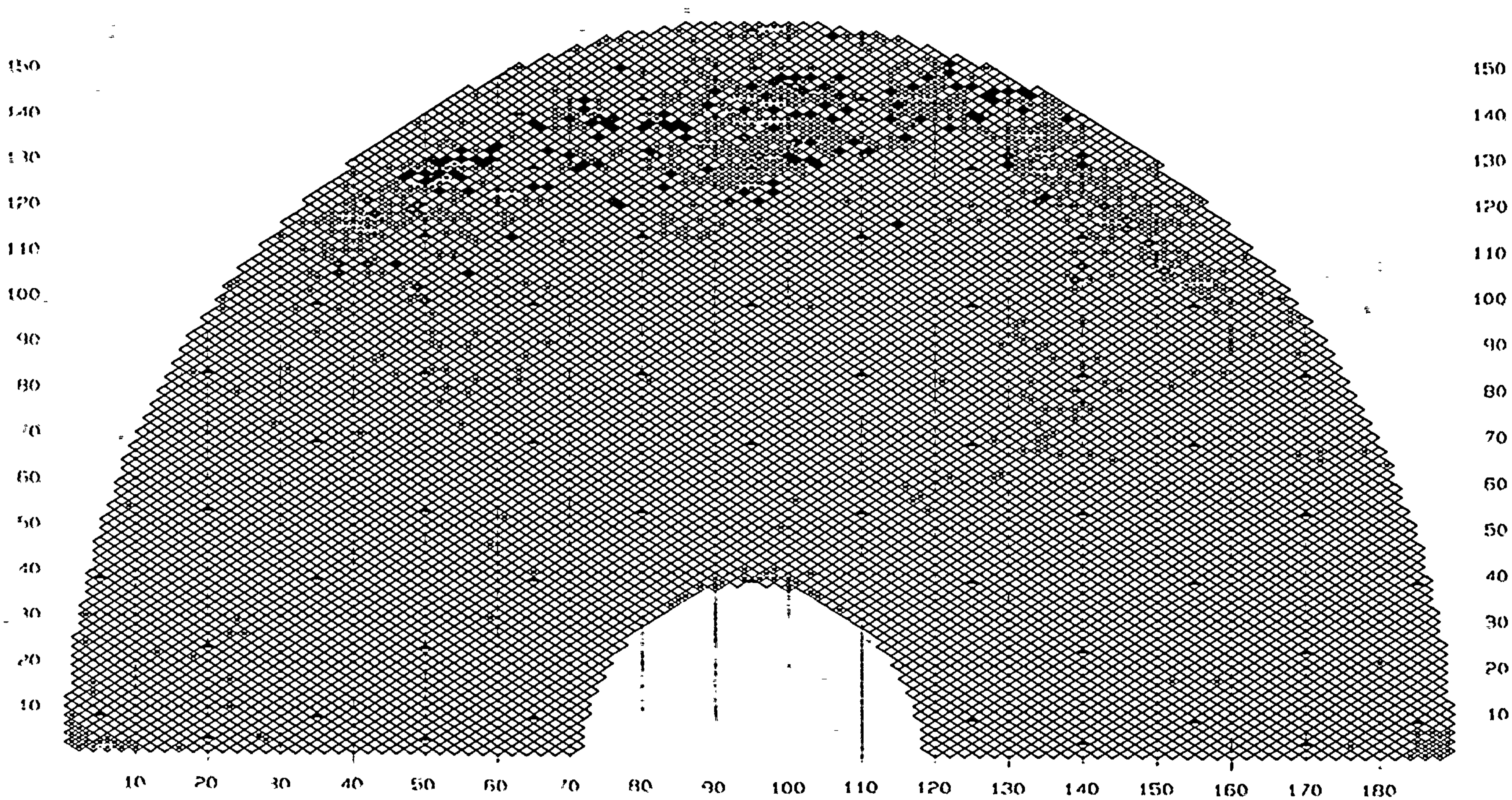


Figure IV-17
SG 22 ARC Region Defects

ROCKRIDGE TECHNOLOGIES

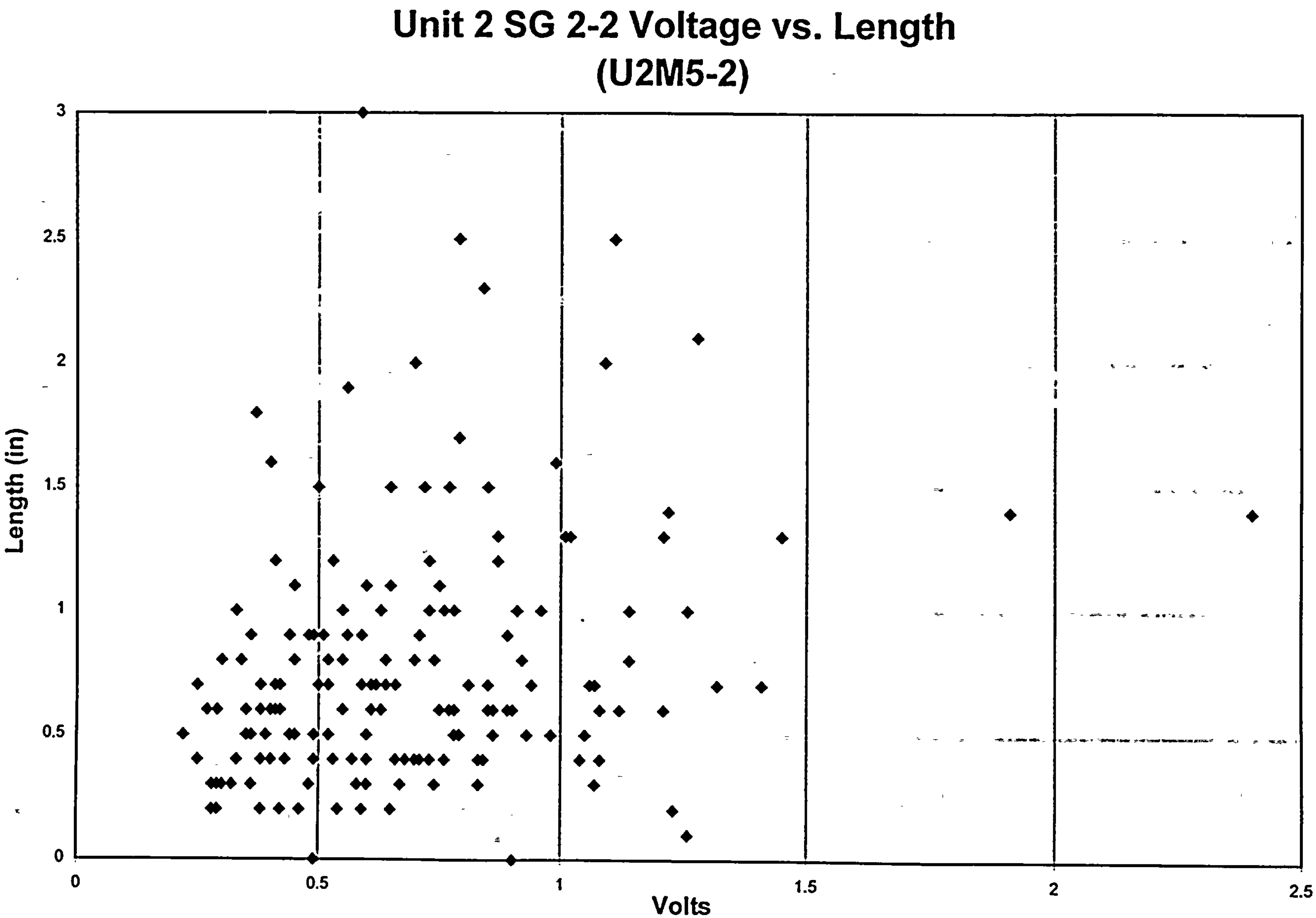

Unit 2 SG 2-2 Voltage vs. Length
(U2M5-2)
Length (in)
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
Volts

FIGURE IV-18

01/94, ARIZONA PUBLIC SERVICE, PALO VERDE, UNIT 2

STEAM GENERATOR: 21
MRPC U-BEND (ARC REGION)
Area of Generator: Include MRPC U-BEND ARC REGION , AND Probe: AND Exam Extent: Tubes Examined to Any Extent Between 07H and VS3

DATE: 08/18/95
TIME: 11:02:36
STAYS

PLUGGED	188	X	BW1-VS2	766	◆	BW1-VS3	8	O	[illegible]	1	◆	07H-VS2	7	O	09H-VS2	3	O
			[illegible]	498	◆				08H-VS1	1315	◆	[illegible]	[illegible]	[illegible]	09H-VS1	2	◆
			[illegible]	5	◆												
															OTHER	3	O

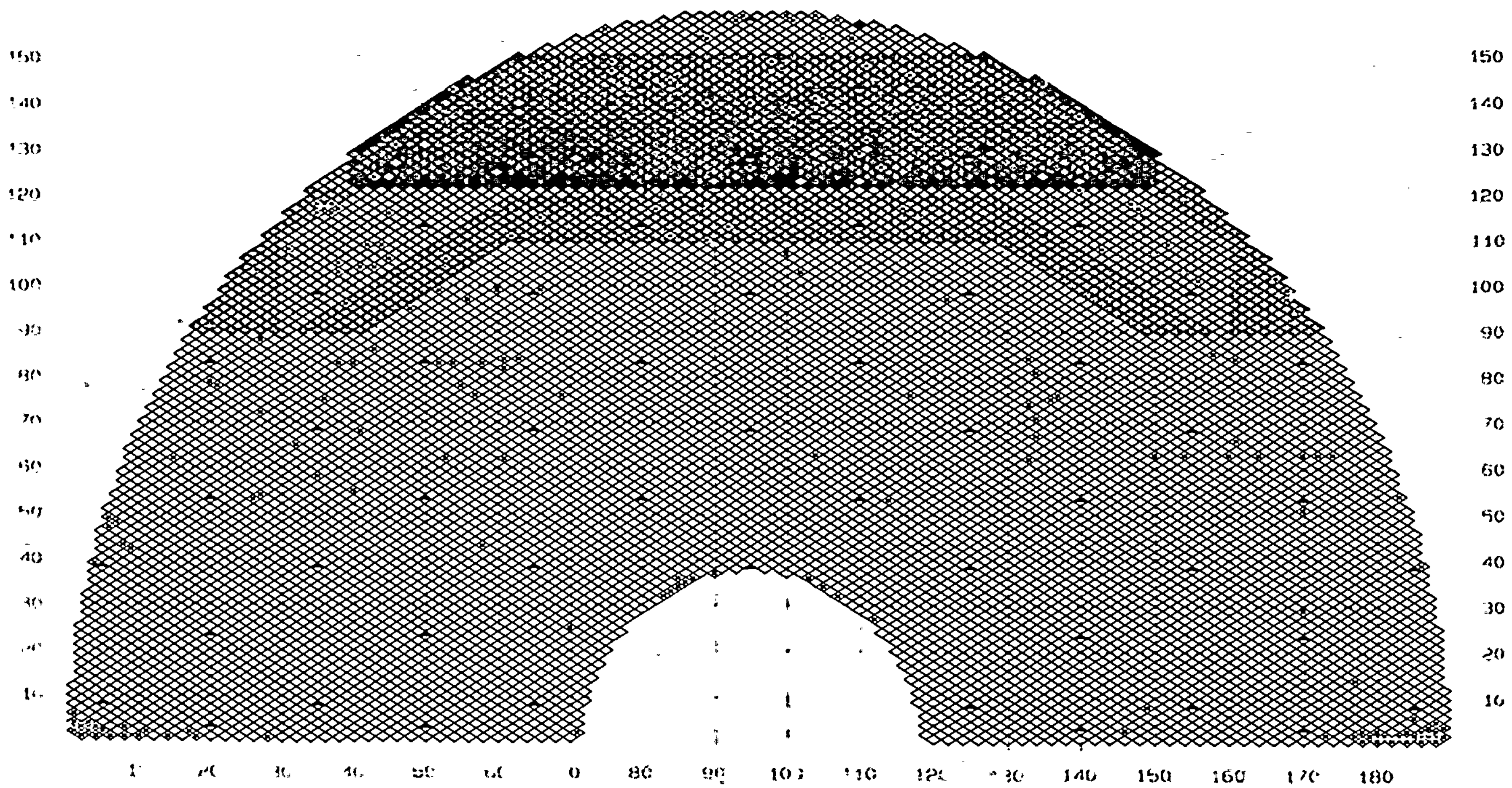


Figure IV-19
SG 21 ARC Region MRPC U2M5-1

ROCKRIDGE TECHNOLOGIES

01/94, ARIZONA PUBLIC SERVICE, PALO VERDE, UNIT 2

STEAM GENERATOR: 21
BOBBIN SCOPE
Probe· AND Exam Extent: Tubes Examined to Any Extent Between TEH and TEC

DATE: 08/18/95
TIME: 11: 10: 19

STAYS ▲

PLUGGED 188 ✕ TEH TEC 4464 ◆

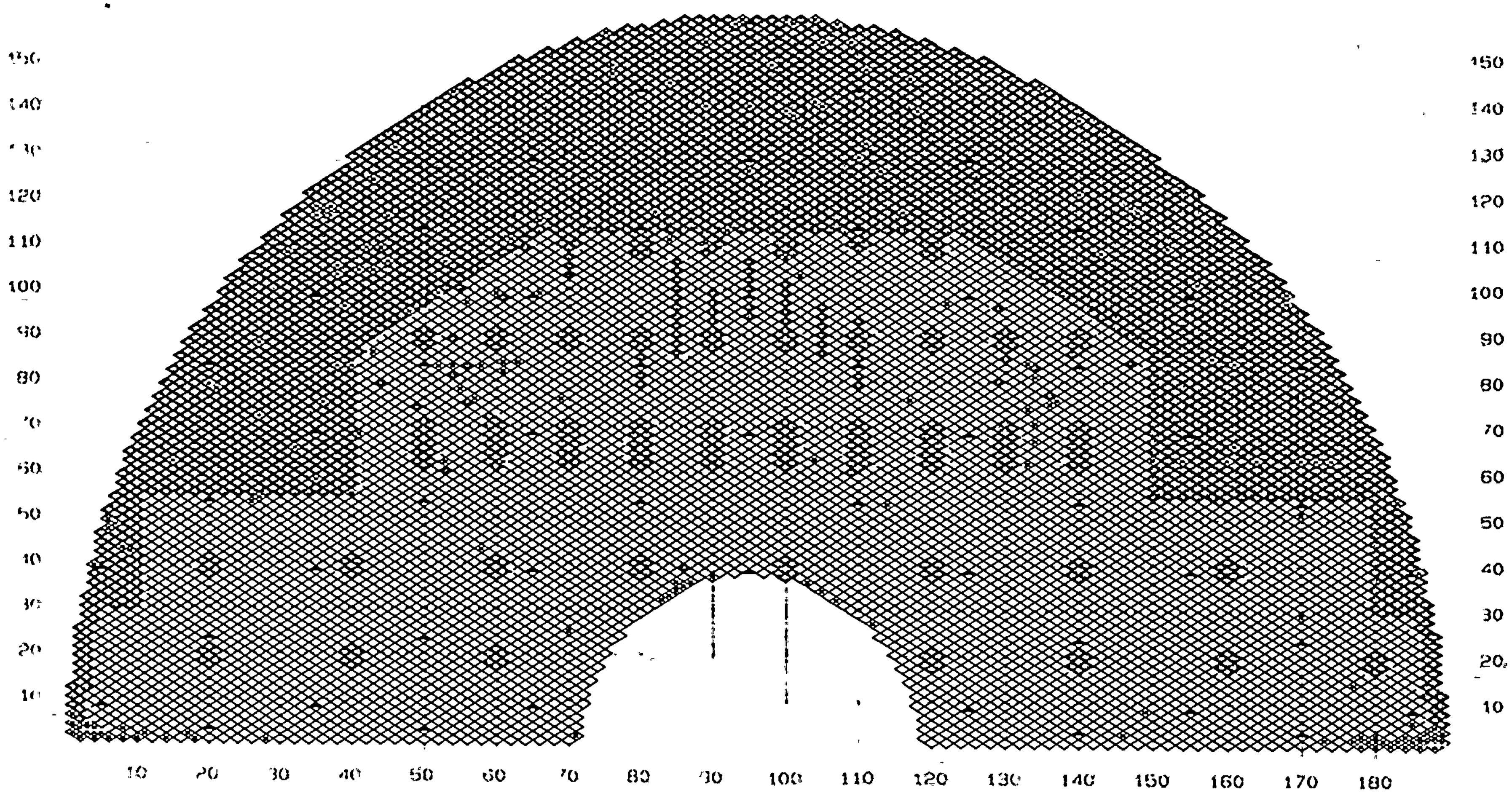


Figure IV-20
SG 21 Bobbin Coil Scope

ROCKRIDGE TECHNOLOGIES

01/94, ARIZONA PUBLIC SERVICE, PALO VERDE, UNIT 2

STEAM GENERATOR: 21
OUTAGE DATA SET · CURRENT
Percent: MAI, SAI AND Area of Generator: Include MRPC U-BEND ARC REGION

DATE: 08/18/95
TIME: 11:27:17

STAYS ▲

PLUGGED 188 X MAI 0 ◆ SAI 22 ◆

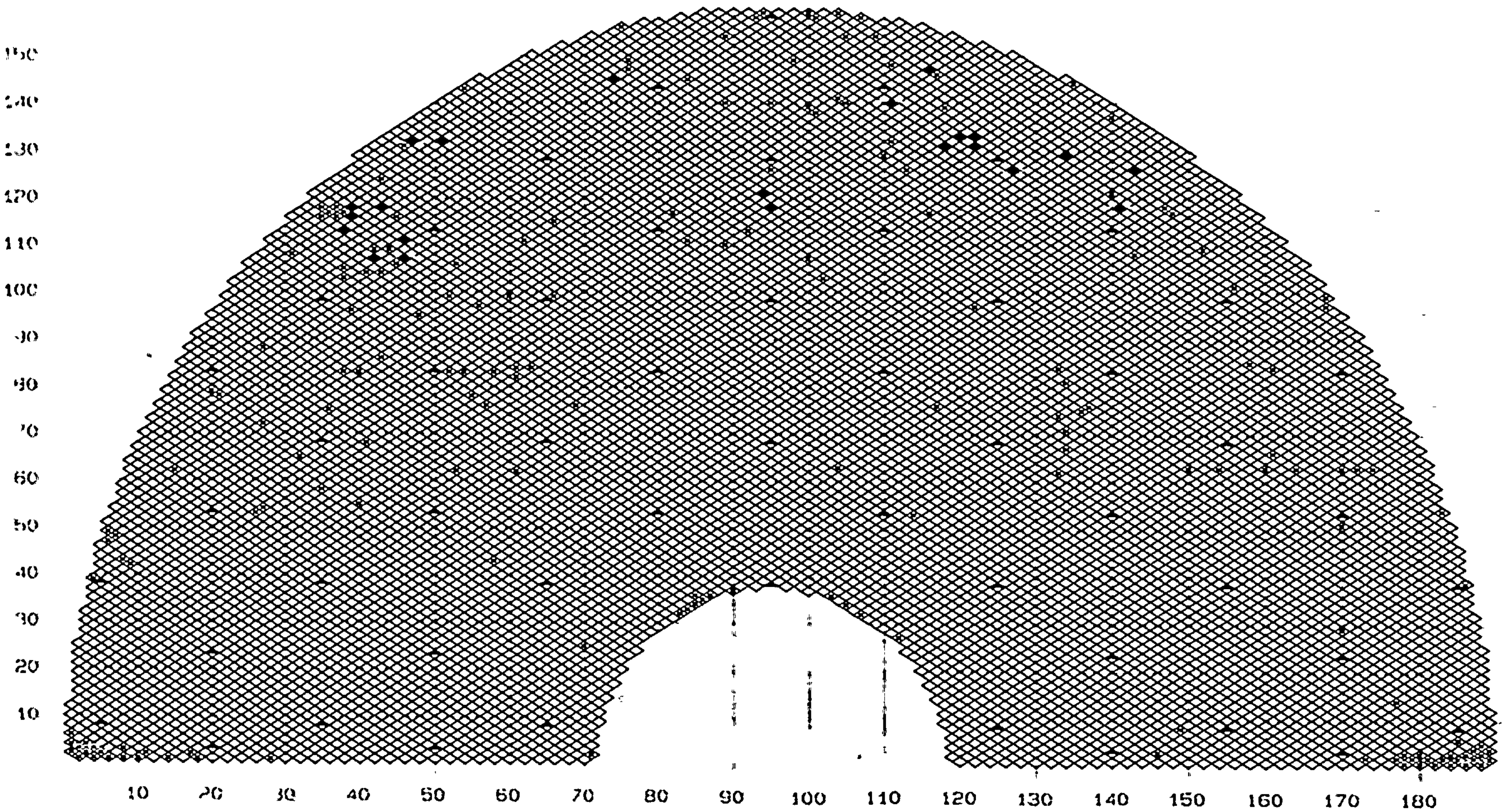


Figure IV-21
SG 21 ARC Region Defects
U2M5-1

ROCKRIDGE TECHNOLOGIES

01/94, ARIZONA PUBLIC SERVICE, PALO VERDE, UNIT 2

STEAM GENERATOR: 22 | DATE: 08/18/95
MRPC U-BEND (ARC REGION) | TIME: 14:50:35
Area of Generator: Include MRPC U-BEND ARC REGION , MRPB U-BEND ARC REGION 3 , AND Probe: AND Exam
Extent: Tubes Examined to Any Extent Between 07H and VS3 | STAYS ▲

PLUGGED 370 X 08H-VS2 1256 ◆ 07H-VS2 9 ◆ 08H-VS1 1408 ◆ 07H-VS1 27 ◆

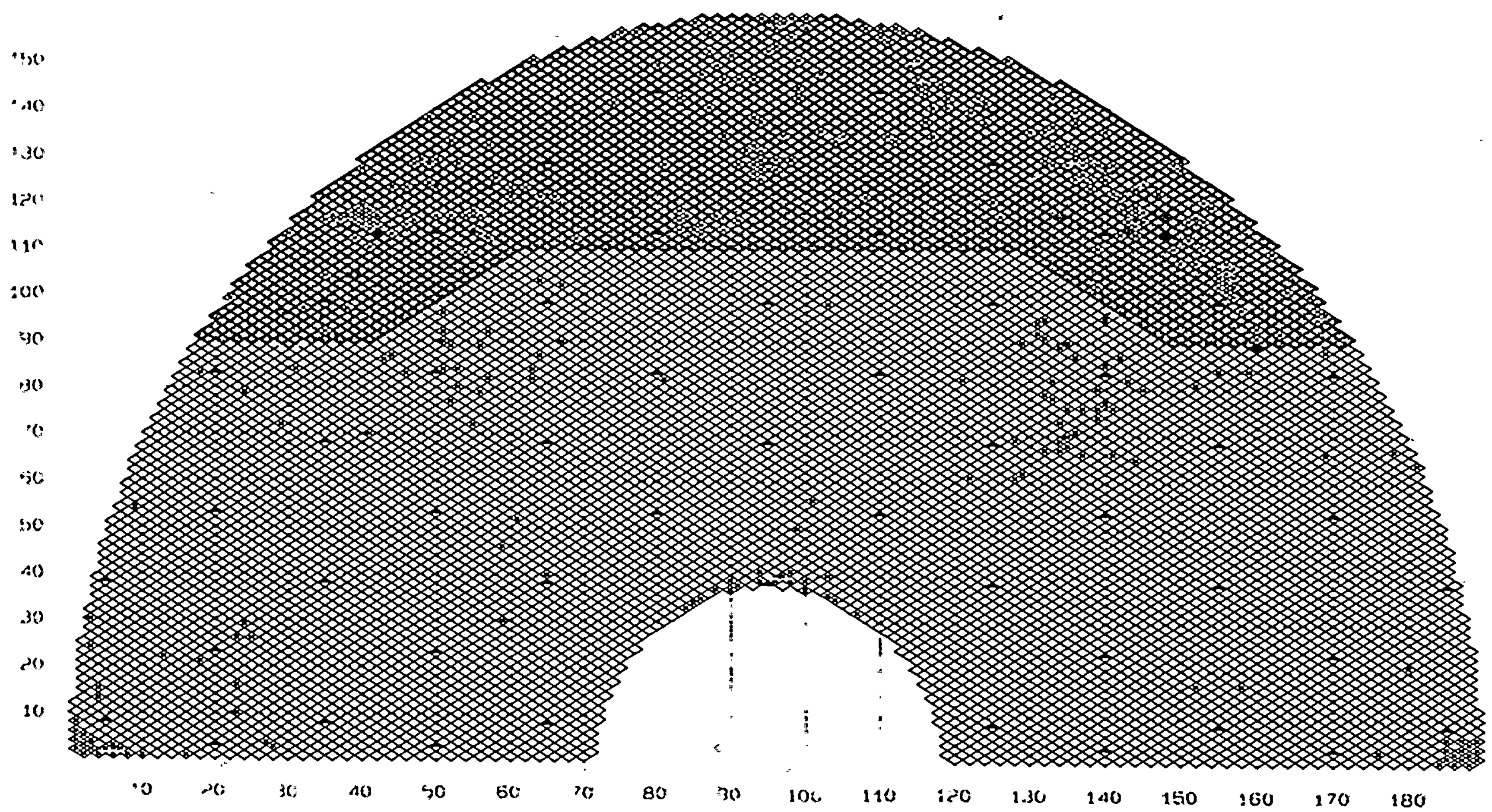


Figure IV-22
SG 22 ARC Region MRPC

ROCKRIDGE TECHNOLOGIES

01/94, ARIZONA PUBLIC SERVICE, PALO VERDE, UNIT 2

STEAM GENERATOR: 22
BOBBIN SCOPE
Probe: AND Exam Extent: Tubes Examined to Any Extent Between TEH and TEC

DATE: 08/18/95
TIME: 14: 29: 22

STAYS ▲

PLUGGED 370 x TEH TEC 1372 ◆ TEH-01C 1 ◆

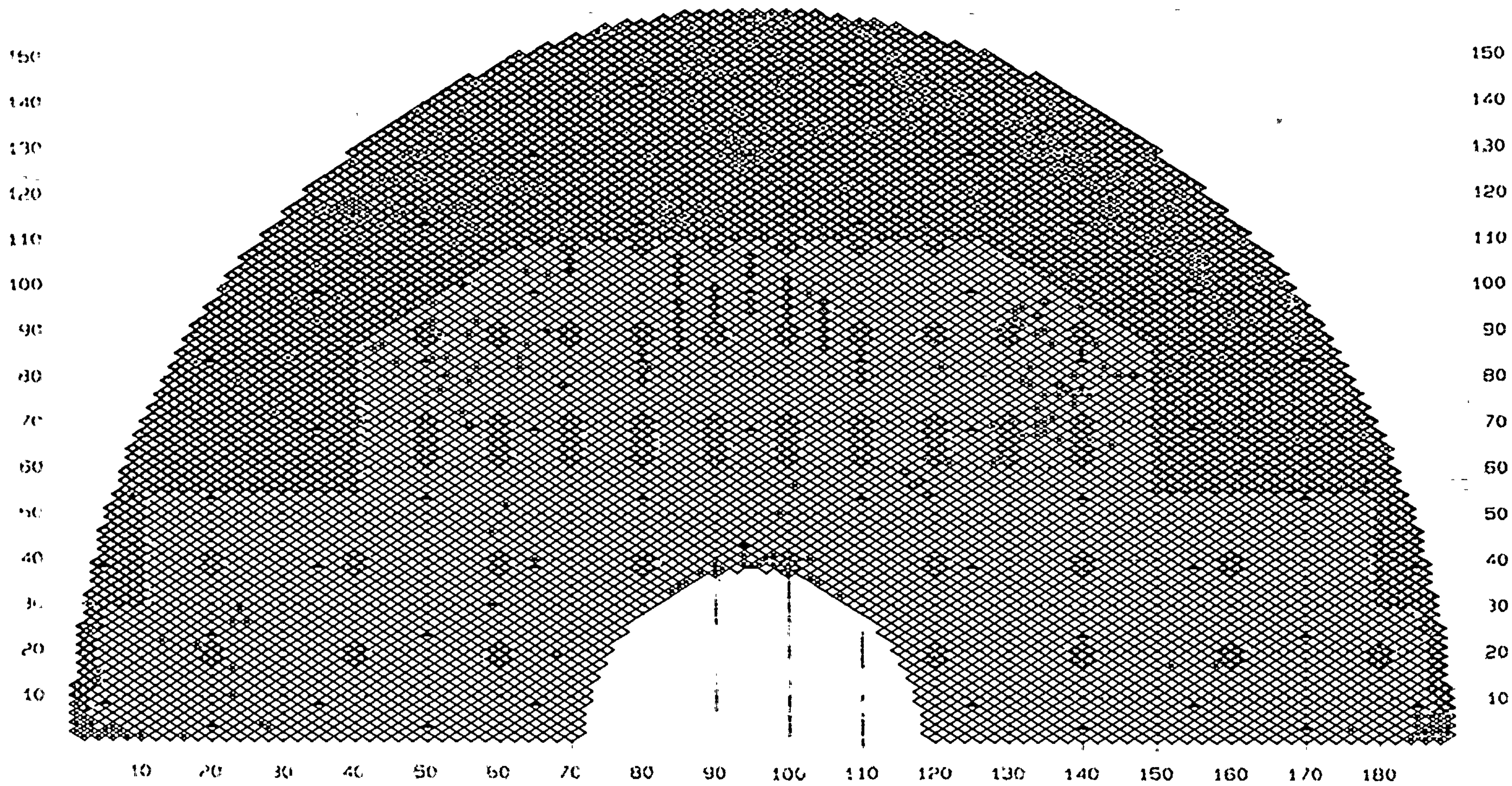


Figure IV-23
SG 22 Bobbin Coil Scope
U2M5-1

ROCKRIDGE TECHNOLOGIES

01/94, ARIZONA PUBLIC SERVICE, PALO VERDE, UNIT 2

STEAM GENERATOR: 22
OUTAGE DATA SET · CURRENT
Percent: MAI, SAI AND Area of Generator: Include MRPC U-BEND ARC REGION , MRPB U-BEND ARC REGION 3 , STAYS

DATE: 08/18/95
TIME: 16: 10: 36

PLUGGED 370 X MAI 13 ◆ SAI 295 ◆

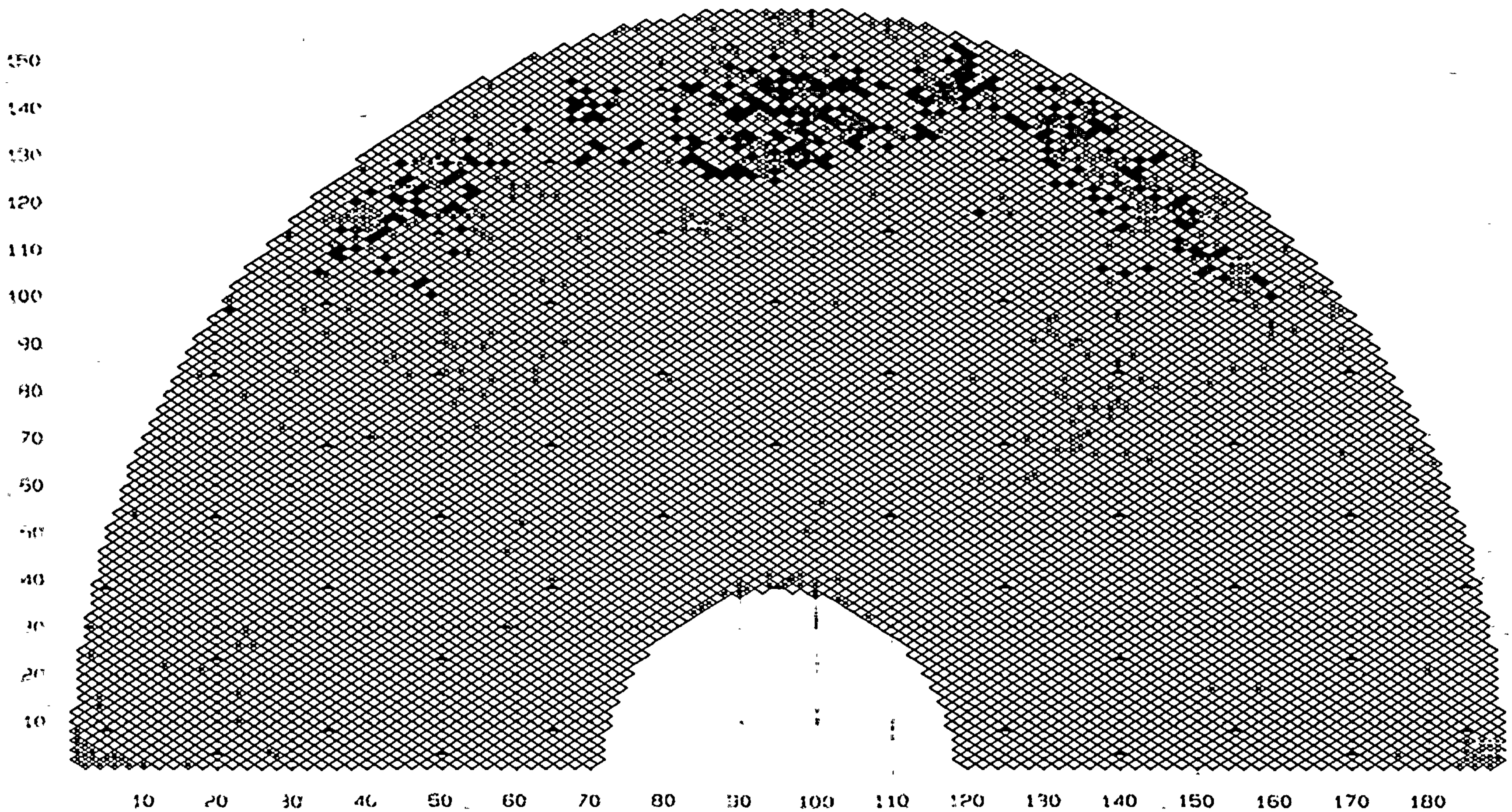


Figure IV-24
SG 22 ARC Region Defects
U2M5-1

ROCKRIDGE TECHNOLOGIES

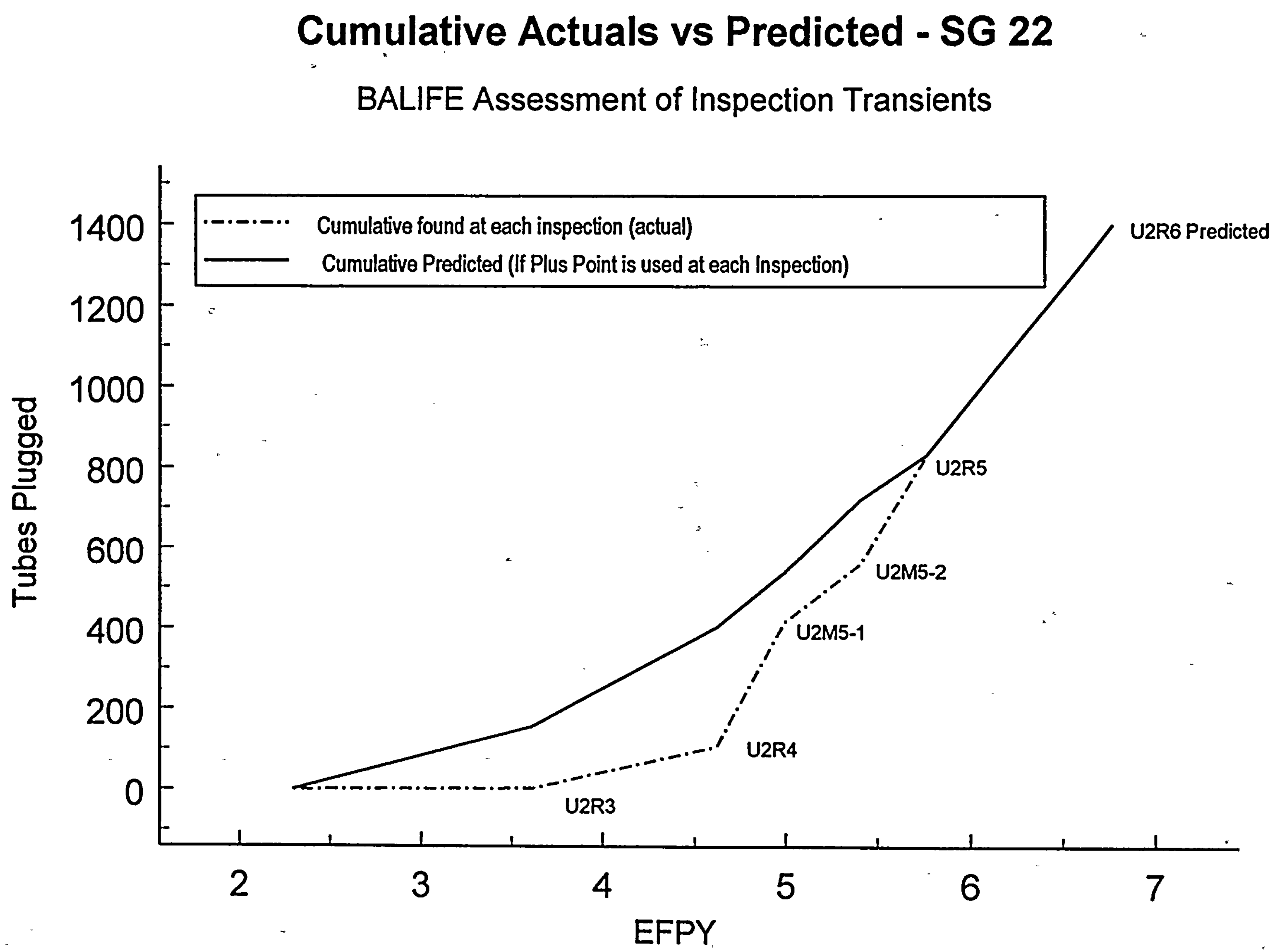


FIGURE IV-25a

BALIFE Predictions for PVNGS SG 22

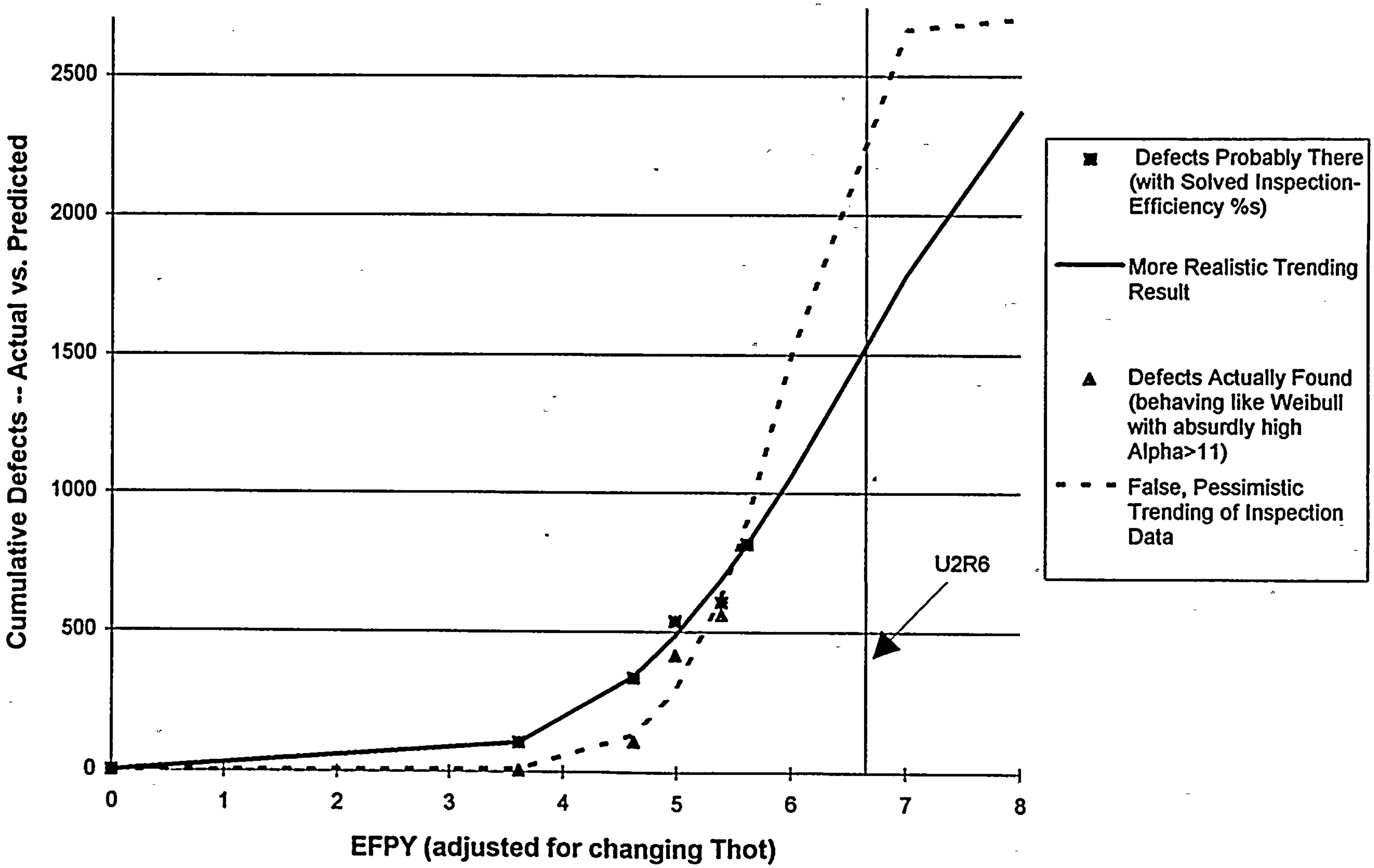


FIGURE IV-25b

Tube Pull Candidates

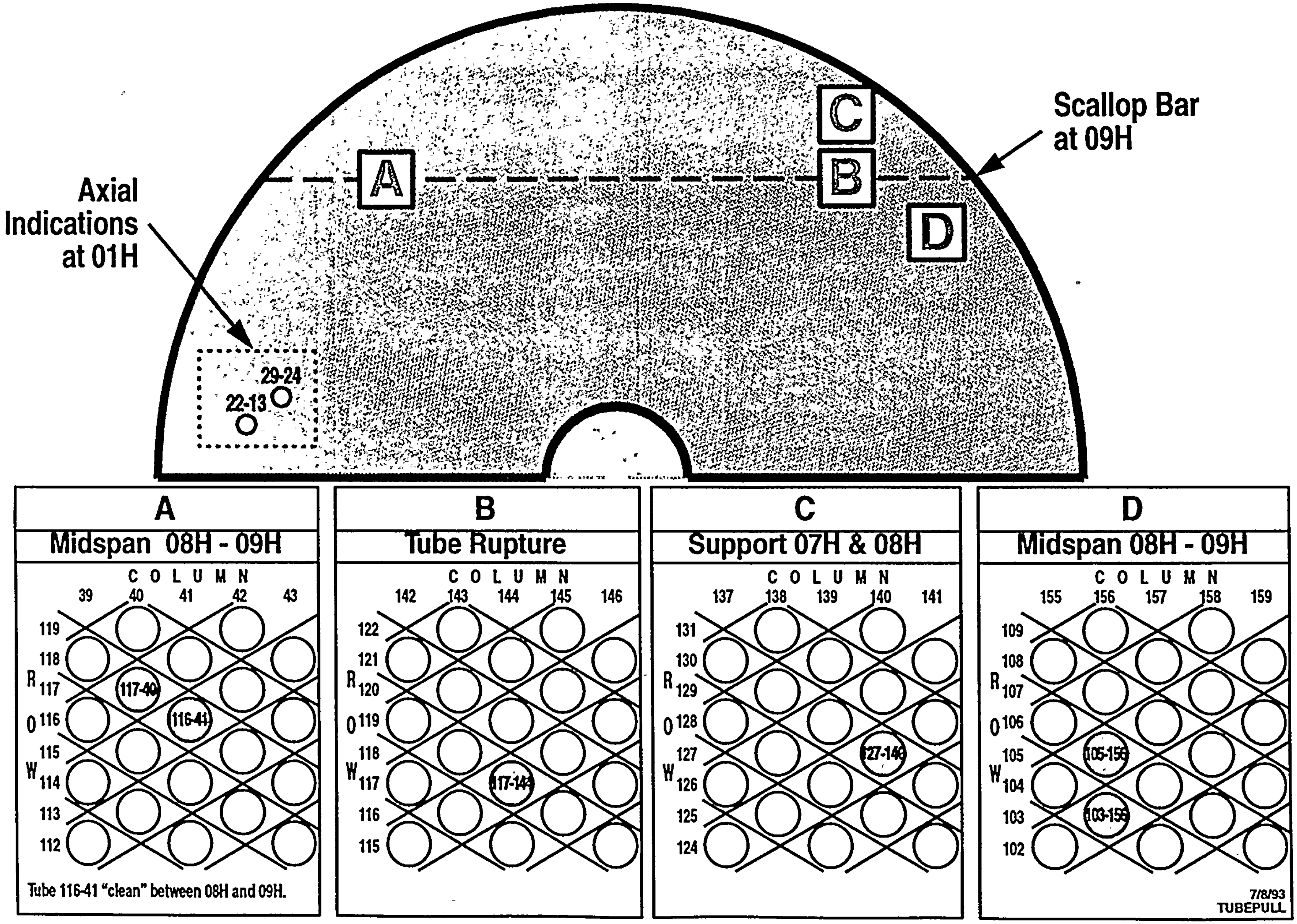


FIGURE IV-26

UNIT 2 SG TUBE VISUAL SW/BT EXAMINATION SUMMARY SHEET

(SW=swell test, BT=burst test)

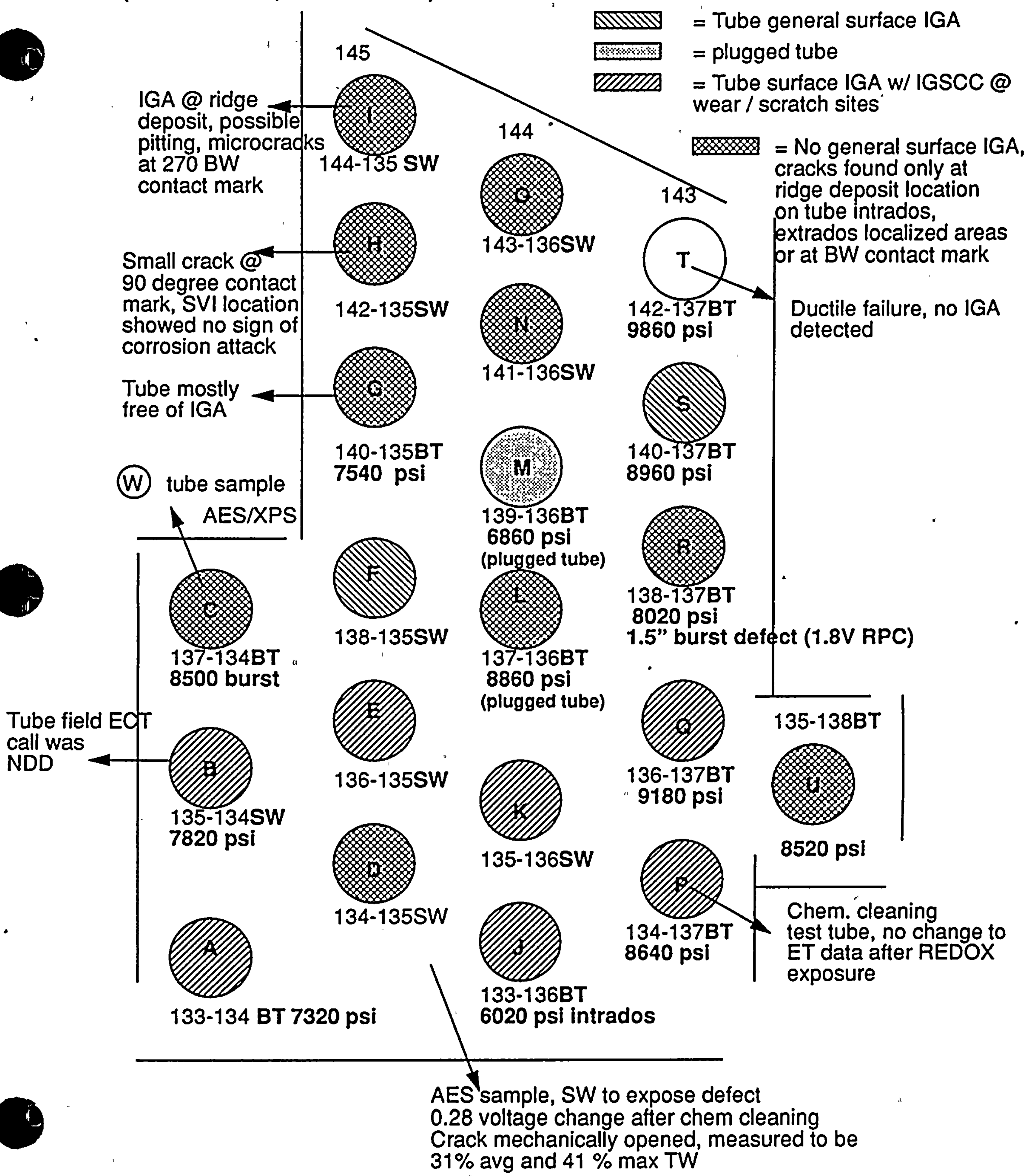
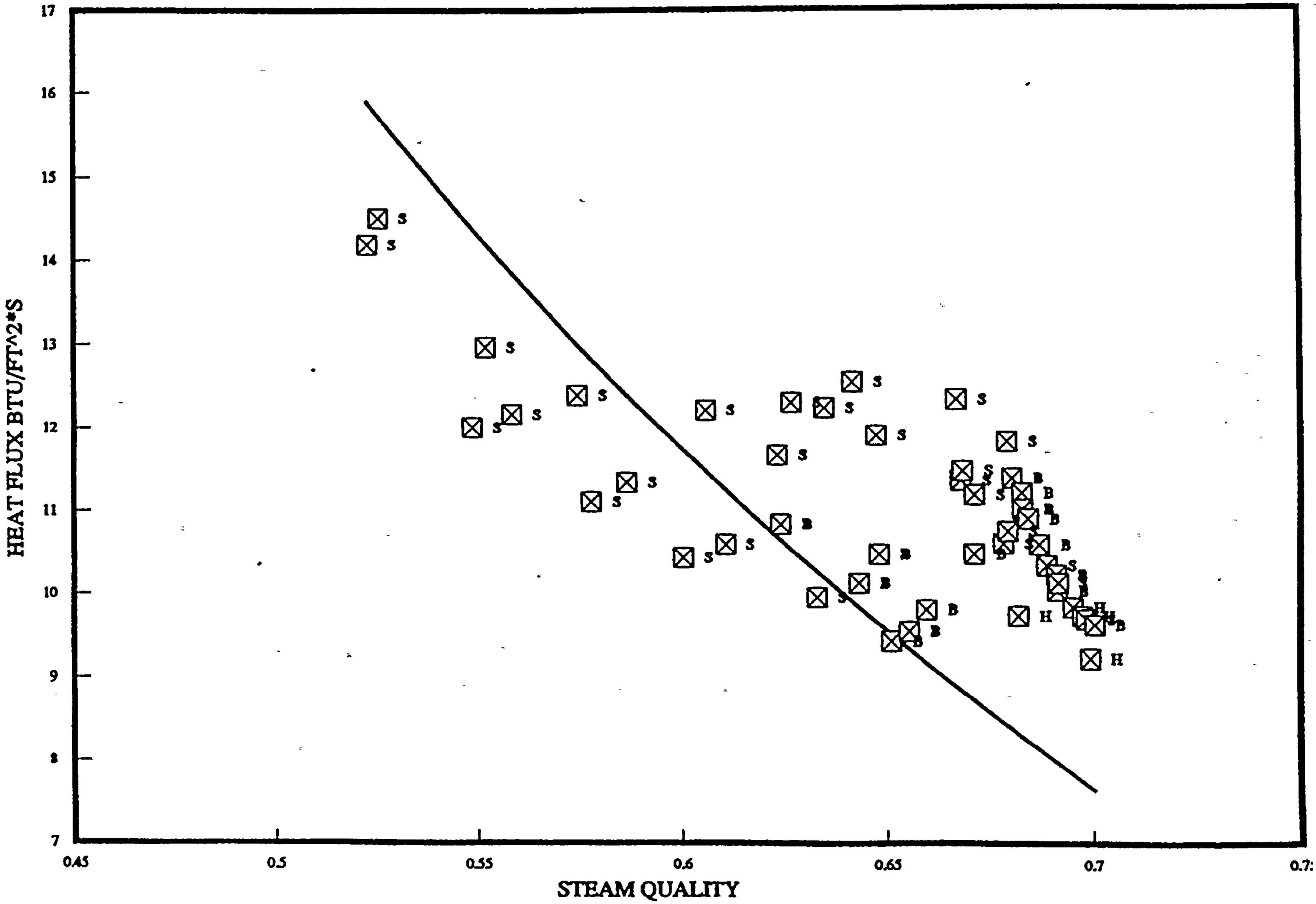


FIGURE IV-27

Critical Heat Flux Correlation

SG22 Cycle 4 Axial Indications 100% Power TCold = 565°F No Mods



S = STRAIGHT, B = BEND, H = HORIZONTAL

FIGURE IV-28

HEATFLUX

100% POWER

Tcold = 555 deg F

As Designed PVNGS Steam Generator

CRITICAL QUALITY >= .65

CRITICAL DEPOSIT PARAMETER >= 180

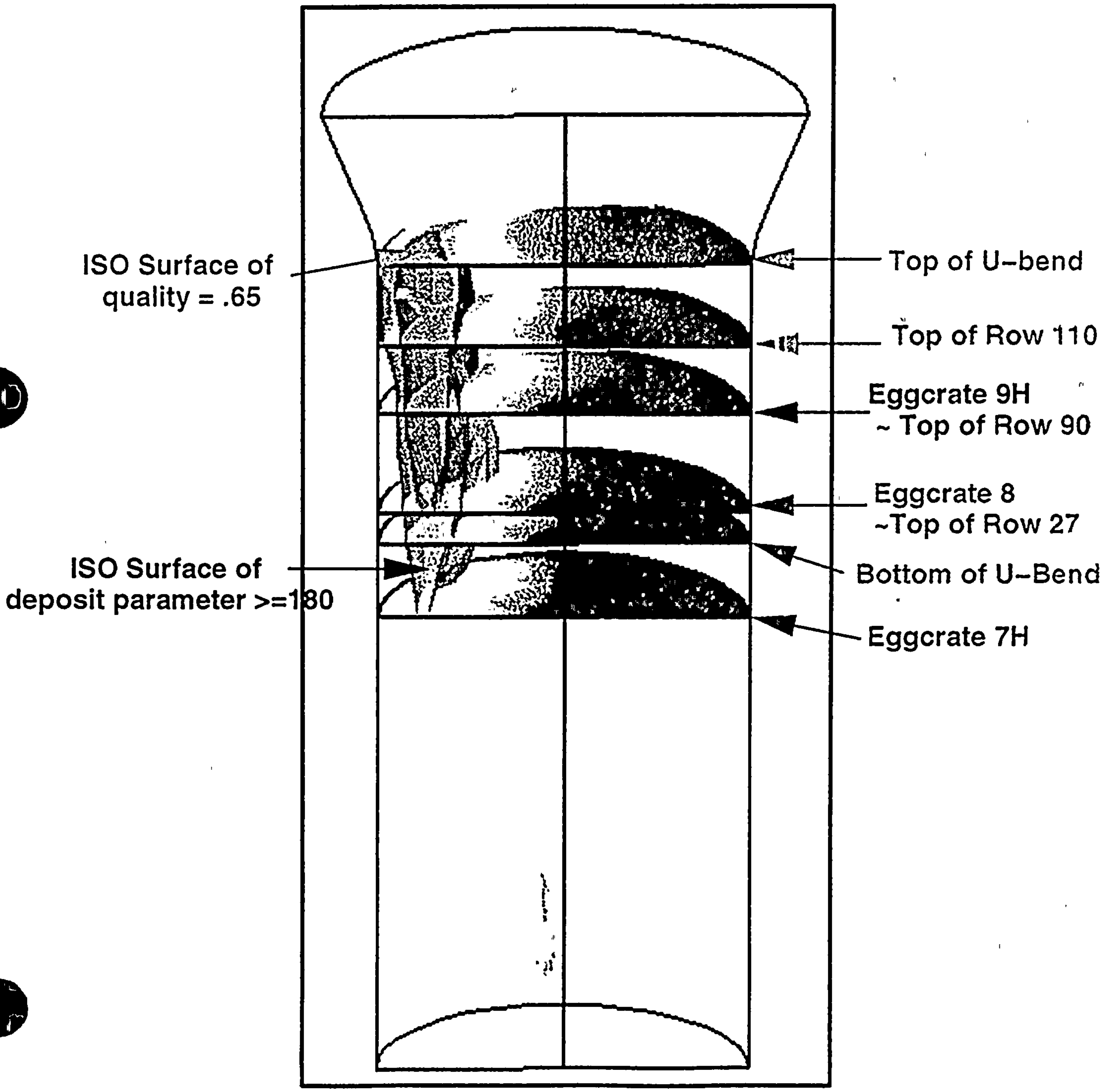


Figure IV-29

100% POWER

Tcold = 555 deg F

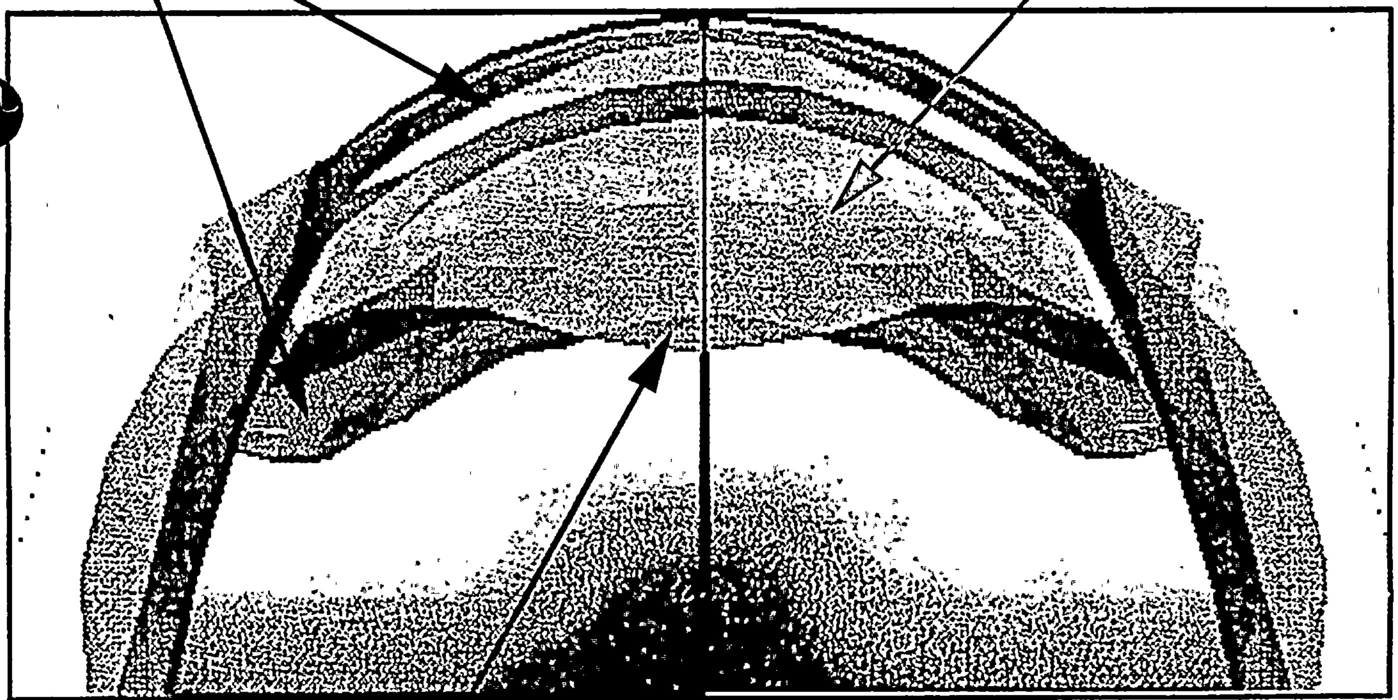
As Designed PVNGS Steam Generator

MAX CONTOUR OF CRITICAL QUALITY >= .65
occurs between 09H and top of U-bend

MAX CONTOUR OF CRITICAL DEPOSIT PARAMETER >= 180
occurs between 08H and 09H

Iso surface of deposit parameter >= 180

Iso surface of quality >= .65



overlap occurs from 09H to top of U-bend

Figure IV-30

Feedring Extension to Hot Leg

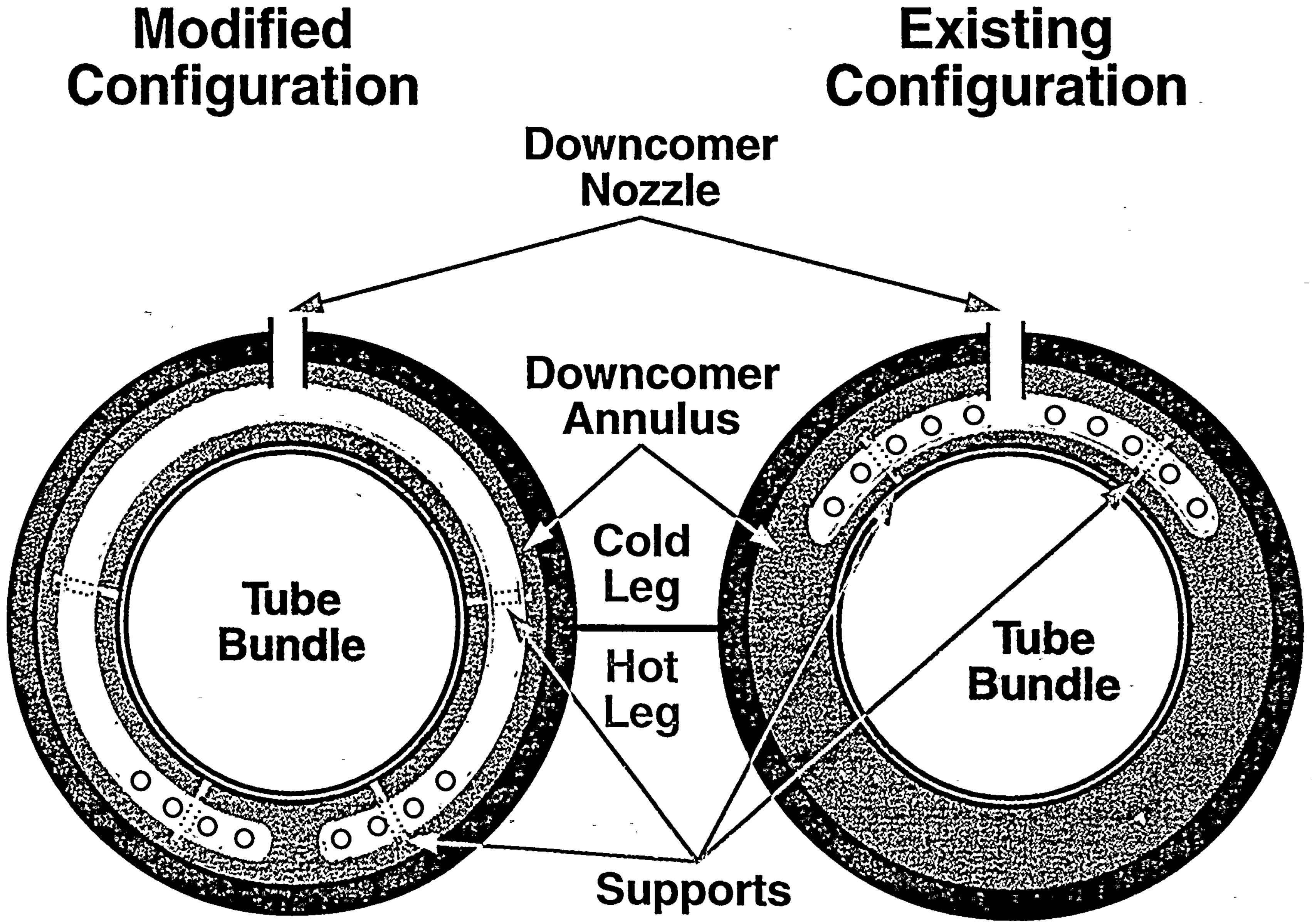
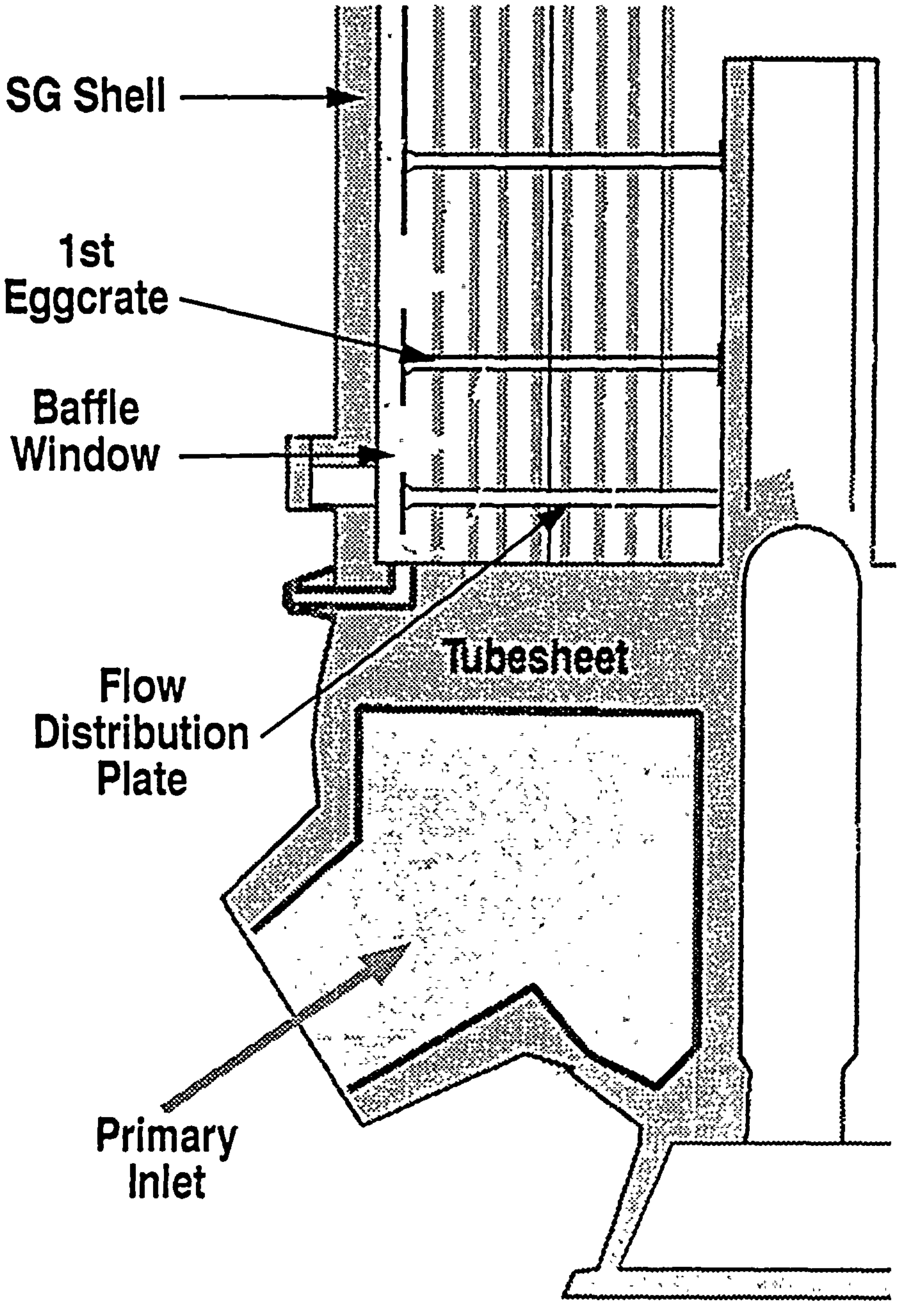


FIGURE IV-31

FEEDRING

Flow Distribution Plate Bypass Holes



MCO-3

FIGURE IV-32

Comparison of Packer and APTECH RG 1.121 Model Results

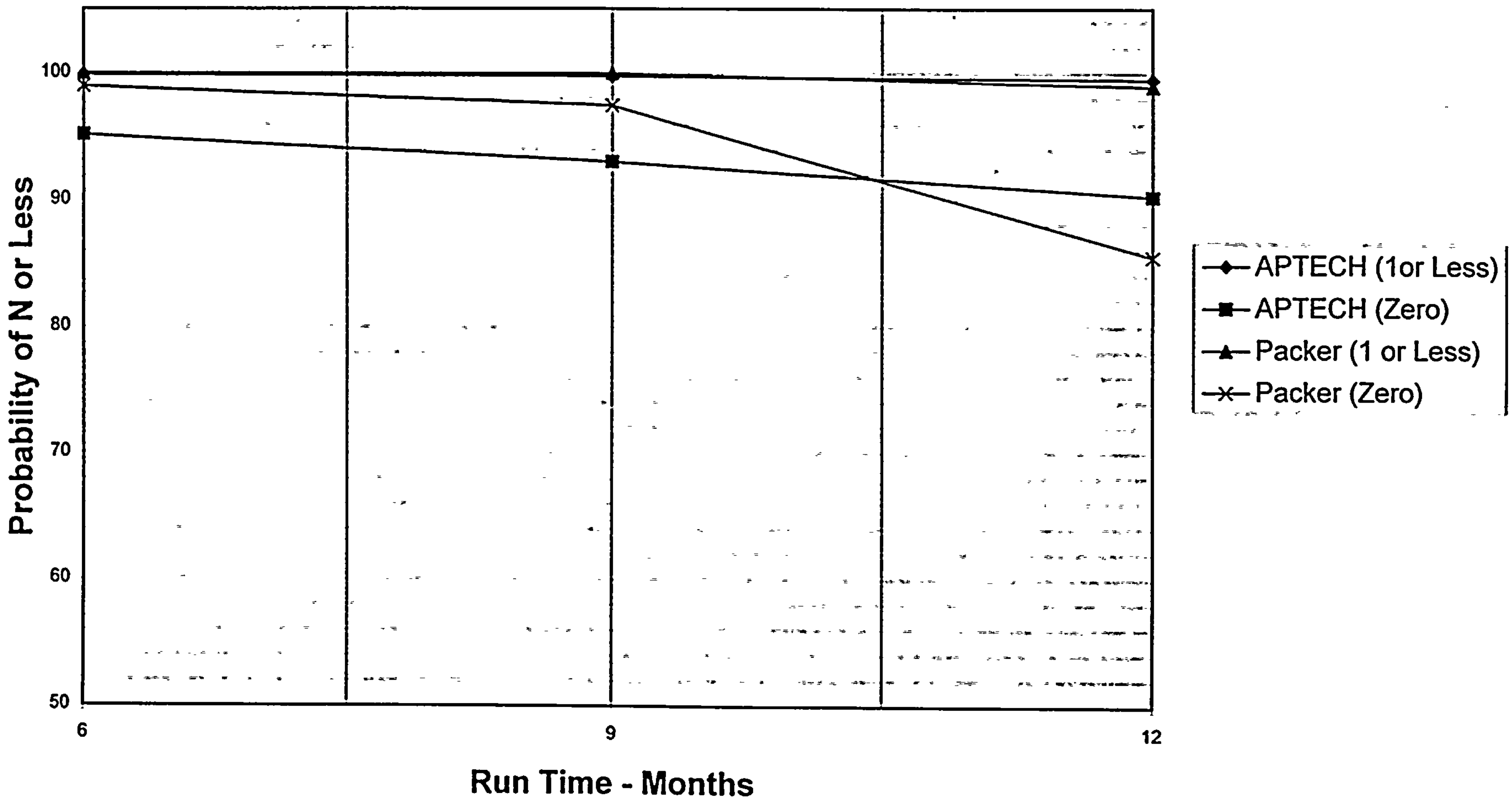


FIGURE V-1

Effect of Improved Inspection on Chance of Zero Reg. Guide Exceedances through April 1996 Inspection of PVNGS Unit 2

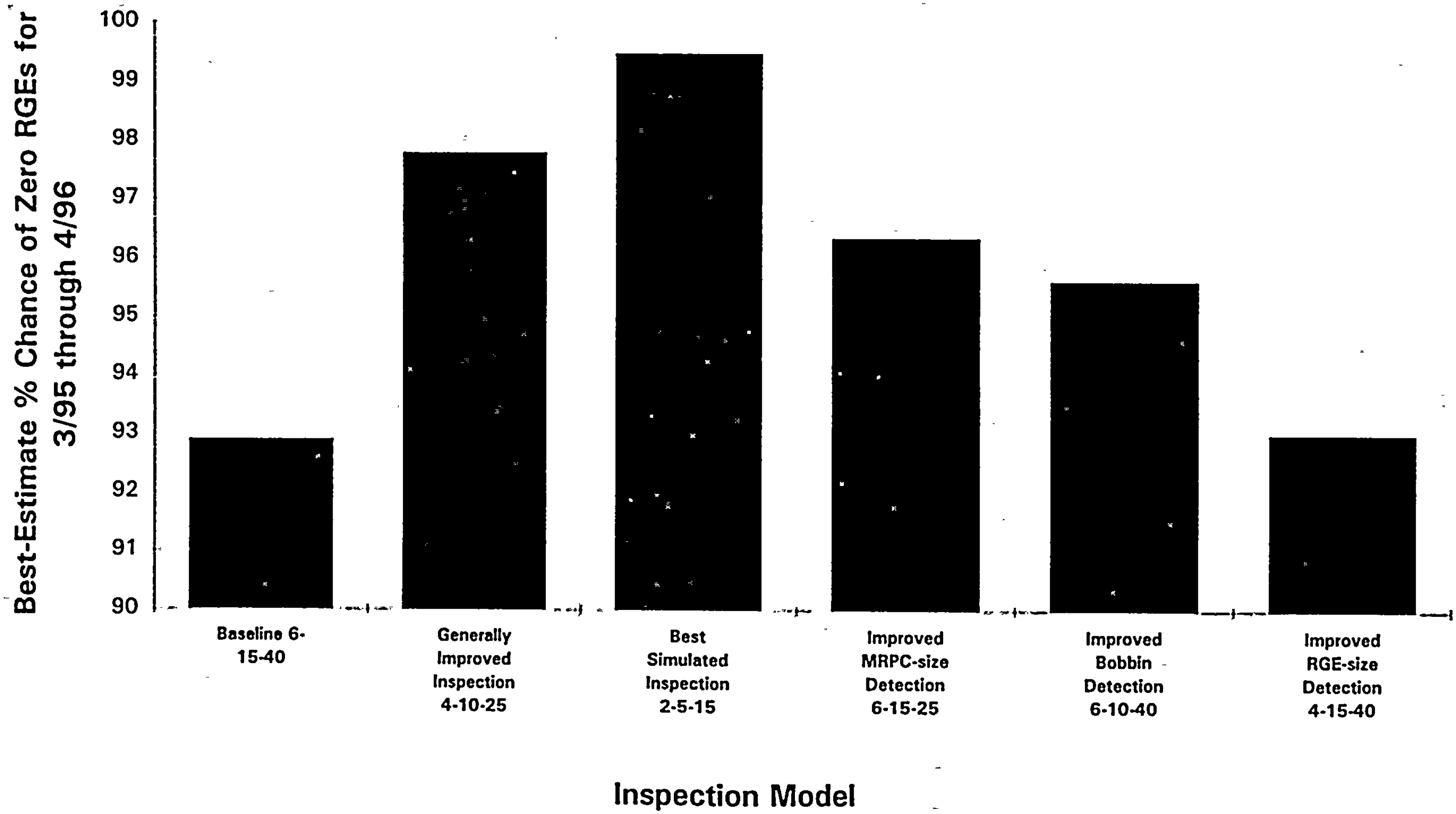


FIGURE V-2

Effect of Reducing Sample Size of ALL Past and Future MRPC Inspections on the Percent Chance of Zero Reg. Guide Exceedances through April 1996 Inspection of Unit 2

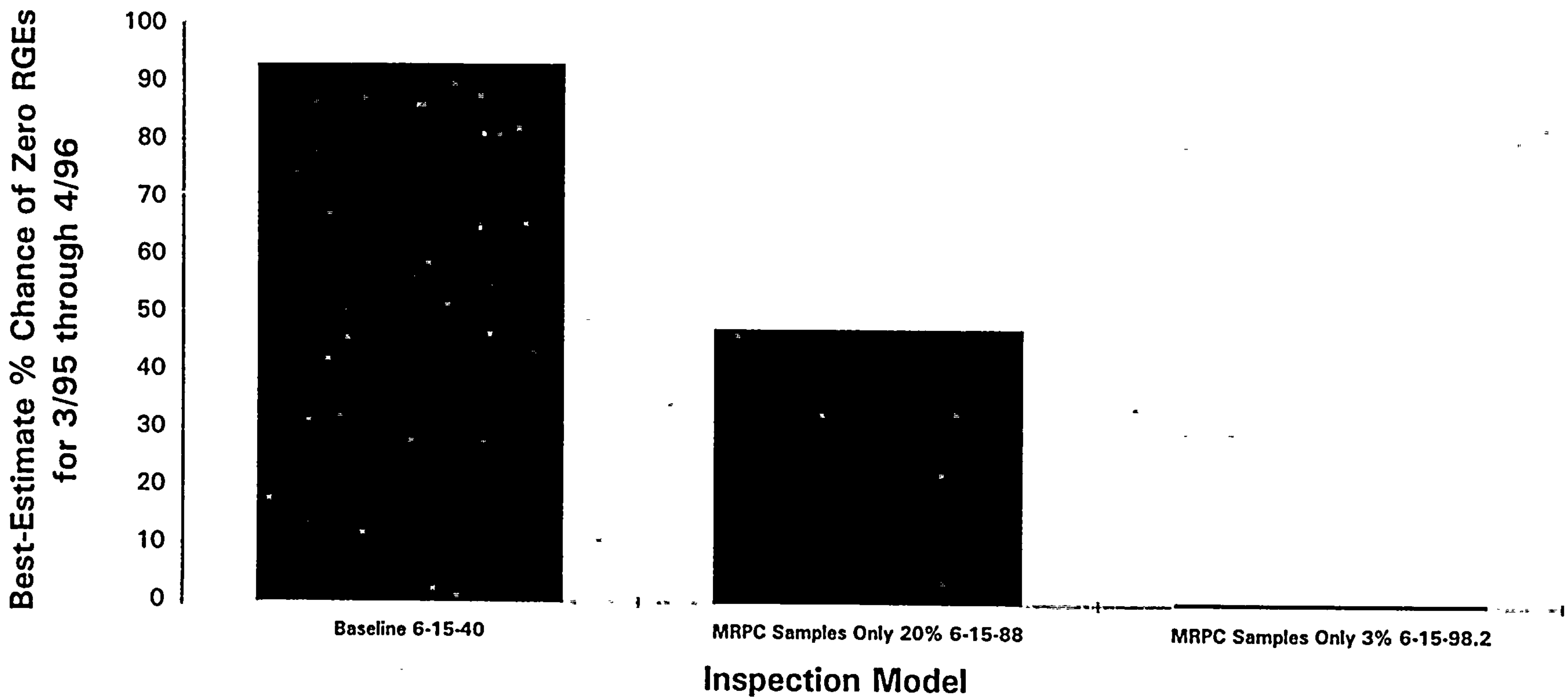


FIGURE V-3

Effect of Inspections to Reduce Reg. Guide 1.121 Exceedances in SG 22 (linear scale)

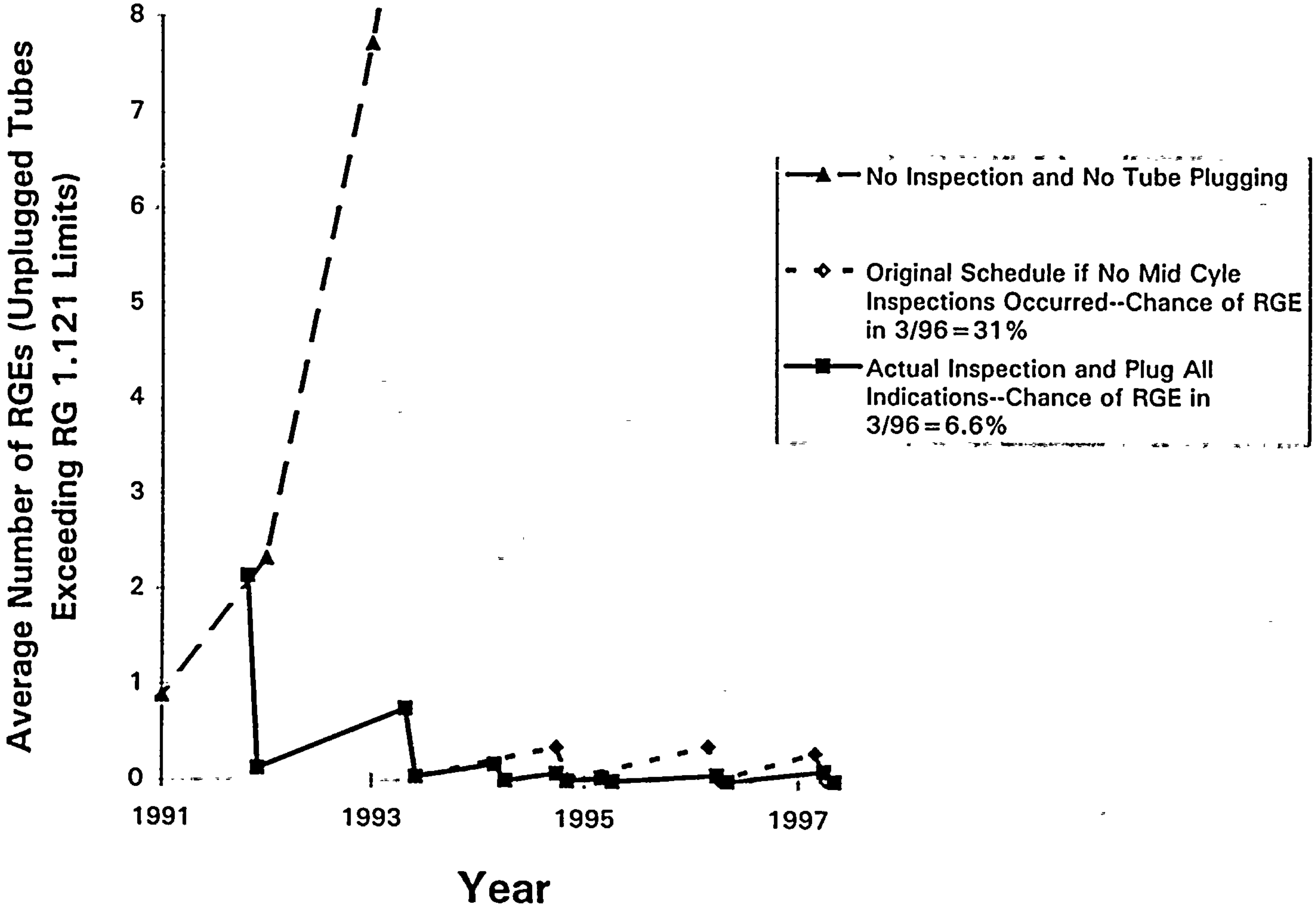


FIGURE V-4

Effect of Inspections to Reduce Reg. Guide 1.121 Exceedances in SG 22 (log scale)

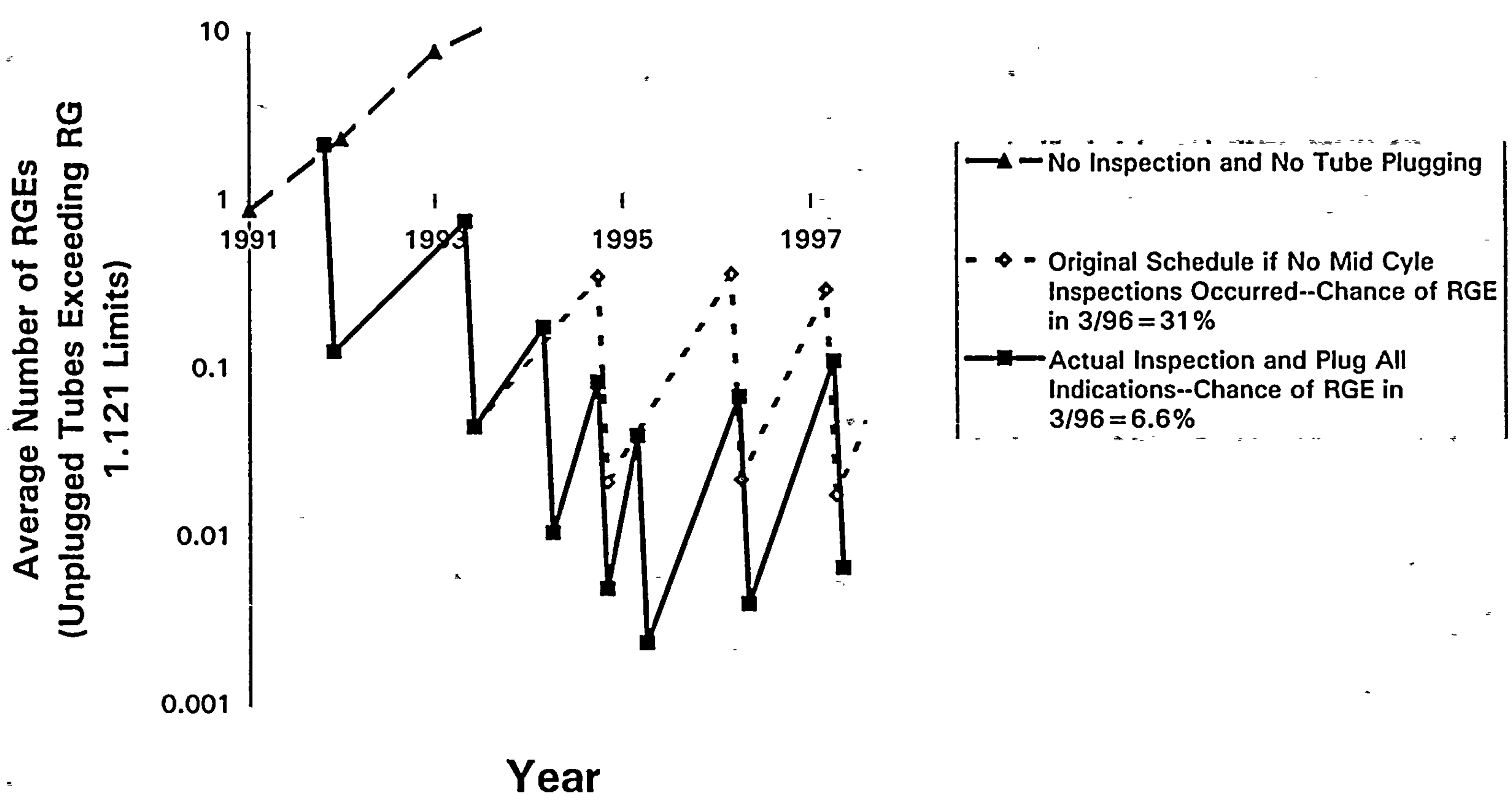
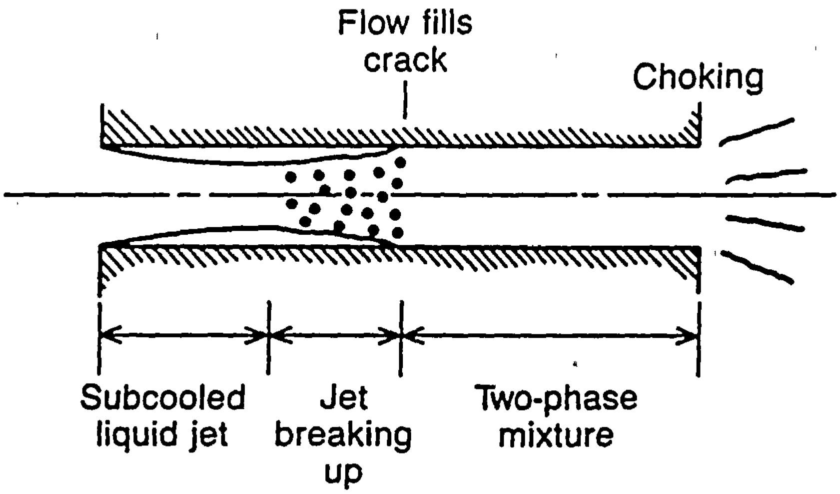
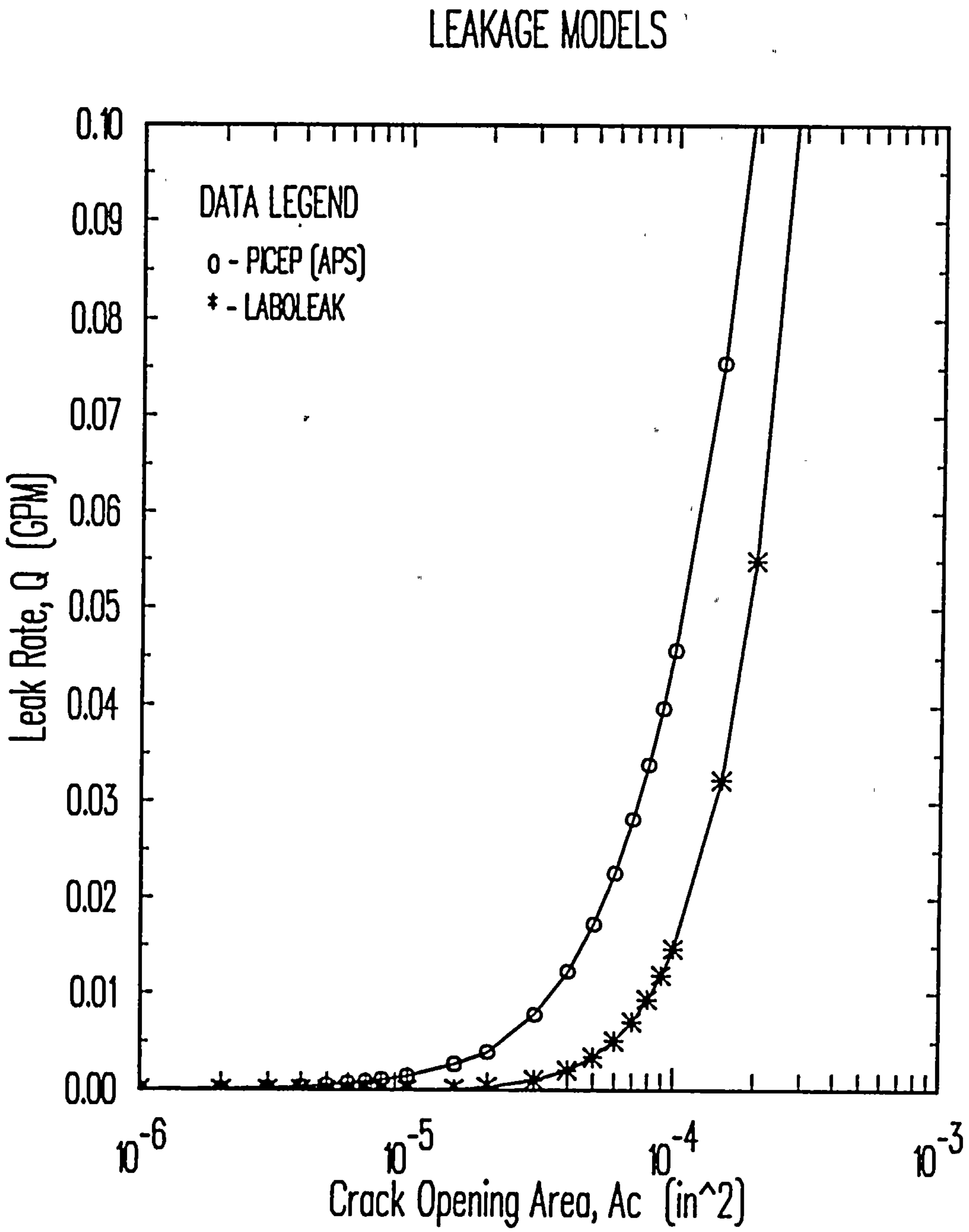


FIGURE V-5



Two-Phase Flow Through a Long, Narrow Crack

Figure V-6



LEAKAGE MODELS
DATA LEGEND
o - PICEP (APS)
* - LABOLEAK
Leak Rate, Q (GPM)
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
10^-6
10^-5
10^-4
10^-3
Crack Opening Area, Ac (in^2)

Figure V-7

CRACK OPENING AREA MODELS

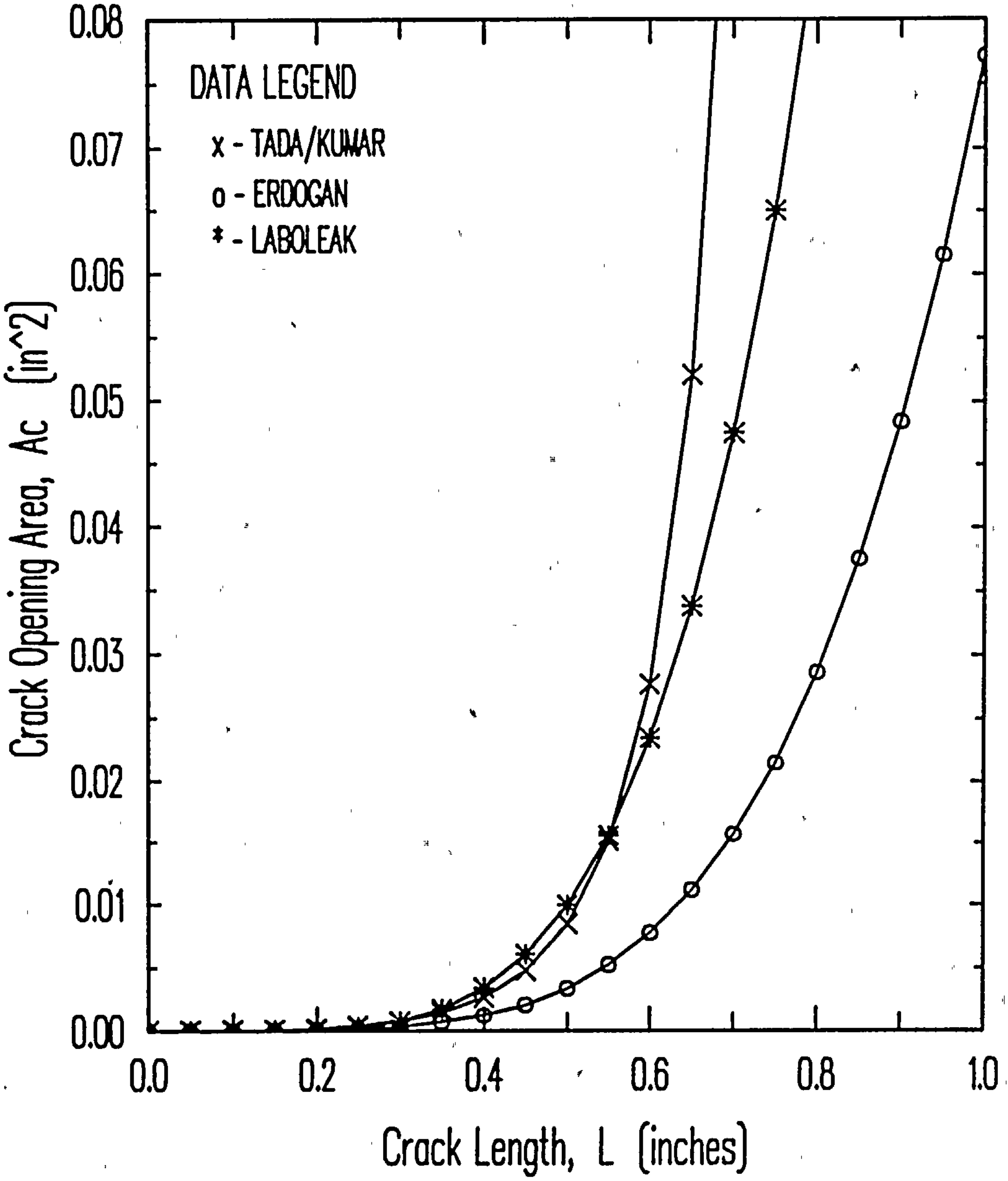
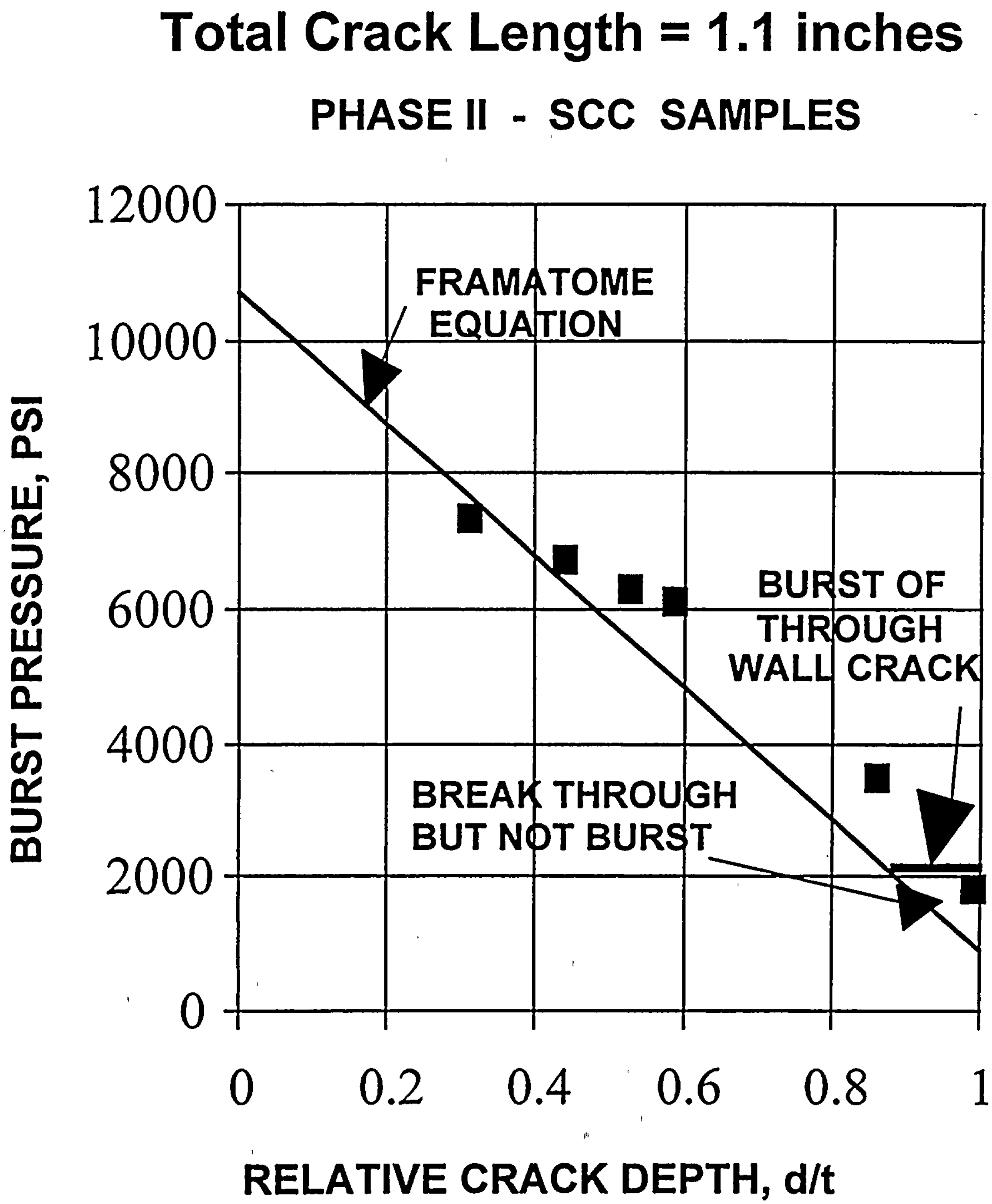


Figure V-8



BURST PRESSURE VERSUS RELATIVE CRACK DEPTH. THE REGION OF ONSET OF LOCAL BREAK THROUGH BUT NOT BURST IS ILLUSTRATED

FIGURE V-9

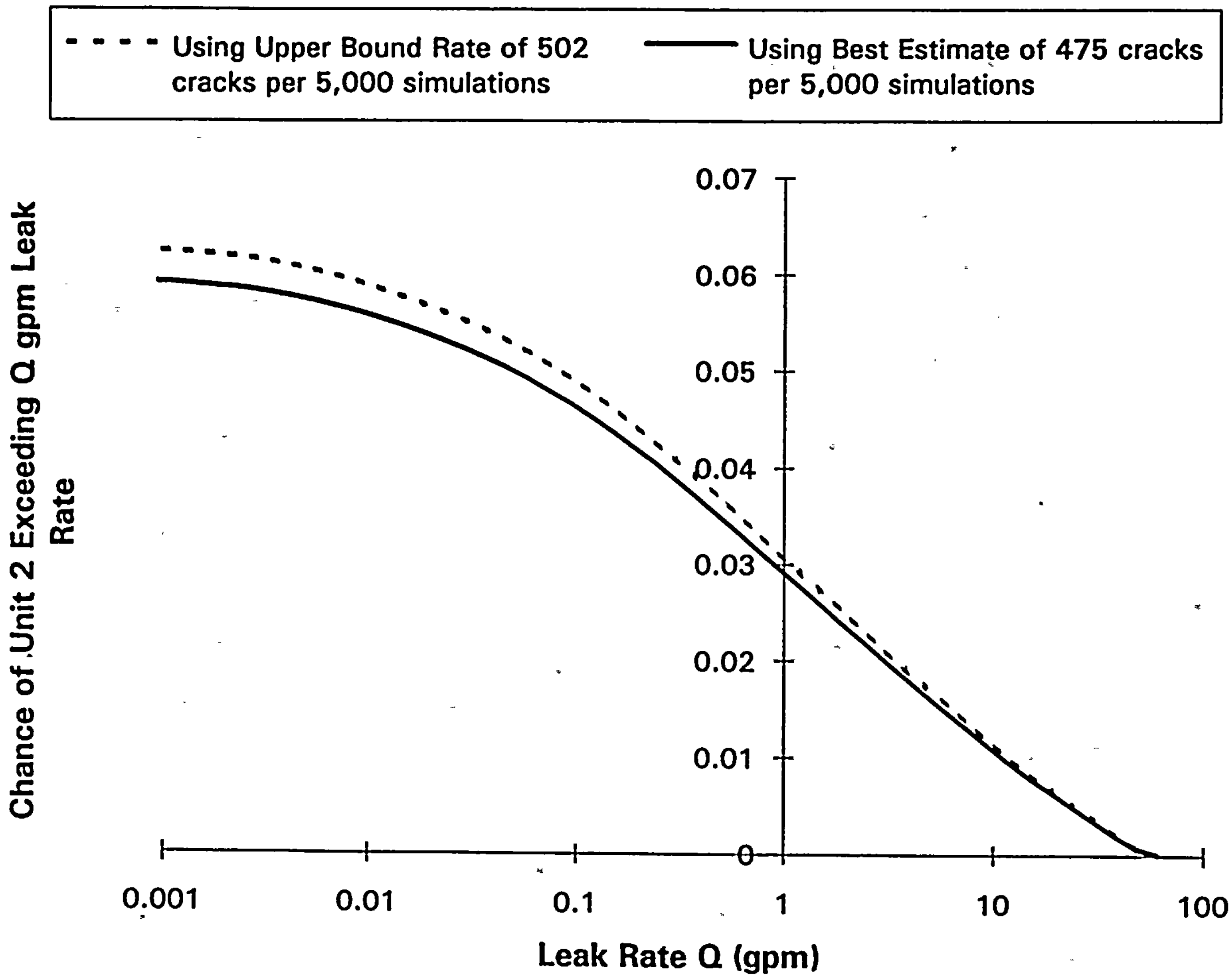
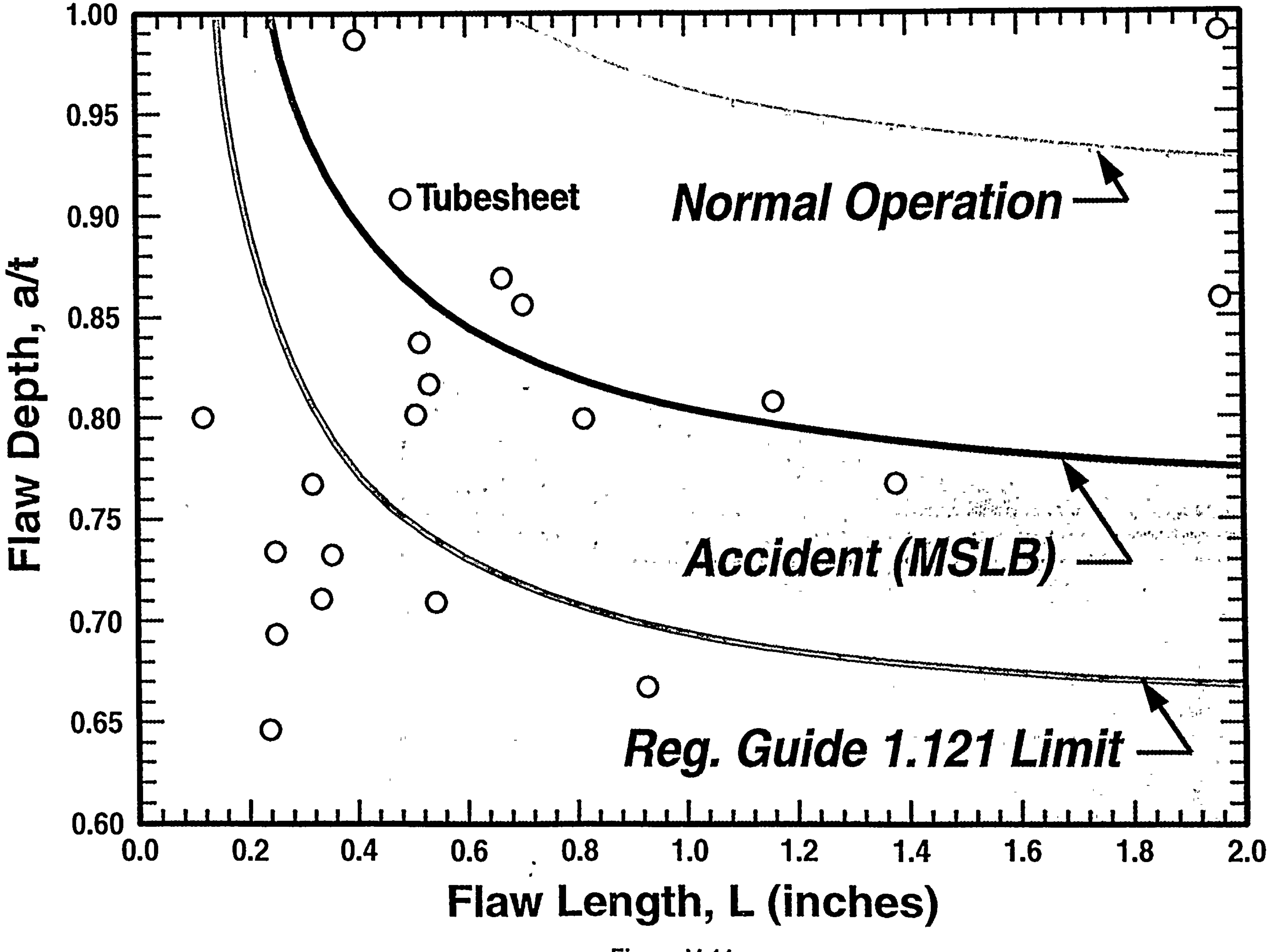

Using Upper Bound Rate of 502 cracks per 5,000 simulations
Using Best Estimate of 475 cracks per 5,000 simulations
Chance of Unit 2 Exceeding Q gpm Leak Rate
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0.001
0.01
0.1
1
10
100
Leak Rate Q (gpm)

Figure V-10

Axial Flaw Size Evaluation



7/23/93
AXIAL-1

Figure V-11

APTECH POD Analysis of Average Depth MRPC POD Data

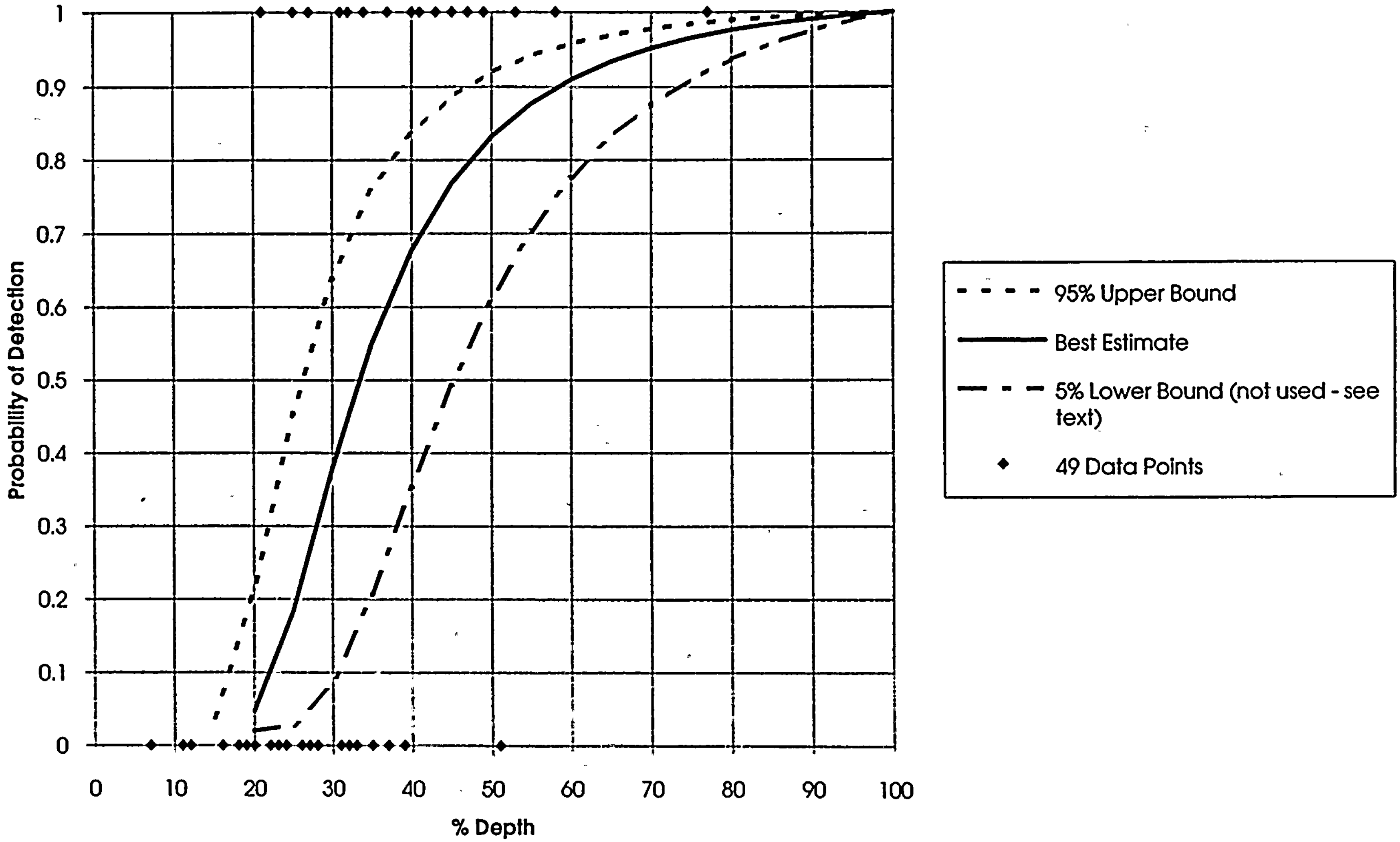


FIGURE V-12

Leak Locations Input For ATHOS N-16 Calculation

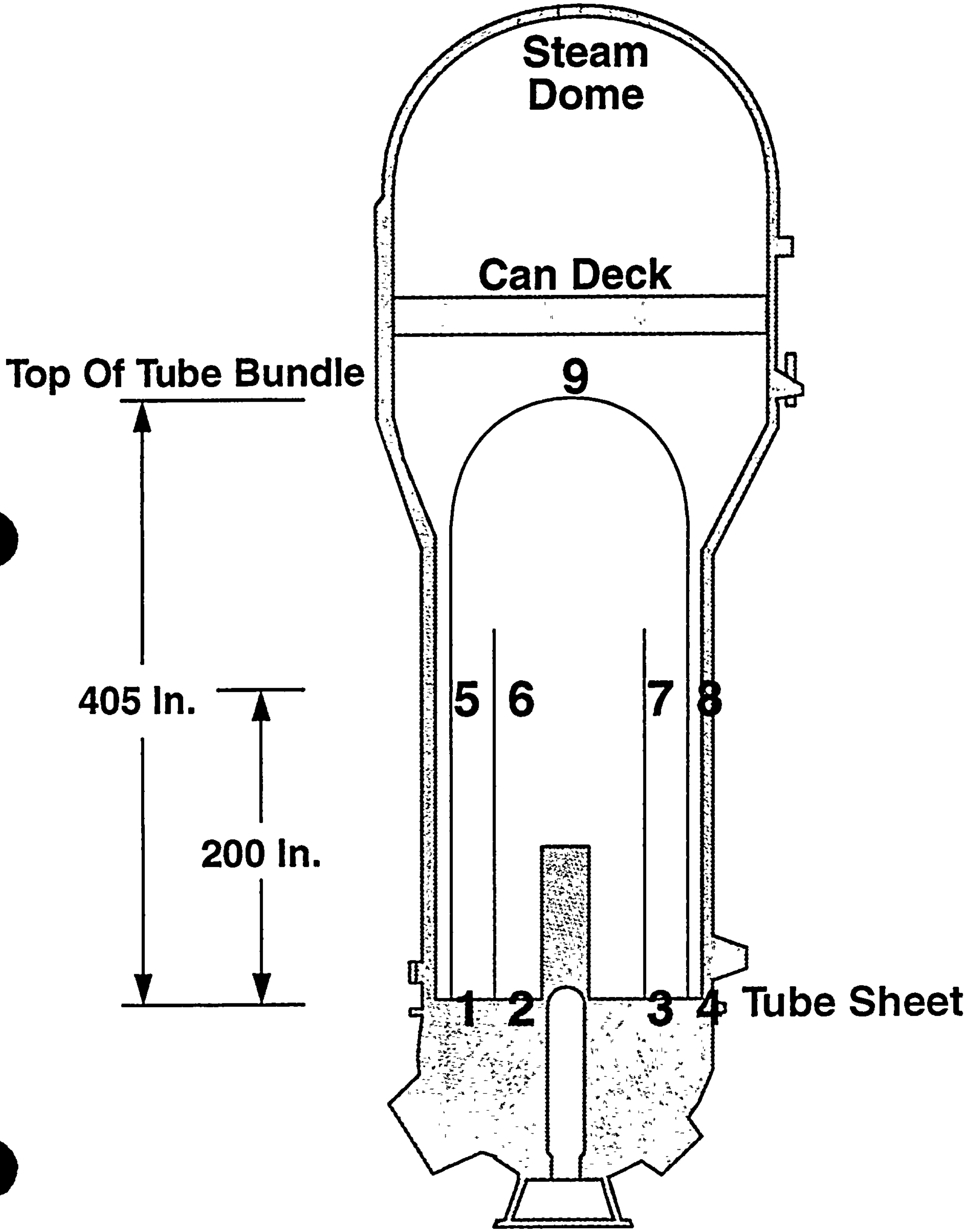


FIGURE VII-1

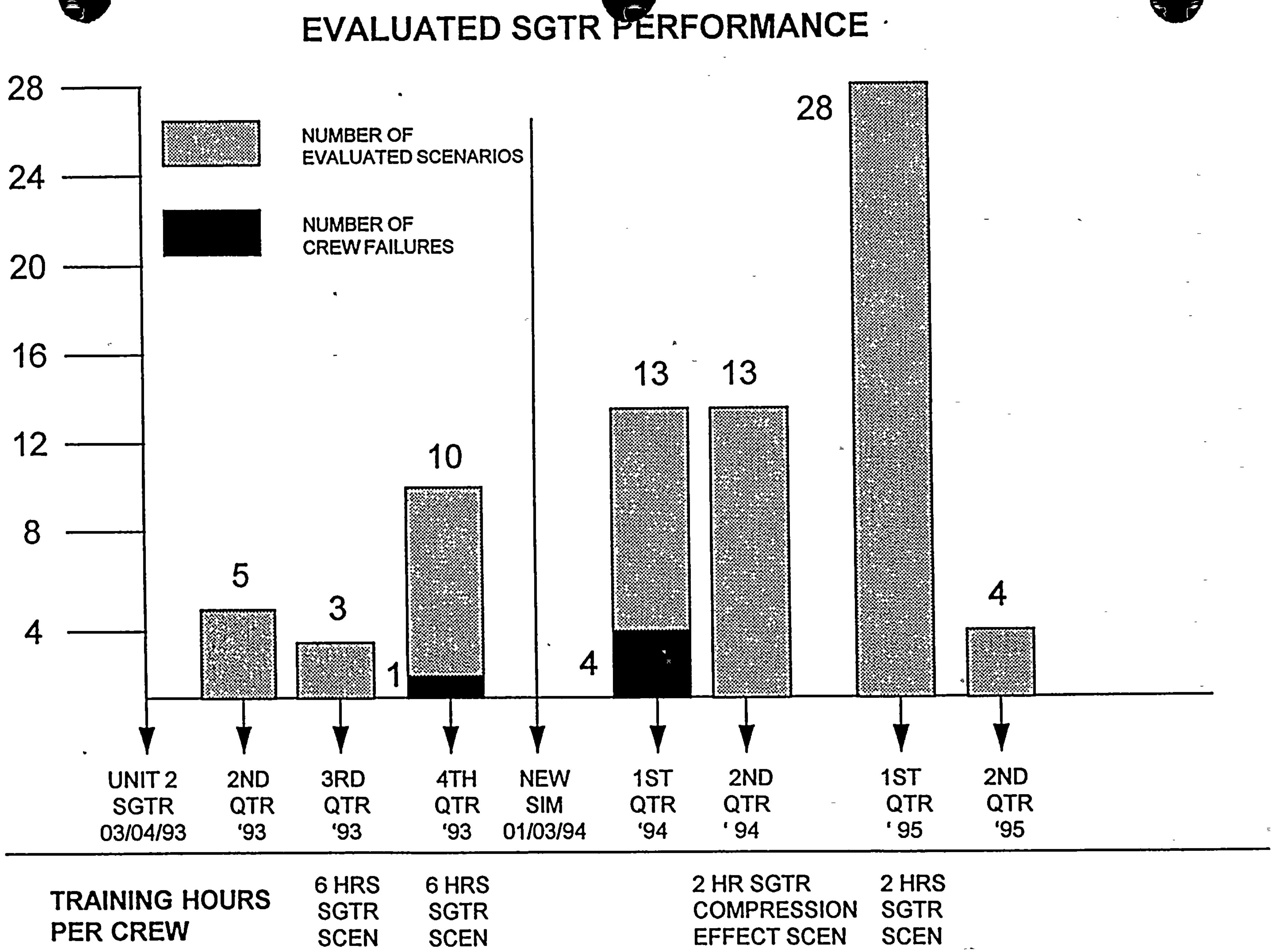

EVALUATED SGTR PERFORMANCE
28
24
20
16
12
8
4
NUMBER OF EVALUATED SCENARIOS
NUMBER OF CREW FAILURES
5
3
1
10
4
13
13
28
4
UNIT 2 SGTR 03/04/93
2ND QTR '93
3RD QTR '93
4TH QTR '93
NEW SIM 01/03/94
1ST QTR '94
2ND QTR ' 94
1ST QTR ' 95
2ND QTR '95
TRAINING HOURS PER CREW
6 HRS SGTR SCEN
6 HRS SGTR SCEN
2 HR SGTR COMPRESSION EFFECT SCEN
2 HRS SGTR SCEN

Figure V11-2

APPENDIX A

Palo Verde Unit - 2
Steam Generator Tube
Regulatory Analysis
For
Axial Cracking

Packer Engineering

PALO VERDE UNIT-2 STEAM GENERATOR TUBE REGULATORY ANALYSIS FOR AXIAL CRACKING

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1.0 INTRODUCTION

An eddy current inspection of steam generator tubing of Unit 2 at the Palo Verde Nuclear Generating Station was conducted in the first quarter of 1995. As expected, eddy current indications show an ongoing process of corrosion degradation in the upper bundle region. Previous tube pull results have identified this degradation as secondary side, axial , IGA/IGSCC[1,2,3]. This report describes an analysis of the probability of axial ODSCC/IGA in the upper bundle of Unit 2 leading to the exceedance of Regulatory Guide 1.121 structural limits as a function of run time during the current period of operation, Cycle 6. The analysis models the historical development of cracks, including, crack initiation, crack growth, detection of cracks and subsequent removal from service. Initiation and growth of new cracks during a given cycle of operation is included as is the population of cracks which have not been detected by eddy current inspections.

The calculational framework is essentially the same as that used in previous analyses of the issue of upper bundle, axial, ODSCC/IGA and the associated question of the probability of observing corrosion degradation which may exceed required structural margins[4,5]. However, recent analytical refinements, as well as those which have been added over the past two years, make the present simulation model considerably more sophisticated than any versions used previously.

Past refinements to calculational procedures have included:

1. The length and depth profiles of cracks in tubes pulled from Unit 2 have been analyzed to identify the critical regions of these profiles relative to burst pressures. Structurally significant crack lengths and structurally significant crack depths have been defined. Structurally significant crack lengths have been correlated to crack lengths determined from eddy current RPC data. Average crack depths over structurally significant crack lengths have been determined and correlated with MRPC eddy current probe voltage readings.
2. Computer modelling of the response of eddy current pancake coil probes to cracks in thin plates has shown the practicality of estimating crack depths from voltage readings in limited but useful circumstances.
3. RPC probe voltage changes have been analyzed to estimate crack growth rate distributions. Variations in the correlation of voltage with structurally significant depth have been included to reflect effects of variable crack morphology.
4. The overall simulation model was benchmarked with respect to observations of the number of NDE indications versus Unit 3 run time.
5. Predictions of the extent of through wall cracking have been added to allow calculation of leakage rates under accident conditions.

Recent refinements to the simulation model have been just as extensive. These have included:

1. Crack initiation parameters has been optimized relative to observations of eddy current indications throughout the history of Unit 2. Sensitivity studies have shown that it is possible to determine reasonably constant crack initiation parameters from the statistics of eddy current indications.
2. A probability of detection curve has been calculated for the Plus Point eddy current probe from observed inspection transients caused by its use in the Cycle 5 inspection.
3. Three different statistical procedures have been used to determine degradation growth rate parameters. Agreement is excellent. Crack morphology effects, uncertainty in voltage measurements and extreme values in voltage growth have been included.
4. Mechanical breakthrough effects have been specifically treated in calculations of through wall cracks lengths for input to leakage computations.
5. In addition to benchmarking of the simulation model relative to the history of the number and severity of eddy current indications, the probability of tube burst during normal operation at the end of Cycle 4 was examined. In agreement with past experience, the model correctly predicts a high probability of tube burst as well as the presence of several severely degraded tubes.

The present probabilistic model of upper bundle corrosion degradation of Unit 2 is highly refined and well benchmarked. It can be used with confidence to predict the effects of corrosion degradation on the structural integrity of steam generator tubing as a function of run time. This has been done for the current Cycle 6. After 12 months of operation, the probability of more than one exceedance of Regulatory Guide 1.121 would be less than 0.01. At this same point in time, the conditional probability of tube burst given the occurrence of a main steam line break is 0.018. These values contain significant elements of conservatism and yet remain within the bounds of historically acceptable risk. With regard to leakage, there is less than a 10% chance of any wall penetration if a steam line break occurs after 12 months of operation.

2.0 BACKGROUND

Eddy current inspections have revealed axial indications of cracking on the outer diameter of steam generator tubing in upper bundle regions of all units at the Palo Verde Nuclear Generating Station[6]. The regions where upper bundle indications are observed are similar. These indications are essentially confined to an arc region of high mass flow and high quality where film boiling and dryout is indicated. Deposit formation and concentration of chemical species are favored under such conditions. Although the operating histories of all units are similar, upper bundle corrosion degradation is most severe in Unit 2 by a very wide margin.

Examination of tubes pulled from Unit 2 has shown the NDE indications to correspond to corrosion degradation on the outer diameter of the tubing. Intergranular stress corrosion cracking (IGSCC) is the principle mode of degradation with some component of intergranular attack[1,2,3] (IGA). In some areas, the nature of the IGA is equivalent to what has been termed intergranular cellular corrosion. A comparison of pulled tube examination results from U2R4 and U2M5-1 indicates a more pronounced cellular corrosion/IGA character to the degradation observed in the most recent pulled tubes[2]. Upper bundle corrosion degradation is observed in the vicinity of eggcrate, batwing and vertical strap support structures and in apparently freespan locations. Cracking at apparently freespan locations is often associated with the presence of long, narrow ridge deposits which may bridge neighboring tubes. Bridging/ridge deposits are envisioned to act as crevice sites, with an ability to lead to concentrated, aggressive chemical environments. There is evidence that easily noticeable bridging/ridge deposits may not be a necessary condition for the onset of upper bundle corrosion degradation.

Root cause evaluations indicate upper bundle corrosion degradation to be related to caustic/alkaline environments in crevices and under significant tube deposits. Sulfur species, surface distress on the tubing OD and less than favorable Alloy 600 microstructures are indicated as contributing factors to the onset of degradation[1-6]. As upper bundle corrosion degradation in Unit 2 continues to lead the extent of upper bundle degradation in Units 1 and 3 by wide margins, the scenario of a resin intrusion in Unit 2 as a significant initiating event gains credence. Work is in progress to use the insights of a simulation model to examine this and other scenarios of degradation and remedial actions.

3.0 STRUCTURAL CONSIDERATIONS

The effect of axial, upper bundle corrosion degradation on the burst pressure of steam generator tubing of PVNGS steam generators can be evaluated by treating the degradation as a single, dominant, partial through wall crack. Because of the high toughness of Alloy 600, the onset of plastic collapse essentially determines the burst pressure. A number of approaches are available to calculate the plastic collapse point of internally pressurized thin walled tubing containing axial partial through wall cracks or slots[7-12]. These methods range from finite element studies to empirical equations. Most give very similar plastic collapse pressures. Often the crack shape is idealized to be a rectangle. Hence the crack depth is constant. Observed crack depth versus length profiles created by ODSCC/IGA exhibit substantial variation. Burst tests of pulled tubes have been analyzed in the past by averaging the crack depth over the crack length exposed in the burst test. Figure 3.1 shows a plot of burst pressure predicted using the Framatome equation[9] versus measured burst pressure. The closed symbols are based on the crack depth averaged over the crack length exposed by the burst test.

The crack length exposed in the burst test is usually a reasonable indicator of the structurally significant crack length. However, this is not always the case. For an arbitrary crack profile there is some segment which determines the burst pressure. The limiting crack segment can be found by systematically computing the burst pressure as a function of crack segment length and the crack depth averaged over that length. A short crack length may have a high average depth but this is balanced by the short length. If a very long length is considered, the average crack depth will be minimized and lead to a high predicted burst pressure. There is some crack section where the length and average depth over this length lead to a minimum predicted burst pressure. Hence some section of the crack profile is the critical section. The length of this section is termed the structurally significant length and the depth averaged over this length is the structurally significant depth.

Figure 3.2 illustrates a systematic evaluation of burst pressure over an idealized profile of a crack. The chosen profile is symmetric and obviously some central section of the crack will exhibit a minimum burst pressure. Figure 3.2(b) shows a plot of calculated pressures as average crack depth is computed over central sections of the crack of increasing length. The critical section of the profile and associated structurally significant depth is shown in Figure 3.2(a). When crack profiles are not symmetric relative to their axial midpoint, the selection of a critical section or even the point to begin calculations is not at all obvious. A short computer program is then used to find the minimum calculated burst pressure and the critical section of the crack profile. The open symbols in Figure 3.2 show that

when the structural minimum method is applied to actual crack profiles, the Framatome equation[9] is a very conservative predictor of the burst pressure.

In a previous report, it was shown that plots of average depth versus maximum crack depth from burst face crack profiles of pulled tubes indicated crack shapes between a triangle and a semi-ellipse[4]. The solid symbols of Figure 3.3 reproduce this plot. If structurally significant crack depths are plotted versus maximum depth, then, as shown by the open symbols, the structurally significant crack shapes are basically semi-ellipses.

Lengths of corrosion degradation are routinely obtained from MRPC inspection results. However, because the eddy current RPC probe does not detect shallow cracking, the actual physical extent of cracking may substantially exceed the length detected by the RPC probe. In Figure 3.4, where RPC lengths are plotted versus structurally significant crack lengths, it is seen that the RPC eddy current results provide an excellent indication of the structurally significant crack lengths. This shows that shallow cracking at the ends of crack profiles, which is not detected by the RPC probe, is not a consequential factor in the burst pressure.

Figure 3.4 also shows that RPC crack length data can be used to construct a distribution of end of cycle crack lengths for use in Monte-Carlo simulations. The mean and variance of the RPC crack length distribution both exceed the respective parameters for the structurally significant crack depths. Although there are individual instances where the RPC crack length is slightly less than the directly corresponding structurally significant crack length, sampling from the RPC crack length distribution provides a conservative estimate of the crack lengths in service. Since no known cracks are left in service, there is no need to adjust an individual crack length to cover the possibility that it may be under sized. An additional element of conservatism, which is far more dramatic, is the fact that the crack length distribution used in the present Monte-Carlo calculations is based on the crack length distribution obtained from U2R5 eddy current inspection data. This crack length data is substantially influenced by the Plus Point probe results. Hence, it is biased toward longer crack lengths.

From the above, it is evident that determination of structurally significant crack lengths and depths will provide a good means of computing burst pressures and thus evaluating whether or not Regulatory Guide 1.121 structural requirements are satisfied. MRPC data provides a means to characterize structurally significant crack lengths in a conservative fashion. End of cycle crack length distributions are very similar from cycle to cycle. As noted above, the influence of the more sensitive

Plus Point probe has biased the present crack length distribution used for sampling toward longer lengths.

Given a structurally significant crack length, the question of structurally significant crack depth remains. However, since no detected cracks are left in service, the problem is not to accurately or conservatively size each indication. The problem is to develop a technique to characterize the distribution of crack growth rates from available eddy current inspection data. This is the required input to the simulation model. The beginning of cycle distribution of crack depths and lengths is determined from the crack initiation, growth and the probability of detection of cracks via eddy current inspections.

In principal, the phase angle of the impedance plane lissajous figure formed as the RPC probe passes over the crack should provide a good correlation with crack depth. Unfortunately, analysis of U2R4 pulled data indicated significant difficulty in the determination of phase angles. An empirical correlation of RPC voltage with crack depth proved to be more successful and has been pursued since that time. Recently, the issue of crack profiles determined from RPC phase angles has been revisited. This ongoing work is described in later paragraphs.

The field of view of an RPC probe is on the order of several times the probe diameter. Hence the RPC probe, either in terms of phase angle or impedance change will respond only to a segment of the crack. A 0.115 inch diameter coil will respond to the nearest 0.2 to 0.4 inch length of crack segment. Figures 3.5 and 3.6 illustrate some computed responses of a pancake coil to cracks in a 0.043 inch thick Alloy 600 plate. The commercial analysis software[13] uses a volume integral approach to solving the electromagnetic field equations needed to compute the probe response. Figure 3.5 shows coil impedance change as a function of probe position relative to through wall, straightsided cracks. When the crack length is on the order of the probe diameter, one observes essentially the impulse response of the probe. When the crack length is several times the probe diameter, the impedance change of the coil as it sits directly over the crack is little influenced by the crack length. The plotted impedance change is the vertical magnitude of the impedance plane plot. This would correspond to reported maximum vertical RPC voltages.

When the length of the crack in the thin Alloy 600 plate is held constant at 0.60 inches, the impedance change of the probe as the crack depth changes is illustrated in Figure 3.6. The largest variation in impedance changes occurs as the crack penetrates the wall from a depth of 80%. However, systematic impedance changes with crack depth occur in the range of interest, 40% to 80%. While

impedance changes are brought about by a number of crack geometry changes, Figures 3.5 and 3.6 illustrate that it is reasonable to attempt an empirical correlation of RPC voltage with crack depth in a restricted set of circumstances. Structurally significant cracks are several times longer than the RPC probe diameter. It is reasonable to attempt to identify the average depth of the central region of such cracks with an RPC voltage. Again, it should be noted that the objective is not to accurately size all indications but to develop a vehicle to use inspection data to arrive at a reasonable distribution of crack growth rates.

Figure 3.7 shows a plot of structurally significant crack depth versus RPC voltage. All data is from pulled tubes from Unit 2. The voltages are the reported field voltages. The fit to the data is not affected by the extreme point marked 127-140-13. The crack profile for this tube section is shown in Figure 3.8. It is somewhat unusual. There is a short deep section in an otherwise shallow profile. There is a goodly amount of scatter in the line fit. However this data can be used to provide a good description of an average crack growth rate and the likely dispersion of crack growth rates about this average. This procedure as well as other approaches to evaluating degradation growth rate distributions are described in the next section.

The approach chosen to characterize the structural integrity of tubing is to use Monte-Carlo simulation of the physical processes of crack initiation, growth, detection via eddy current inspection, and removal from service. Obviously, other approaches are available. For example, burst strength can be empirically correlated with some combination of RPC voltage and RPC crack length. Correlations of this type have been developed and examined. However, the end result is basically trading less uncertainty in one area for more uncertainty in another. In a simple case, if one correlates burst pressure with RPC voltage, the past history of end of cycle voltage observations leads to confidence in the prediction of future end of cycle distributions of voltages. Less uncertainty in this area, which corresponds to the physical processes of crack initiation, growth and inspection, is offset by more uncertainty in the correlation of voltage with burst pressure. Conversely, high confidence in the prediction of burst pressures from given crack lengths and depths is offset by more uncertainty in crack growth rates derived from RPC voltage measurements. A key feature limiting combined RPC voltage/RPC length burst pressure correlations is a pulled tube database which contains only one long length - high voltage - low burst pressure tube. Data from drilled support plate plants with ODSCC may be useful, but here maximum crack lengths are limited to about 0.75 inches[14]. There is no such limit on the distribution of crack lengths for the present case.

With regard to leakage calculations, the assumption of maintenance of a semi-elliptical crack shape but constant crack length as growth occurs in the depth direction is reasonable and consistent with the Monte-Carlo simulation model. Hence, following maximum crack depths in excess of the wall thickness permits calculation of the through wall crack lengths. There is some population of crack geometries where mechanical breakthrough may occur without leading to a full tube burst. That is the case for deep cracks whose total length is less than the critical through wall crack length for burst. The Framatome burst equation does not extrapolate to the true burst pressure for a through wall crack. This burst pressure is given by the EPRI equation[15], which has received a full industry review. For very deep cracks, the Framatome equation does correlate with the onset of local but not necessarily global fracture. Figure 3.9 shows a plot of burst pressure versus relative crack depth for steam generator tubes containing stress corrosion cracks approximately 1.1 inches in length. The data is taken from NUREG/CR-2336[8]. The test was terminated upon loss of the pressurizing medium. A full tube burst was not required to terminate the test. The Framatome equation together with the EPRI equation for burst pressure for through wall cracks provide a good definition of the combinations of crack lengths and depths where local breakthrough but not full burst will occur. At breakthrough, the through wall crack length is taken as equal to the total crack length and this is input to leak rate calculations.

As noted in previous paragraphs, substantial confounding variables exist in the correlation of crack depth with RPC voltage. Better methods of characterizing crack geometry are being developed as described in the following paragraphs. This effort meshes with new industry wide programs.

The ability to dimensionally profile discontinuities using rotating probe eddy current data represents a valuable tool in providing detailed data on growth dynamics and dimensional data e.g., length and depth, for structural integrity calculations. Profiling is accomplished by capturing the in-phase and quadrature signal components of rotating probe eddy current data from which two dimensional arrays ($X_{i,j}$, $Y_{i,j}$) are constructed for subsequent processing in a Packer Engineering developed signal processing toolbox. The matrix (i,j) dimensions correspond to the circumferential and axial directions respectively.

Figure 3.10 shows an eddy current rotating probe graphic for Tube R137L134 removed from Palo Verde Unit 2. Mix 1 vertical channel data are plotted showing a single axial indication riding atop an axial ridge deposit. The small cyclical variations in signal amplitude represents mix residual due to tube deposits on the tube outer diameter.

Two general approaches to dimensional profiling can be imagined. Axial profiling is the simplest and is accomplished by taking a slice of the data axially *through* the indication of interest; in matrix notation, this corresponds to scanning in the j direction. Figure 3.11(a) shows the vertical channel response through the indication of interest from which length estimates can be made by noting the indication start and end points. Crack length estimates are made by counting the total number of axial sample points and multiplying by the pitch of the eddy current rotating probe. For the example shown in the figure, the total number of sample points is 59 which when multiplied by the RPC pitch (0.30") gives a length of approximately 1.5 inches which compares with the length measured destructively of 1.9 inches. An *axial lissajous* is constructed using the matrix data by plotting the in-phase and quadrature signal components for i = 15, with j variable as shown in Figure 3.11(b) the trace which can then be converted to a depth estimate using a calibration standard. For the example considered in Figure 3.11(b), an angle of 76 degrees is measured which corresponds to a depth estimate of 55 percent through wall. The maximum depth measured by metallography was 47 percent through wall.

Circumferential profiling can provide greater detail with regards to crack characterization since depth information is provided at more than one sample point. Profiling is accomplished by measuring the angle of the impedance plane trajectory during each rotation of the probe *across* the discontinuity. At each axial sample point, a depth estimate is made using standard phase angle-versus-depth calibration procedures. Examples of circumferential impedance plane trajectories for two axial positions corresponding to j = 38 and j = 52 are shown in Figure 3.12. An axial depth profile is then constructed using the total number of sampled data values. Figure 3.13 shows the profile constructed for tube R137L134 from eddy current data and its comparison with metallographic data. For this example, the eddy current profile is conservative, overestimating on the average by approximately 10% through wall. Detailed information regarding crack growth dynamics, e.g., growth in length and depth, could be obtained by comparing profiles for the same indication from consecutive outages. Standarized procedures are being developed and will be applied to crack profile measurements and the evaluation of crack growth rates.

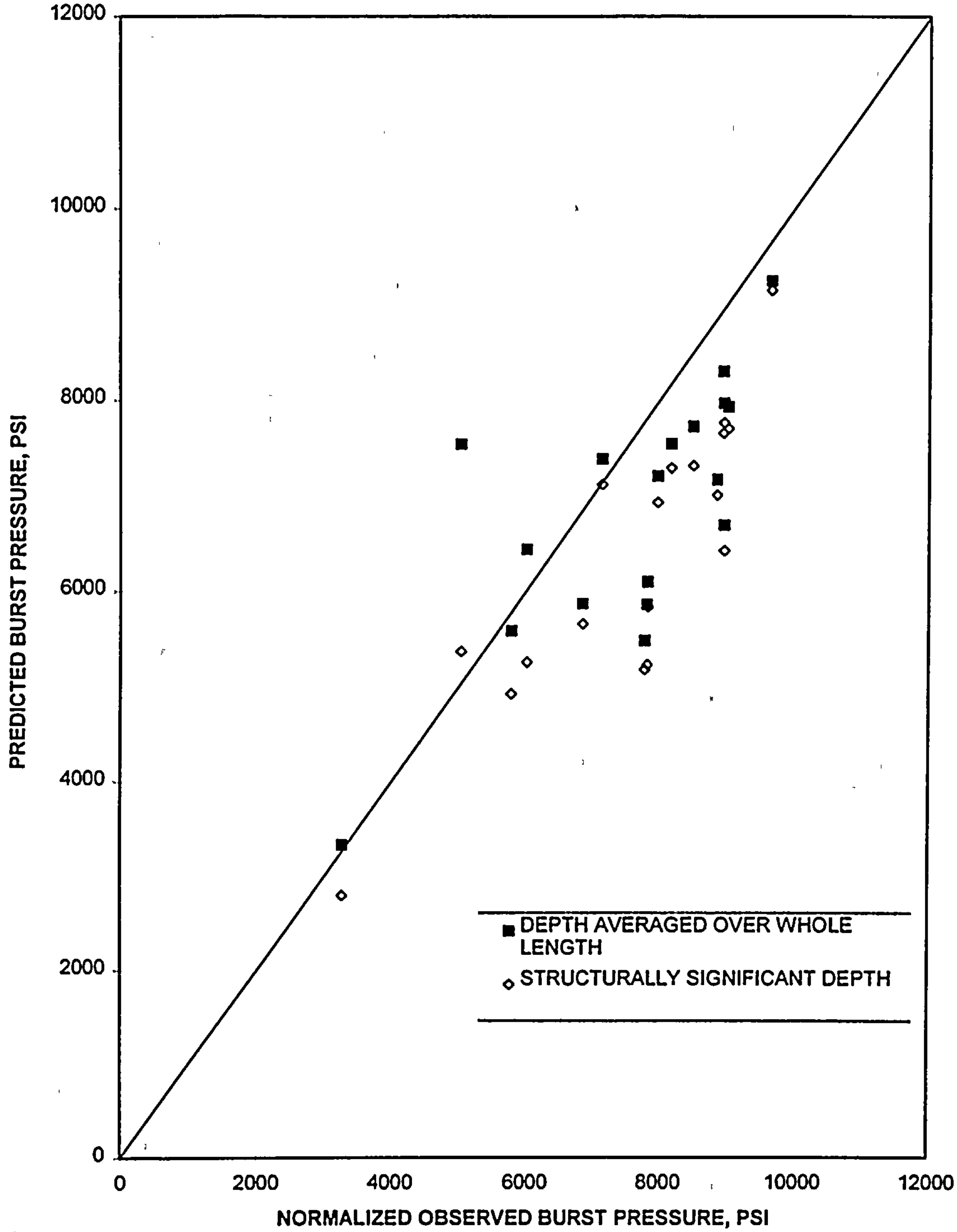
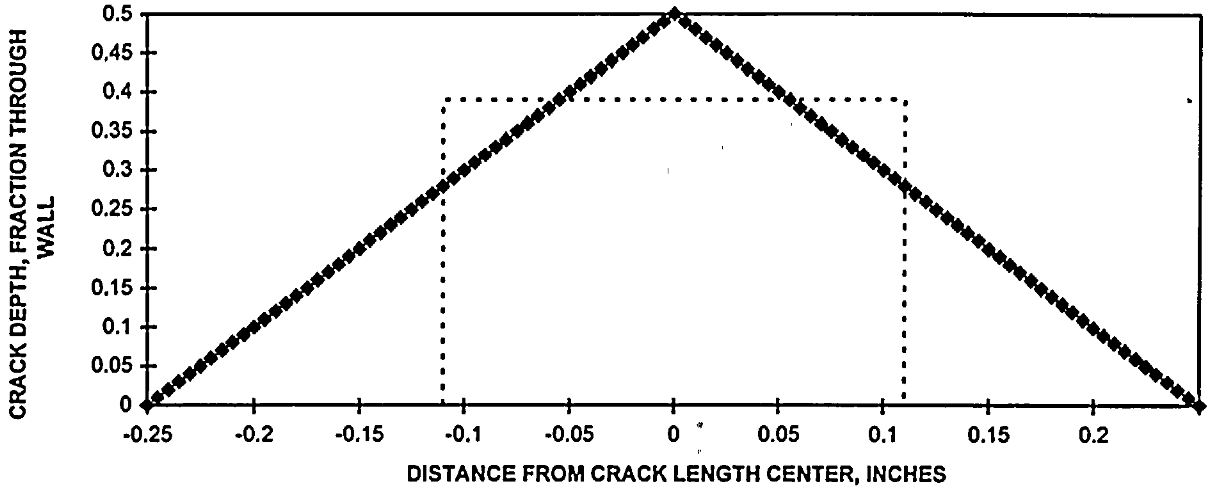
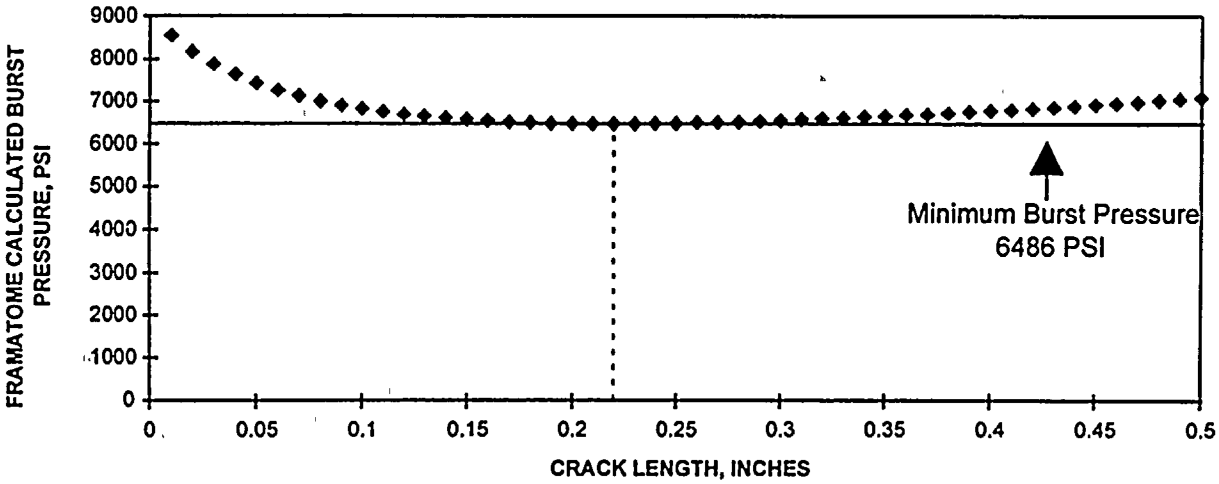


Figure 3.1 PREDICTED BURST PRESSURE VERSUS NORMALIZED OBSERVED BURST PRESSURE



(A) TRIANGULAR CRACK PROFILES



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

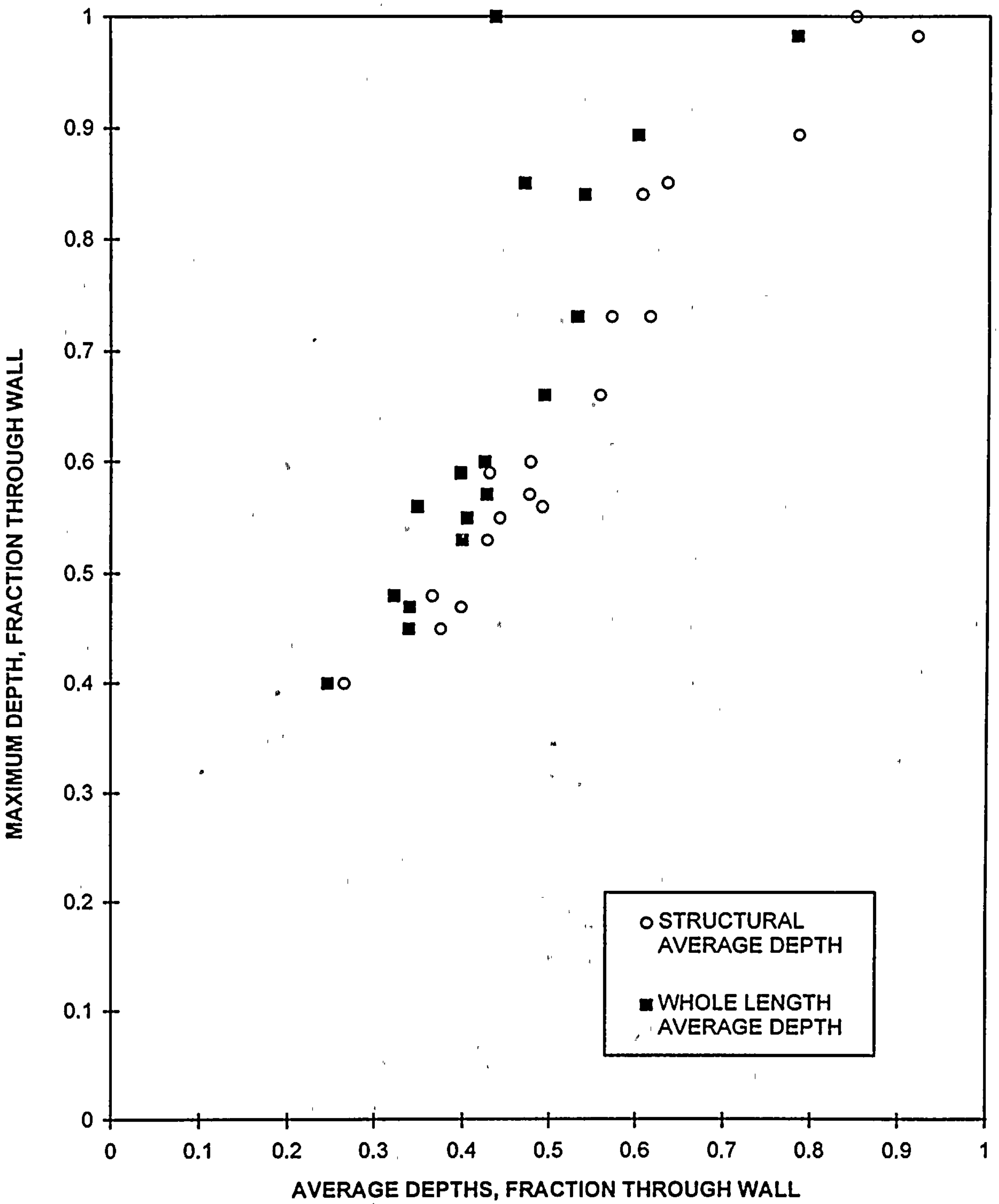


Figure 3.3 AVERAGE CRACK DEPTH VERSUS MAXIMUM CRACK DEPTH

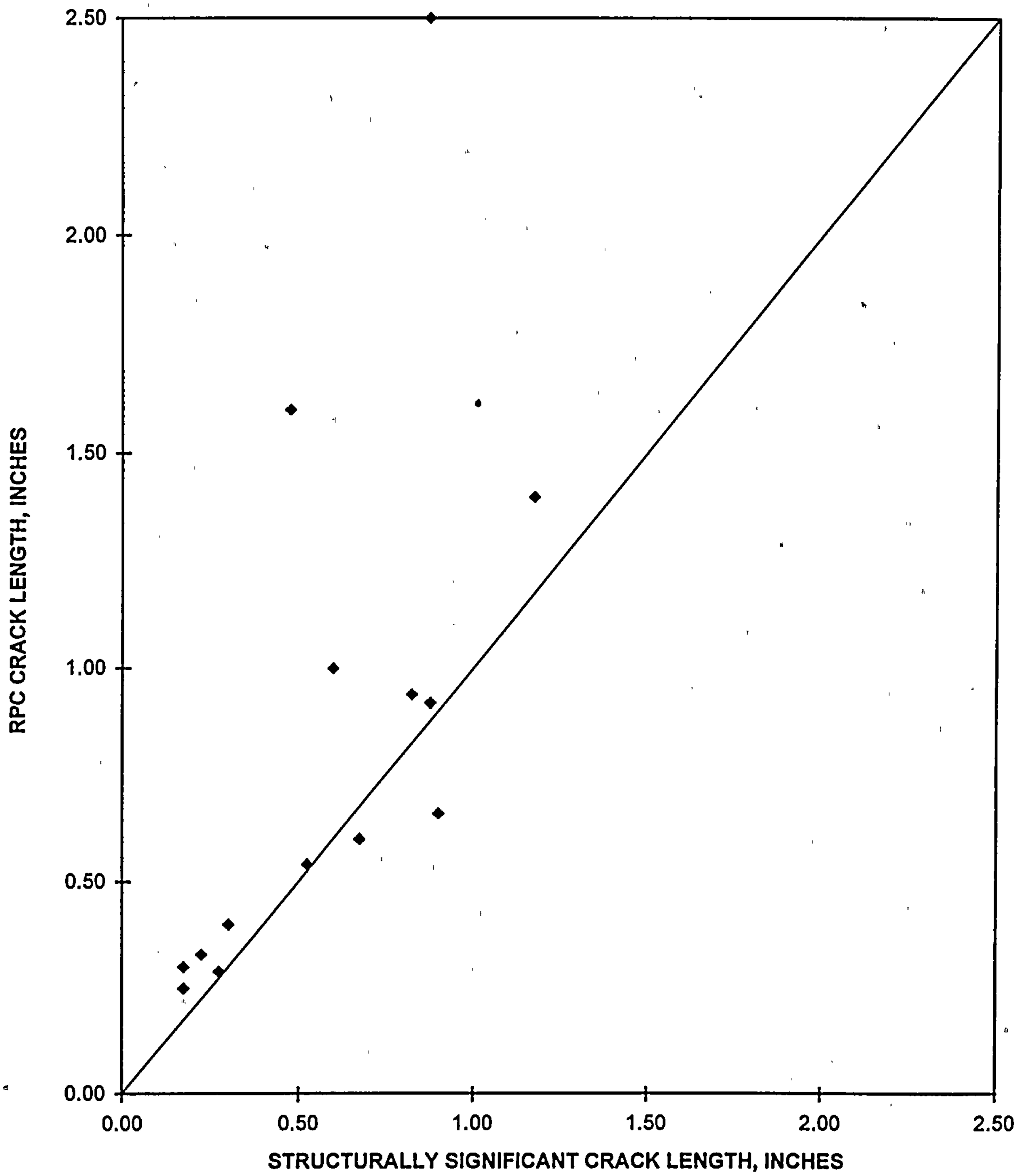


Figure 3.4 RPC CRACK LENGTH VERSUS STRUCTURALLY SIGNIFICANT CRACK LENGTH

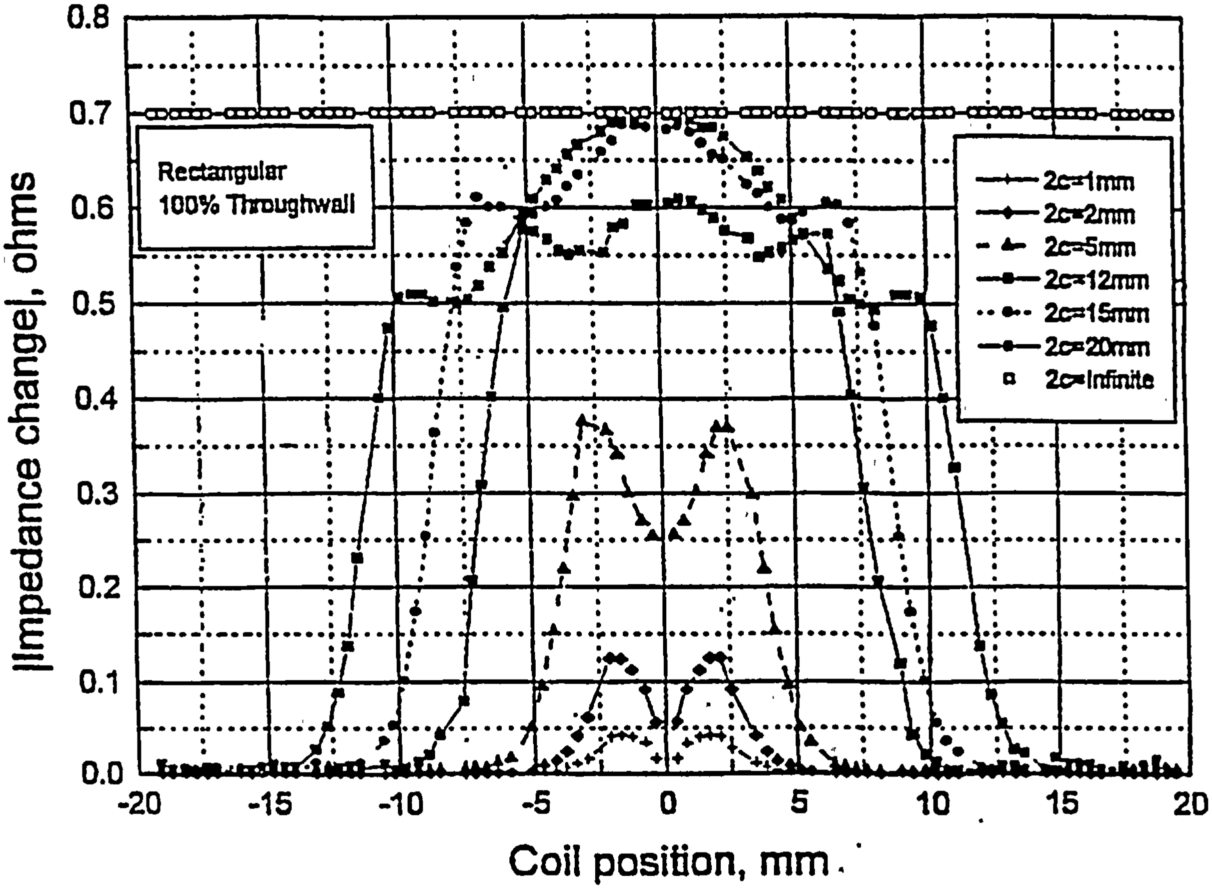


Figure 3.5 PANCAKE COIL VOLTAGE AS A FUNCTION OF COIL POSITION RELATIVE TO THROUGH WALL CRACKS

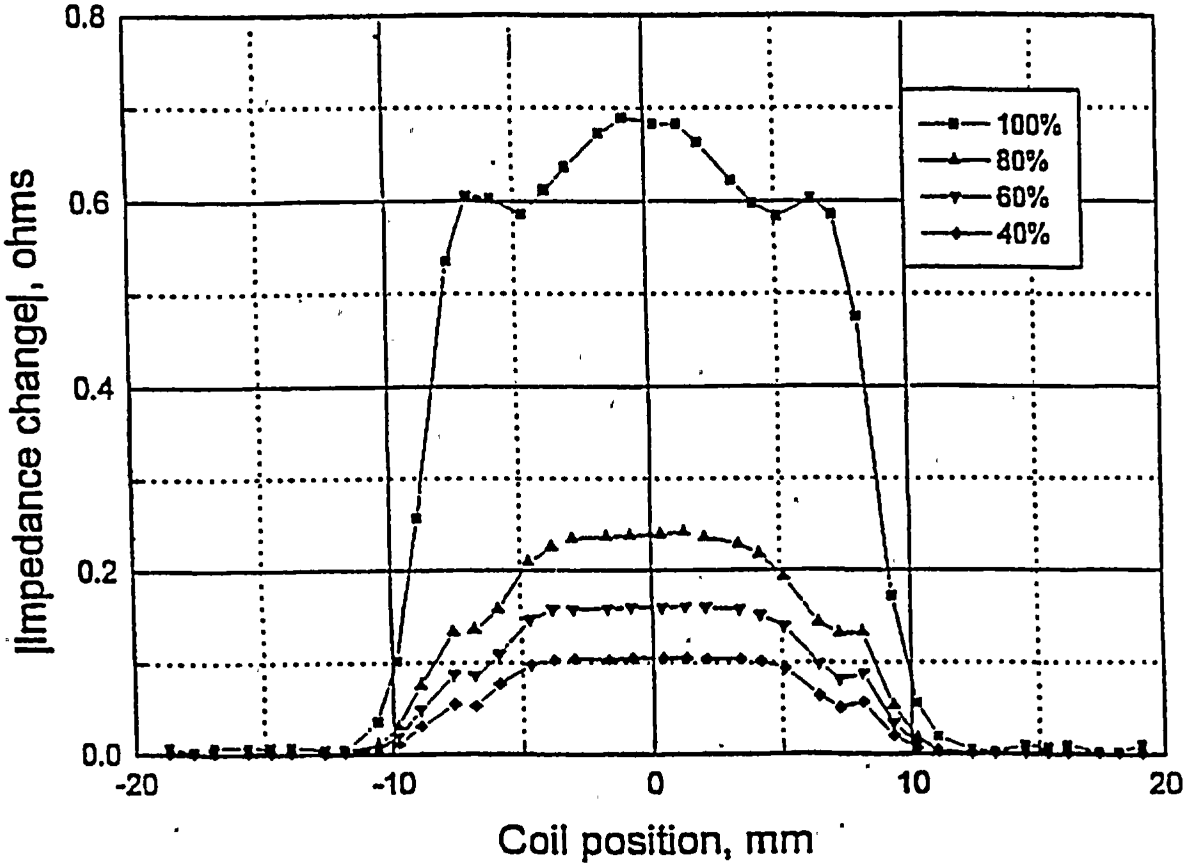


Figure 3.6 PANCAKE COIL IMPEDANCE CHANGE VERSUS CRACK DEPTH FOR A CONSTANT CRACK LENGTH OF 0.6"

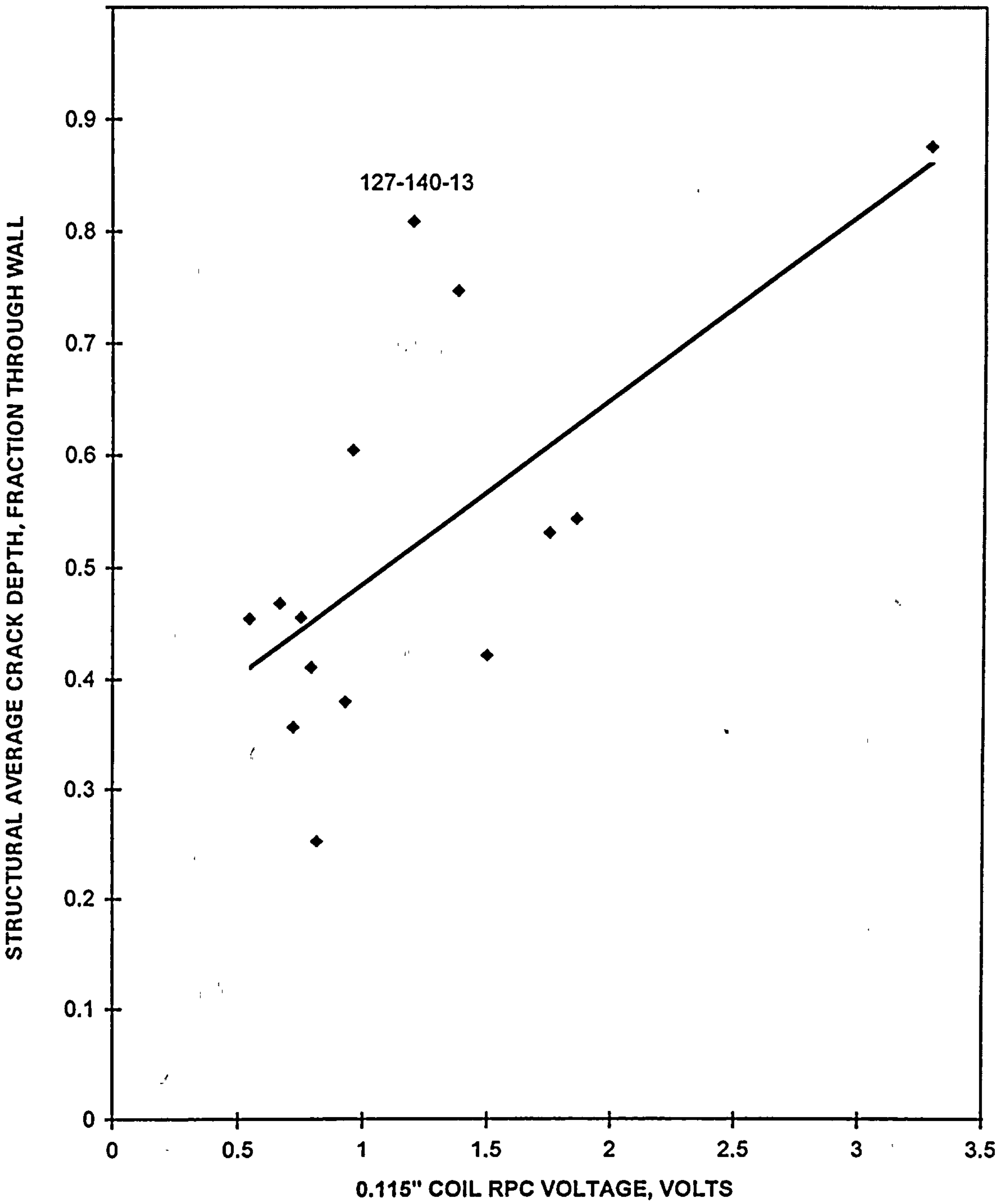


Figure 3.7 STRUCTURAL AVERAGE DEPTH VERSUS RPC VOLTAGE

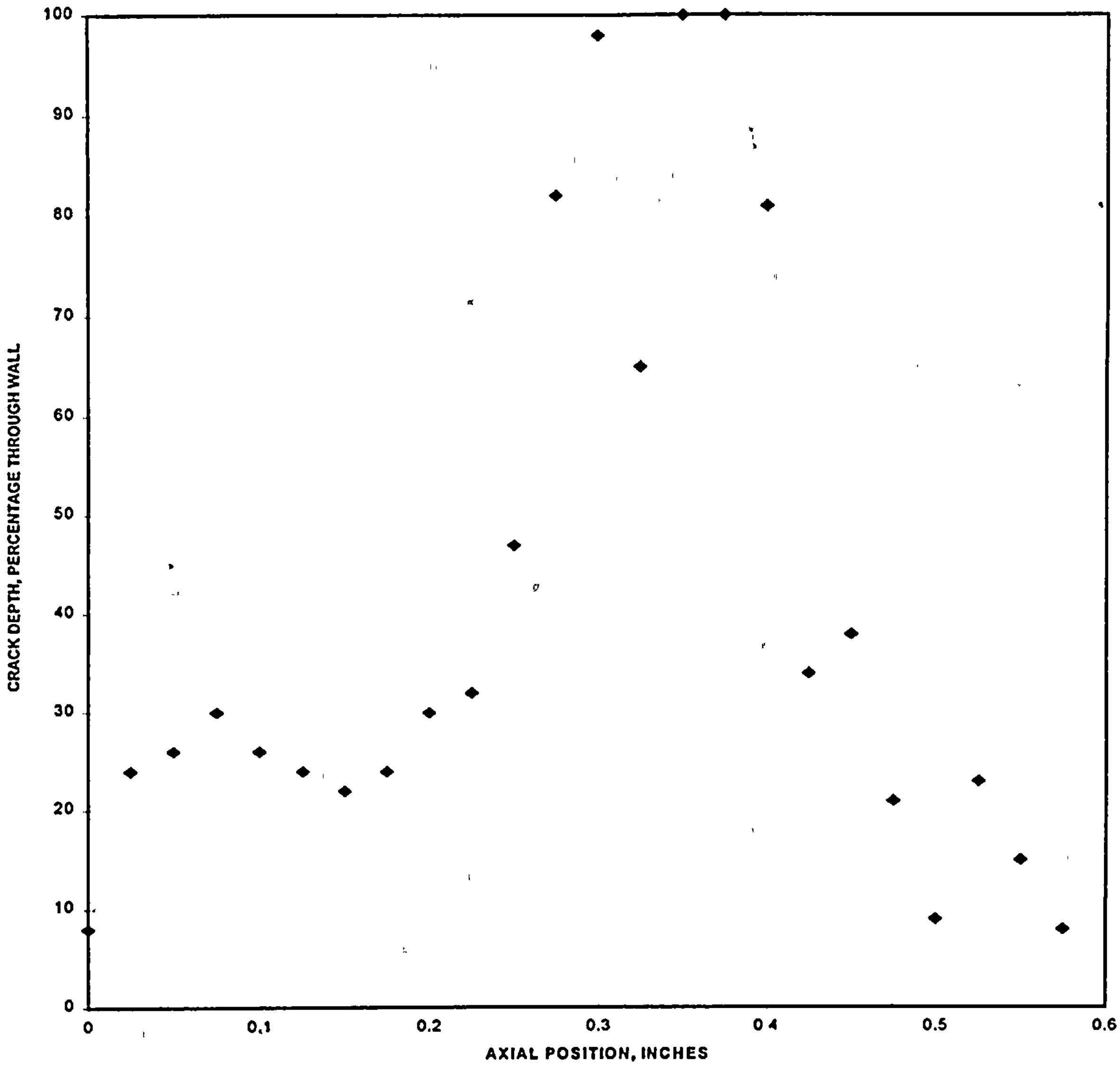


Figure 3.8 DEPTH VERSUS LENGTH CRACK PROFILE OF TUBE SECTION 127-140-13

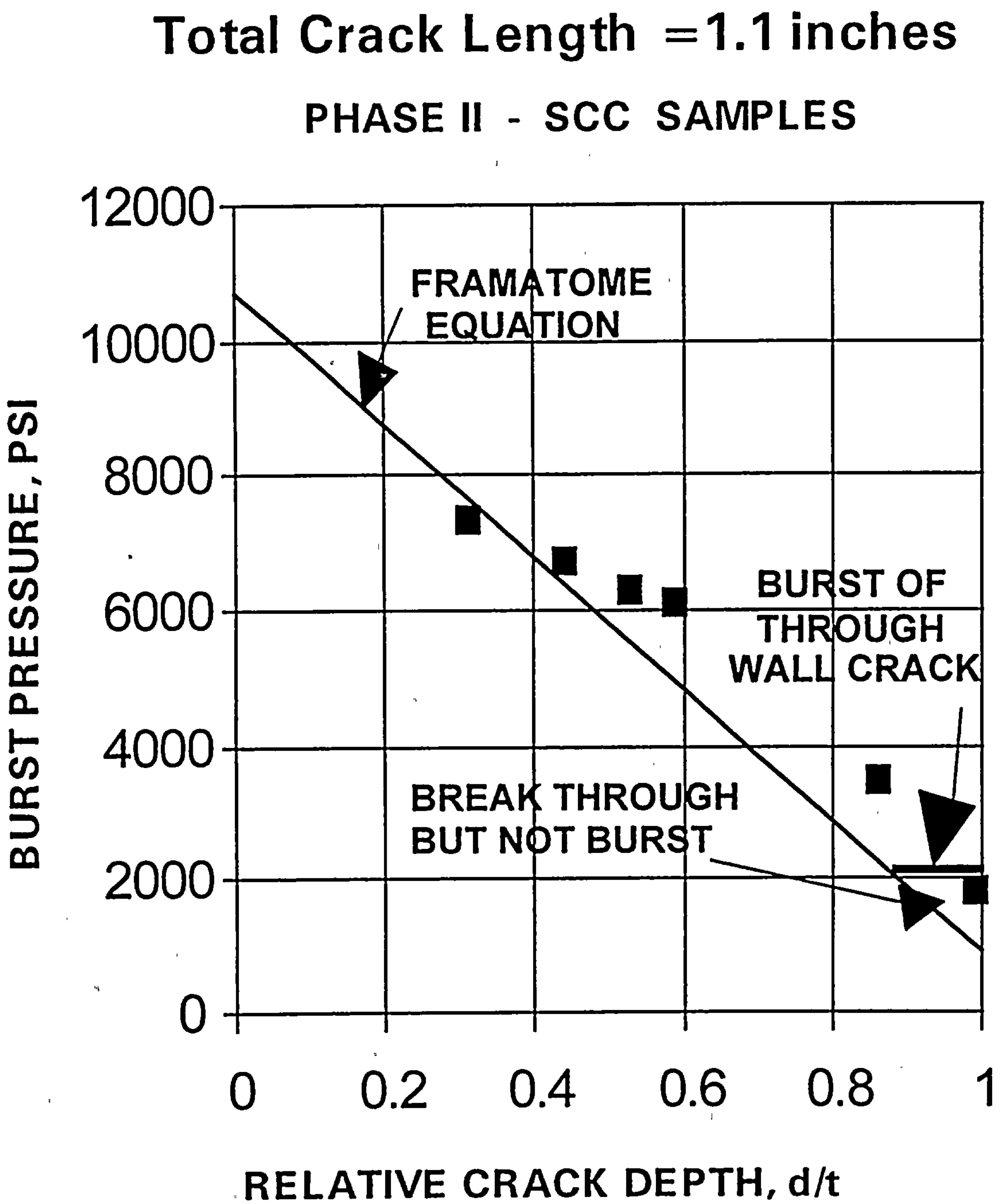


Figure 3.9 BURST PRESSURE VERSUS RELATIVE CRACK DEPTH. THE REGION OF ONSET OF LOCAL BREAK THROUGH BUT NOT BURST IS ILLUSTRATED

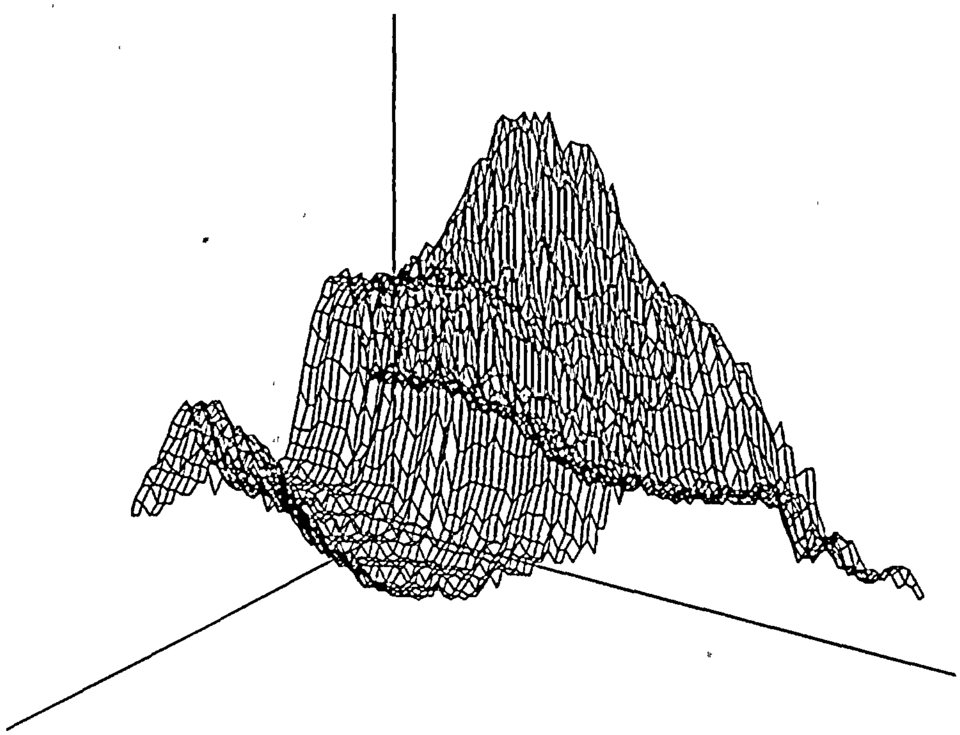
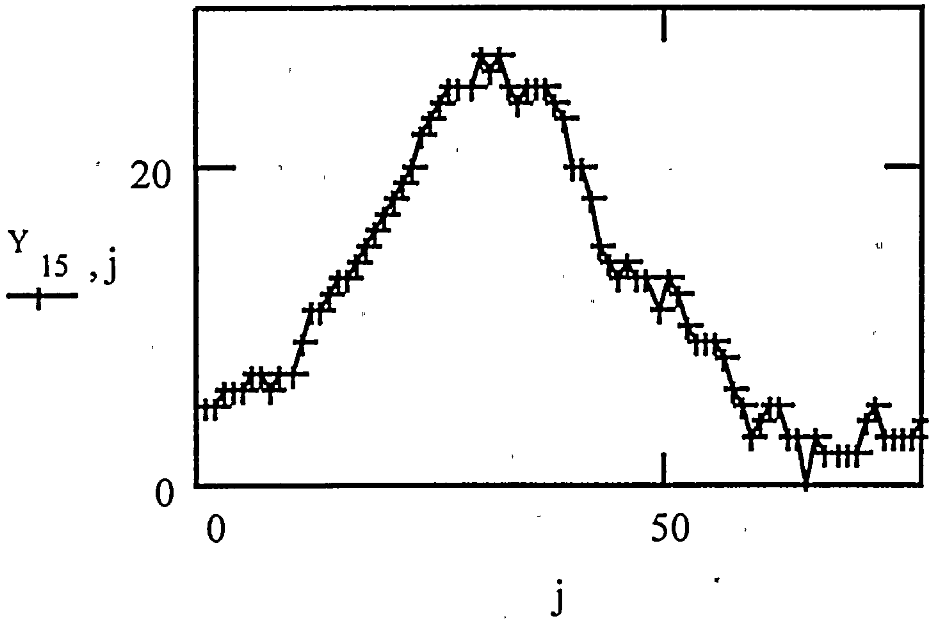
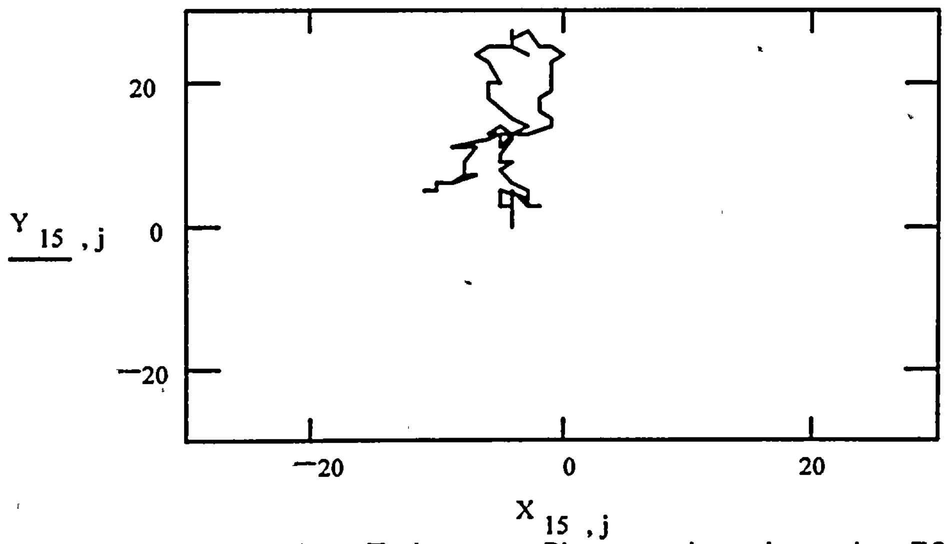


Figure 3.10 EDDY CURRENT ROTATING PROBE GRAPHIC - PV UNIT2 TUBE R137L134

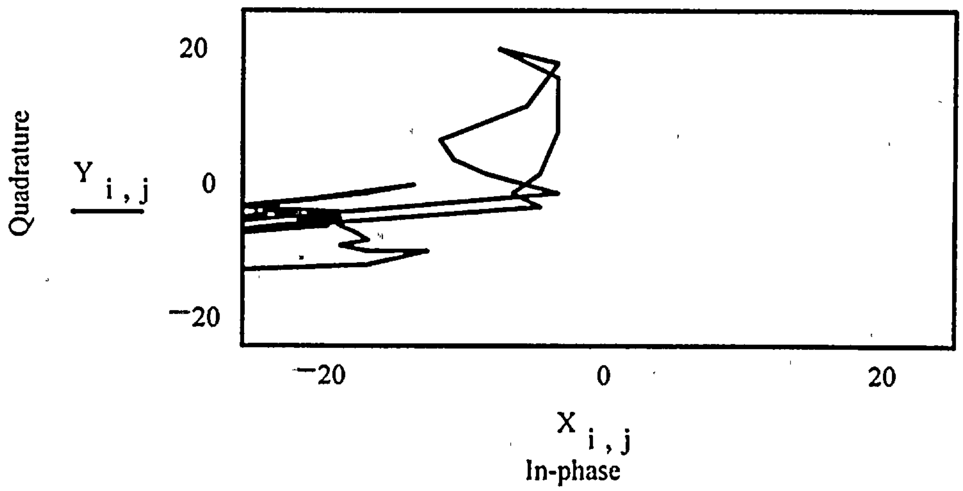


(a) Axial amplitude trace showing indication endpoints at j=5 and 64 corresponding to a length of 1.5 inches.

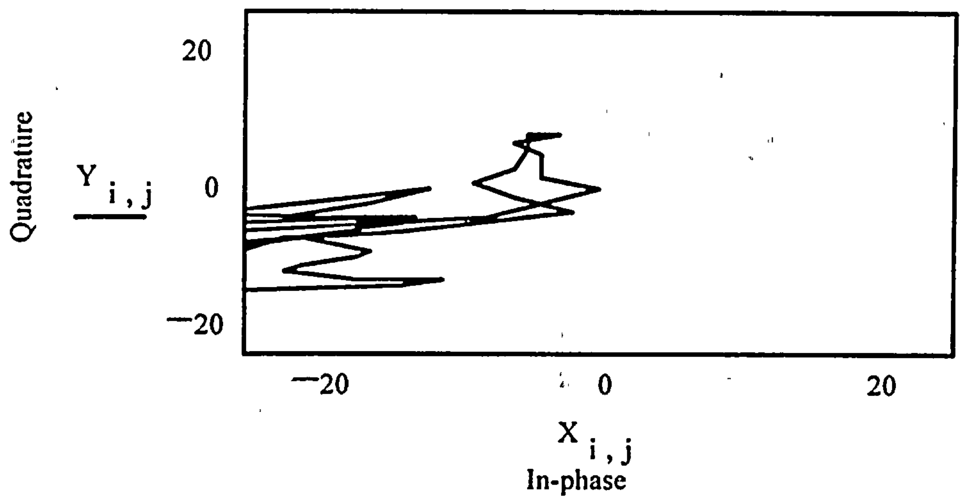


(b) Axial Impedance Plane Trajectory - Phase angle estimated at 76 degrees which corresponds to a depth estimate of 55% though-wall.

Figure 3.11 AXIAL PROFILING - TUBE R137C134

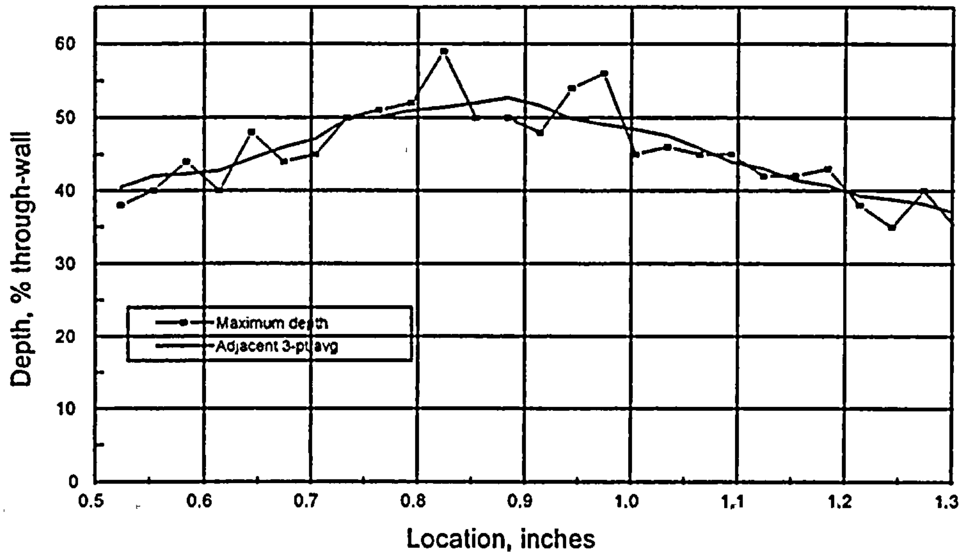


(a) Impedance plane trajectory at j = 38

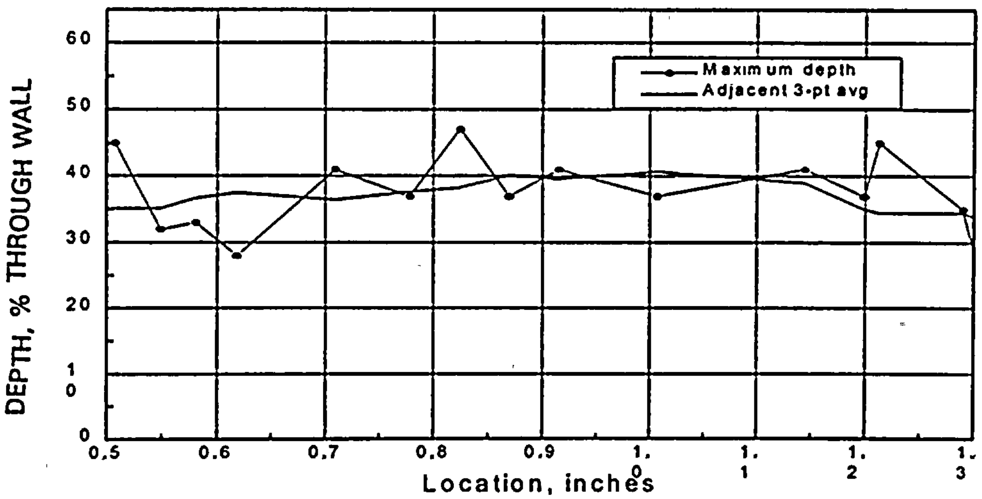


(b) Impedance plane trajectory at j = 52

Figure 3.12 IMPEDEANCE PLANE TRAJECTORIES AT VARIOUS AXIAL SAMPLE POINTS - TUBE R137L134



(a) Eddy Current



(b) Metallography

Figure 3.13 DEPTH PROFILE COMPARISON - R137L134

4.0 CRACK GROWTH RATES

Eddy current records of tubes found to contain RPC indications during the U2R5 inspection were revisited to determine if precursor signals were present at the time of the previous U2M5-2 inspection. Figure 4.1 shows that precursor signals were found and that a plot of voltage change versus initial voltage at the start of the run period reveals growth in signal amplitude combined with significant scatter. The presence of more than a few negative voltage changes points to a non trivial uncertainty in voltage measurement compared to voltage growth. In a broad sense, voltage growth points to an increase in the severity of corrosion degradation relative to structural requirements. The problem at hand is to separate voltage measurement uncertainties from real voltage growth and then quantitatively relate voltage growth to reduction in structural margins. As noted in the previous section, the chosen approach is to relate RPC voltage to structurally significant depth.

Given the presence of confounding variables and a correlation of RPC voltage with structurally significant crack depth with considerable scatter, three different statistical approaches were developed to use the distribution of voltage changes to arrive at a distribution of degradation growth rates. As a further check, this calculated growth rate distribution was compared to data in the literature. Data in the literature permitted a check of both the mean and variance of the calculated lognormal growth rate distribution. The degradation morphology of Unit 2 pulled tubes also helped to benchmark the calculated growth rate distribution.

A voltage change can be converted to crack growth by simply dividing the voltage change by the slope of the linear correlation of crack depth to voltage. A variation in this slope can be interpreted as particular paths followed by the confounding variables of length, crack shape and crack face ligaments as growth occurs. Hence, different slopes are reflections of various evolutions of crack morphology with time. Since a large number of voltage changes are available, use of the best fit slope to calculate an average growth rate should yield a reliable value. The effect of confounding variables, which may lead to either high or low growth rate calculations, will be compensated in the development of an average growth rate. This average was computed in several ways. Negative values were included, considered as zero or eliminated by deconvolving the voltage change distribution into a lognormal voltage growth distribution plus a zero mean, Gaussian noise component. The average growth rate was stable and did not markedly vary with the method of calculation. The uncertainty or noise deconvolution approach led to a mean growth rate of 6.1%/EFPY. These units are growth in percentage through wall per effective full power year.

A lognormal distribution provides a good description of growth rate data. Having calculated a reliable mean growth rate, the needed growth rate distribution is fully defined with the determination of a standard deviation. Figure 4.2 schematically illustrates the first method of determining this parameter. A lognormal distribution of growth rates is assumed with the given mean value. Crack growth rates are converted to voltage changes by sampling from a distribution of possible correlation slopes obtained from the correlation curve fit analysis. A noise or uncertainty component is then added to the calculated voltage changes to arrive at final values. The standard deviations of both the lognormal growth rate distribution and the Gaussian voltage change uncertainty distribution are then varied until a best fit is obtained between the predicted and measured cumulative distribution functions of voltage changes from the U2M5-2 to U2R5 inspections. The optimized standard deviation for the lognormal growth rate distribution was 0.55.

Figure 4.3 shows an approach to determine the standard deviation of the lognormal growth rate distribution through consideration of predicted and observed extreme values of voltage changes from the U2M5-2 to U2R5 inspections. As above, a lognormal growth rate distribution is assumed with the given mean value. A slope distribution is sampled to convert growth rate to voltage changes. The most likely extreme value of a voltage change is then determined for a sample size of about 300. Most likely extreme values of voltage changes were obtained as a function of assumed standard deviations for the growth rate distribution. Examination of the observed voltage changes and the maximum values of these changes yields a growth rate standard deviation of 0.65.

The final calculated standard deviation was obtained by deconvolution of the voltage change distribution into lognormal growth and Gaussian noise components. Again correlation slope sampling was used to convert voltage changes to growth rates. The standard deviation of the lognormal growth rate distribution was found to be 0.64.

Three calculational approaches lead to expected standard deviations of the needed lognormal growth rate distribution between 0.55 and 0.65. A variation in growth rates of this magnitude matches expectations from data in the literature and from consideration of degradation morphology. A previous review of growth rate and time to cracking data for SCC/IGA phemomena revealed that most often a factor of 5 scatterband covered about 95% of the spread in the growth rate or time to cracking data[5,16]. A factor of 10 scatterband has been argued as a reasonable upper bound in terms of covering about 95% of the total data range for a given data set[5]. This includes data sets of large numbers of specimens/tubes from different heats of material. Considering a lognormal distribution, about 95% of

growth rate values are included within +/- 2 standard deviations from the mean. A factor of 10 scatterband covering 95% of the data is essentially an indication of a standard deviation of 0.575. Hence, calculated standard deviations between 0.55 and 0.65 are consistent with the ongoing corrosion degradation phenomena.

Examination of tubes pulled from Unit 2 show the corrosion morphology to be a combination of IGA/SCC. Figure 4.4 and 4.5 illustrates this point. This morphology is similar to that observed in tubes at drilled tube support plate crevices in other plants. Figure 4.6 illustrates ranges in growth rates as determined in the laboratory for IGA/SCC in high temperature concentrated caustic solutions, as taken from NUREG/CR-5117[1]. The selected growth rate distribution with a standard deviation of 0.65 and a mean of 6.1%/EFPY is also shown. The mean and spread in growth rate values of the selected growth rate distribution matches well with the spread in laboratory data and the variation in corrosion morphology. The agreement is quite good considering the concentrated test environments and the fact that laboratory tests typically markedly overestimate actual service degradation rates. For example, if only laboratory growth rates were considered, application of tube support ODSCC alternate repair criteria for multiple cycles would not appear at all realistic. Such criteria have been applied to both foreign and domestic plants for multiple cycles with excellent success.

Eddy current RPC voltage data has been analyzed to develop a degradation growth rate distribution. Separate calculational approaches yield very similar answers. The calculated distribution is a good match to data in the literature and is in good agreement with considerations of degradation mechanisms and observed morphology. Figure 4.7 is a good summary and ties the present analysis to past efforts. For convenience, the calculated lognormal degradation growth rate distribution is plotted on Weibull paper.

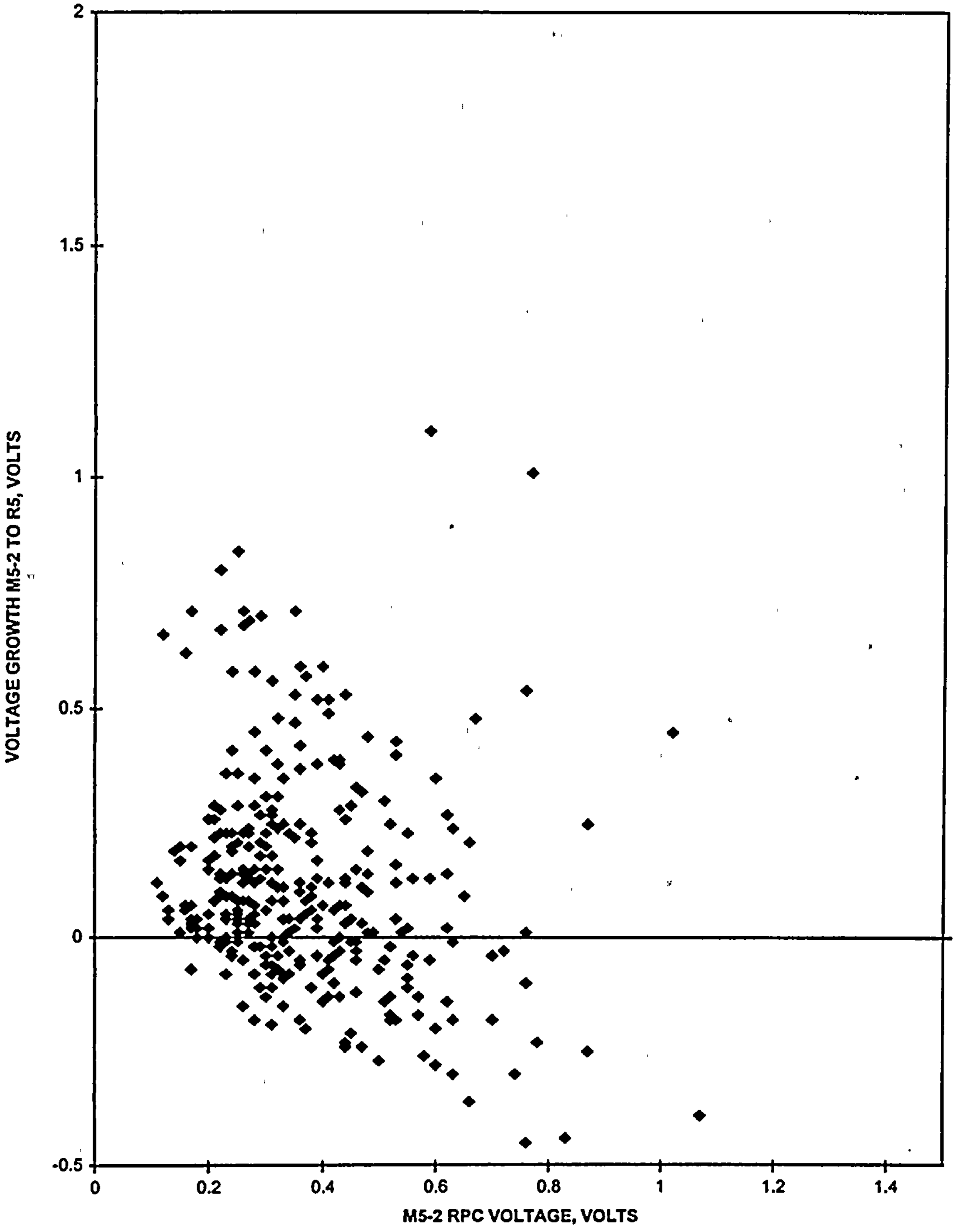


Figure 4.1 MRPC VOLTAGE CHANGE, U2R5 - U2M5-2, VERSUS U2M5-2 VOLTAGE

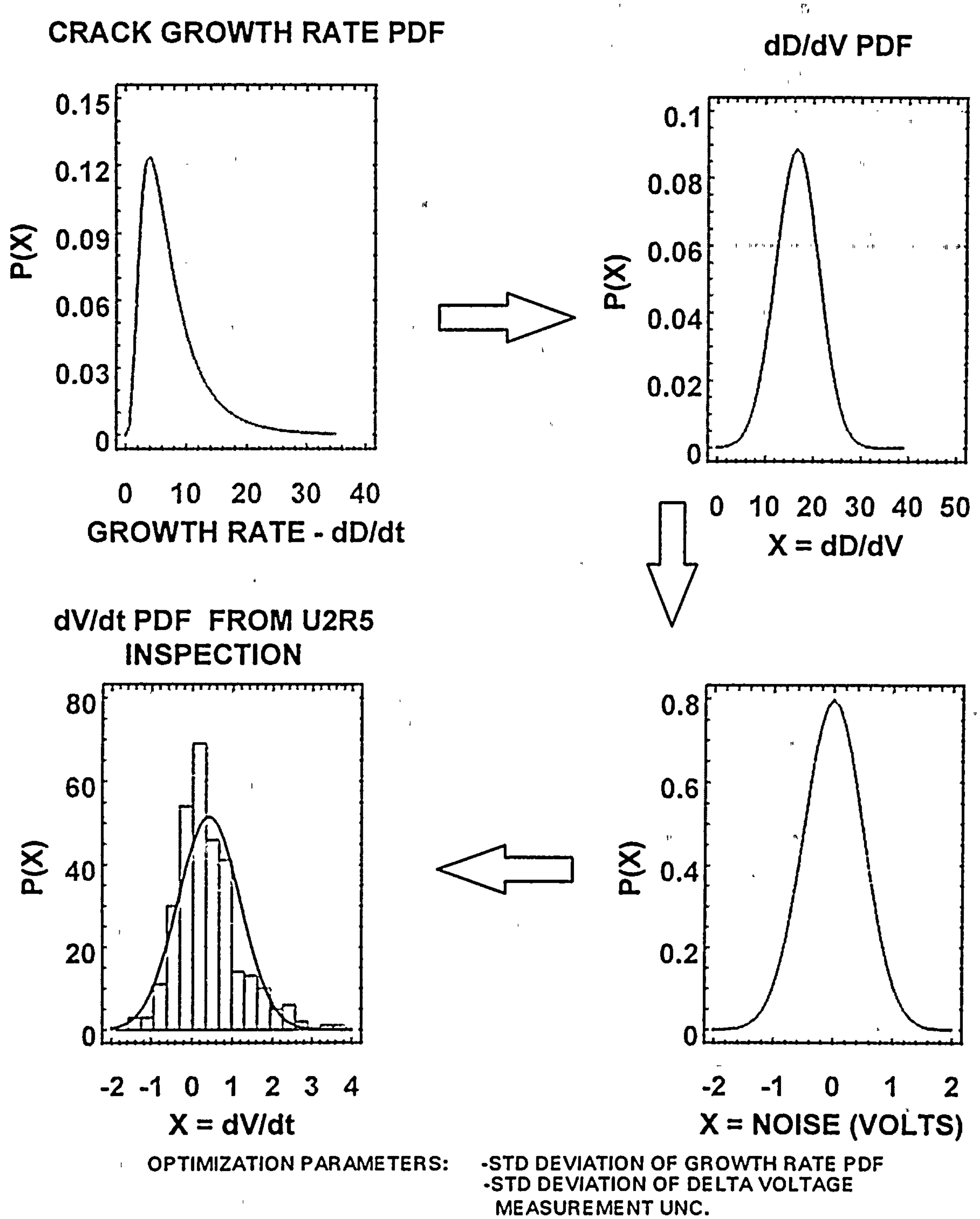


Figure 4.2 SCHEMATIC ILLUSTRATION OF ONE METHOD OF OPTIMIZATION OF CRACK GROWTH PROBABILITY DENSITY FUNCTION

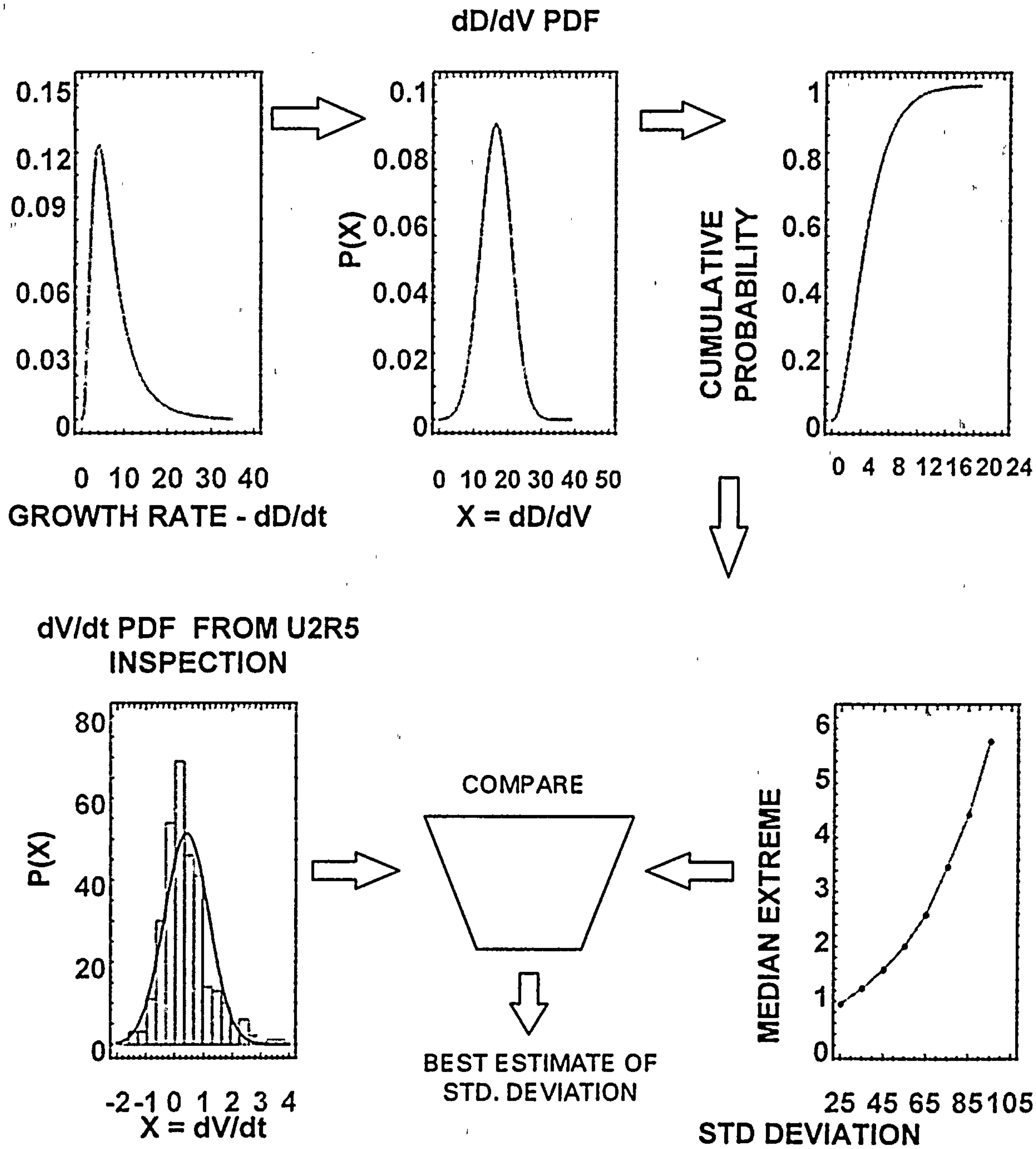
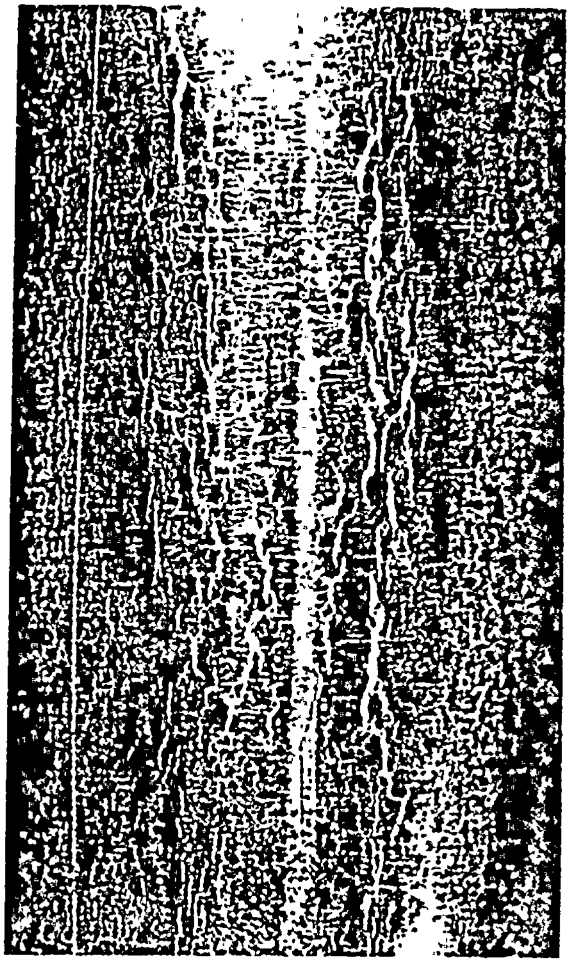


Figure 4.3 SCHEMATIC ILLUSTRATION OF THE METHOD OF ASSESSMENT OF CRACK GROWTH RATE STANDARD DEVIATION USING EXTREME VALUES

UPPER PART



LOWER PART

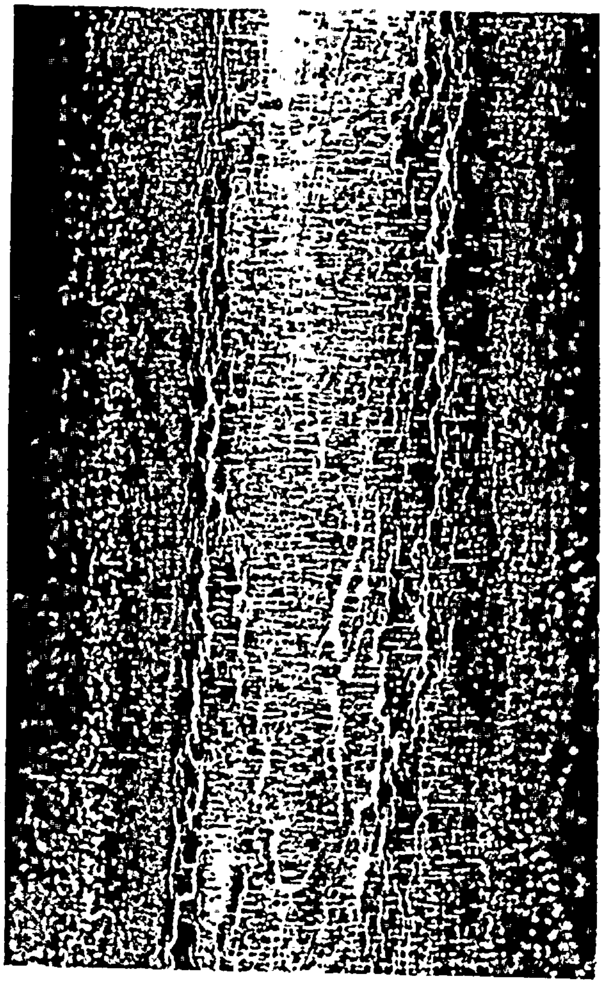


Figure 4.4 CRACKING AND IGA AT THE 270° BATWING CONTACT OF UNIT 2 PULLED TUBE A (5X)

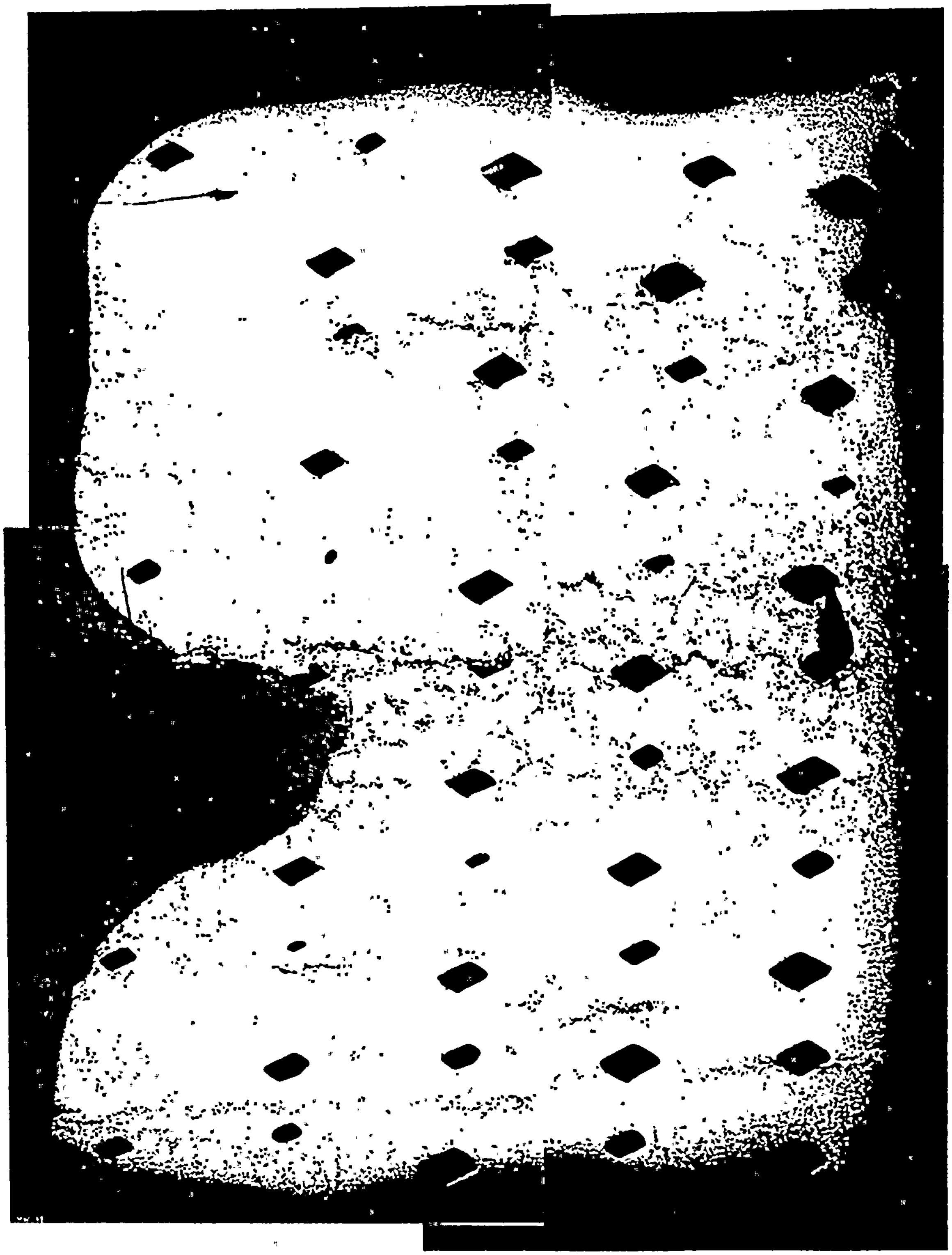


Figure 4.5 LIGHT PHOTOMICROGRAPHS OF UNIT 2 PULLED TUBE J, RADIAL POLISH, (2nd GRIND, 6 MILS) 10X

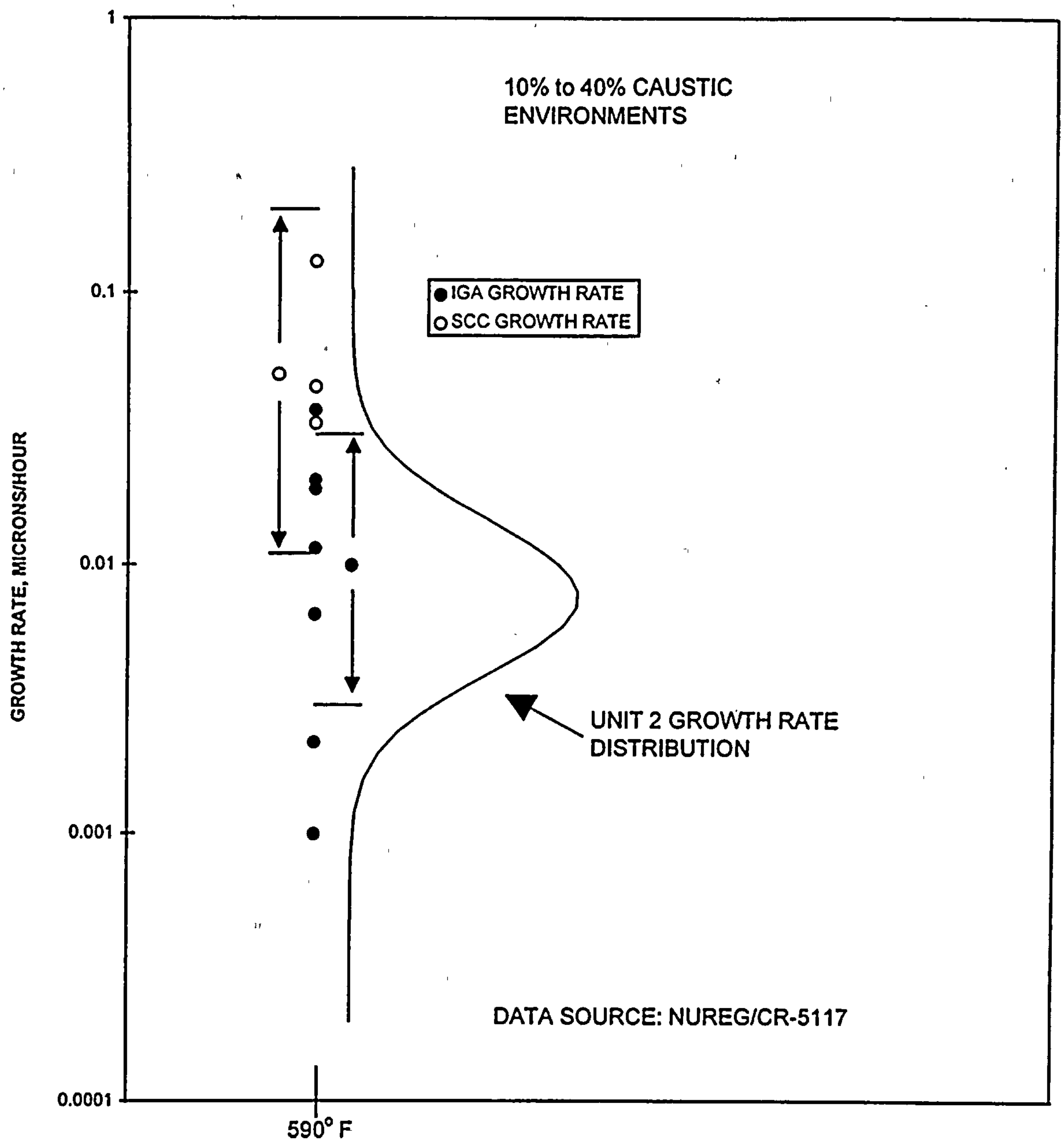


Figure 4.6 ILLUSTRATION OF LABORATORY GROWTH RATE MEASUREMENTS IN CONCENTRATED CAUSTIC ENVIRONMENTS, MORPHOLOGY VARIATIONS, AND THE UNIT 2 GROWTH RATE DISTRIBUTION

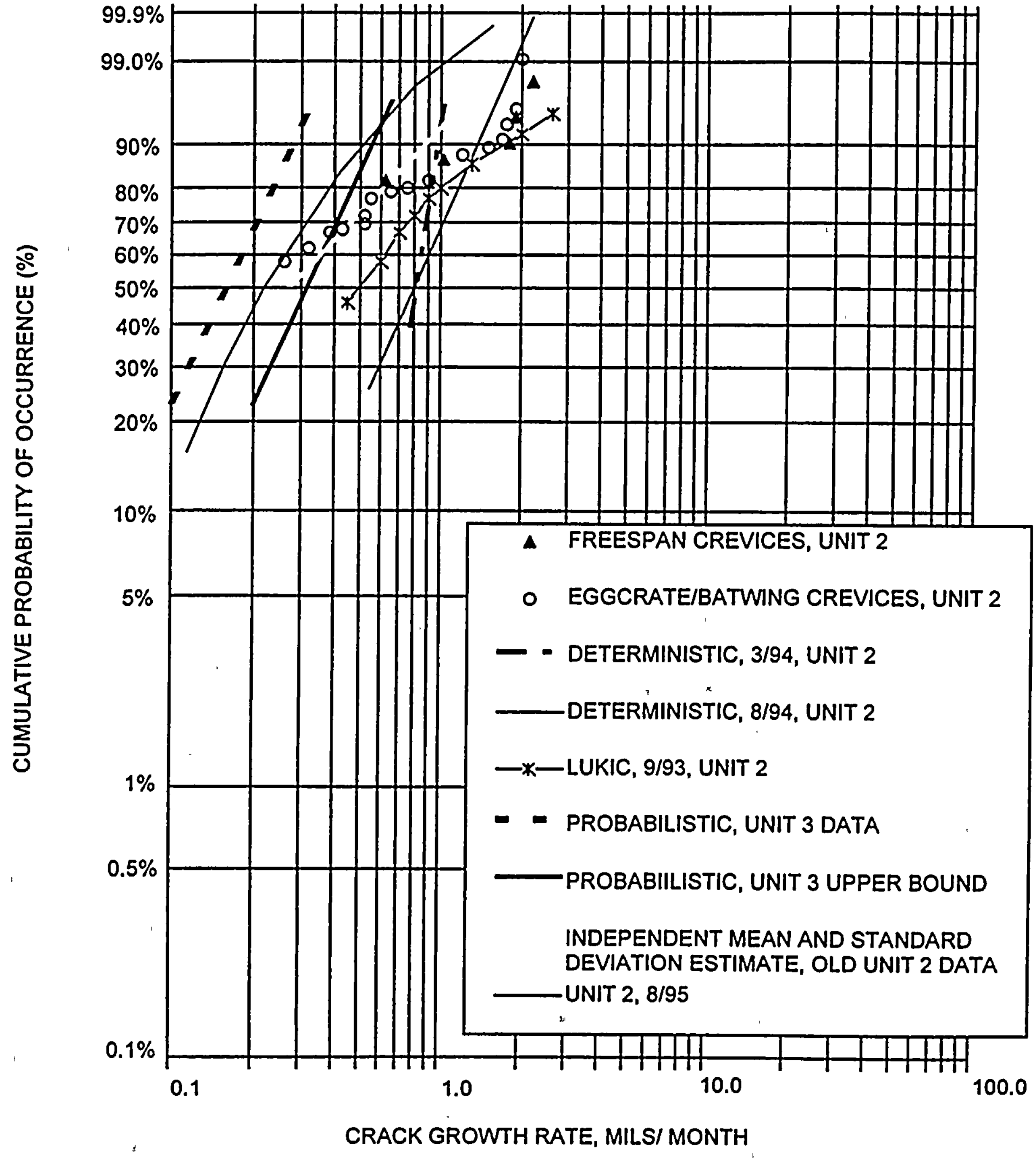


Figure 4.7 SUMMARY OF ESTIMATES OF GROWTH RATE DISTRIBUTIONS

5.0 PROBABILISTIC MODEL

5.1 DESCRIPTION OF PROBABILISTIC MODEL

The probabilistic model applied to the Regulatory Guide 1.121 evaluation of upper bundle corrosion degradation of Unit 2 is designed to simulate four basic processes:

- Upper bundle axial crack initiation
- Crack growth
- Inspection - MRPC/Plus Point
- Removal/repair of degraded tubes

These processes have large components of associated uncertainty. Therefore a probabilistic model is a good choice to realistically assess Unit 2 operating/inspection periods to ensure that an ongoing process of corrosion degradation does not lead to the exceedance of required structural margins. The following sections describe the inputs to the Monte-Carlo simulation model, the overall simulation process and Unit 2 specific results.

5.1.1 Crack Initiation and Growth Models

The crack initiation process is simulated by the well known Weibull time-to-failure function given by:

$$P(t) = 1 - EXP\{-(t/B)^N\} \quad (1)$$

where: P (t) = proportion of tubes experiencing cracking by time t
N = shape parameter
B = scale parameter

The parameters for the Weibull distribution have physical significance. The scale parameter (B) is the exposure time at which approximately 63% of the population at risk is expected to have failed. The shape parameter (N) has significance in terms of hazard rate. For $N<1$, the hazard rate is decreasing such as is typical of electronic components during the "burn-in" period. For $N=1$, the hazard rate is constant and the Weibull model becomes equivalent to an Exponential model. For $N>1$, the hazard rate increases with exposure time, a situation typical of most corrosion phenomena. The range of interest for steam generator tube modeling appears to be:

$$1 < N < 6$$

Reference 16 provides an extensive catalog of Weibull parameter estimates based on worldwide operating plant data. This of course represents data from cracks which have progressed well beyond initiation into the detectable regime. It has been found in previous analyses[4,5] that a simple time shift or delay function provides an adequate representation of crack initiation for reasonable crack growth rate distributions. In the case of the Palo Verde Unit 3 analysis the required time delay incorporated in the crack initiation model varied from 2 to 4 EPPY depending on the crack growth rate distribution chosen.

For Palo Verde Unit 2, which has experienced much more extensive upper bundle cracking, the simple time-delay approach to developing an initiation model proved far too conservative. The behavior of the initiation model developed in this manner resulted in consistent underprediction of early inspection results (R4, M5-1) and overprediction of later inspection (M5-2, R5) results. This behavior suggested a systematic effect caused by an overestimate of the Weibull shape parameter (N) from the observed data.

A more sophisticated approach to the development of a crack initiation function was, therefore, developed as part of the present Unit 2 evaluation. This methodology used a simplified version of the RG 1.121 simulator in conjunction with an optimization module to evaluate the best-fit Weibull initiation model parameters including the time-delay value. The approach is shown in Figure 5.1. The data utilized in the analysis is given in Table 5.1. It should be noted that the Weibull shape and scale parameters were not treated as independent in the analysis. In the mathematical sense, this can be viewed as forcing the results through a specific observed point, in this case, the observed R5 cumulative results.

The optimization surface in terms of Weibull shape parameter and time-delay parameter is shown in Figure 5.2 as a 3-D function and in Figure 5.3 as a contour plot. It can be seen, particularly in Figure 5.3, that the optimum in terms of Weibull shape parameter and time-delay parameter is well defined. Figure 5.4 shows a comparison of predicted and observed numbers of cracks for M5-1(+R4), M5-2, and R5. The R4 inspection comparison is not included separately because of large differences in inspection hardware and procedures with respect to the later inspections. It should be noted that the MRPC inspection POD function was used in the development of the crack initiation function.

5.1. 2 Inspection/Repair Model

The inspection/repair process for axial cracking is completely dependent on the capabilities of the inspection methodology, in this case MRPC. Simulation of the inspection/repair process requires the probabilistic implementation of a probability of detection function (POD). For this purpose the POD function used in Reference 4 was included in the simulation. Implementation of the inspection process is straightforward. At a given inspection time, each of a group of active cracks is subjected to a probability of detection function. Corresponding to each crack is a POD based on the function. A uniformly distributed random number is chosen to decide if a given crack is detected. If the crack is detected it is removed from further service or subsequent inspection.

For the Unit 2 analysis, a significant modification was made to the program to permit incorporation of a simulated Plus Point probe POD function. This modification allowed realistic simulation of the R5 and R6 inspections and a quantitative realization of the benefit of the more capable Plus Point inspection capability.

The inspection transient at R5 and the quantification of the proportion of Plus Point defect calls which could have been detected by MRPC provided the basis for the development of an "effective" Plus Point POD function. As shown in Figure 5.5, the simulated POD function in the program was systematically varied until the agreement was reached with R5 inspection results. The Plus Point POD function is shown in comparison with the MRPC POD function in Figure 5.6. The distribution functions for the number of cracks detectable by the Plus Point probe in R5 and R6 simulated inspections are shown in Figure 5.7.

5.1.3 Material Property and Crack Length Effects

Variations in mechanical properties of tubing are included in the model. As mentioned in Section 3.0, structurally significant crack lengths are obtained from measured RPC crack lengths. The material property effects are included by obtaining randomized flow strength values specific to Unit 2 tubing. See Figure 5.8. The crack length effects are included by sampling from Unit 2 measurements, which are illustrated in Figure 5.9. In both cases, the probabilistic effects are reflected as distributional terms in the evaluation of Regulatory Guide limits for axial cracks.

5.1.4 Computation of Potential Leaker Tubes

The modifications to the computational algorithm for Unit 2 analysis include the incorporation of an additional output file which contains a census of all cracks with a peak through wall depth of greater than 100%. This edit permits leakage computations based on the depth, length, and probability of such cracks. The phenomenon of crack "breakthrough" in which a crack becomes through wall for its entire length, is explicitly modelled.

5.1.5 Simulation of Overall Process

The computer simulation of the overall process is shown conceptually in Figures 5.10 and 5.11 and consists of steps reflecting the four basic processes discussed in Section 5.0 The initial sequence involves the computation of crack population size, crack initiation times, and crack growth rates for a given Monte-Carlo trial. The population size (NMAX) is determined from the Weibull initiation model and the final inspection time for a given case. The crack initiation times (TI_i) for a given sample are determined from the basic Weibull distribution.

Log-normal random deviates are used to obtain crack growth rates (V_i) for each crack and are assumed to be constant throughout the propagation process. The second sequence computes a matrix of crack sizes (D_{ij}) for each inspection time (T_j) in the simulation process:

$$D_{ij} = V_i (T_j - TI_i) \qquad (2)$$
$$D_{ij} = 0 \text{ if: } TI_i > T_j \qquad (3)$$

i.e. crack has not initiated prior to inspection
i = crack identity index
j = inspection time index

The third sequence is the simulation of the inspection/repair process. The process proceeds in time sequence beginning with the first inspection time ($T_{j=1}$). Each crack is subjected to a pseudo-inspection in which the POD function is used in conjunction with a uniform random number to determine if a given crack is detected. An identification matrix (I_{ij}) is used to track the status of crack detection and repair (removal from service):

$I_{ij} = 0$ for undetected cracks
$I_{ij} = 1$ for newly detected cracks
$I_{ij} = 2$ for repaired cracks
($I_{ij} = 2$ if $I_{ij-1} = 1$)

The final sequence in the simulation is the examination of newly detected cracks ($I_{ij} = 1$) to determine the number of exceedances of RG 1.121 criteria. This is performed by examining crack depths (D_{ij}) for each inspection period. For the Palo Verde Unit 2 cases, criteria reflecting variations in tube material properties and crack lengths were used. The above sequences, taken in total, represent one outcome or Monte-Carlo trial. The overall process is repeated up to 10,000 times to develop distribution functions for the number of RG 1.121 exceedances for each inspection interval.

5.2 OPERATING CYCLE LENGTH EVALUATION

The Palo Verde Unit 2 operating cycle length evaluation base case consists of a simulator run for Unit 2 operating conditions of 611°F for a 12 month period. Specific model input characteristics include:

- Unit 2 specific crack growth rate distribution
- Unit 2 specific tube material property distribution
- Axial crack length distribution (from Unit 2 MRPC inspections)

All Unit 2 cases were run with a POD function which permitted detection of no cracks with average depths less than 5% through wall and permitted detection of all cracks with average depths greater than 75% through wall. The extensive Palo Verde pulled tube database permitted the development of a Palo Verde specific RPC eddy current probe probability of detection curve. This curve is in excellent agreement with an industry wide RPC POD curve[4]. The arguments presented in the last paragraphs of Section 3 point out that differences in POD curve fits are substantially less significant in the simulation approach where undetected cracks are specifically modelled. A simulated Plus Point POD function was utilized for the R5 and R6 inspections.

For the purposes of crack initiation, a temperature correction was performed using an activation energy of 50 Kcal/mole. For crack propagation an activation energy of 30 Kcal/mole was used. The output for the base case is included in Appendix A

Table 1. The probabilities of various numbers of tubes exceeding RG 1.121 limits are given for U2R6 and four previous outages.

A reasonable probability criteria for meeting Regulatory Guide 1.121 structural margins is:

- There must be a 90% probability that one or fewer tubes will be expected to violate RG1.121 limits for axial cracks during the current operating period.

The results of the base case presented in Figure 5.12 show the 12 month operating period to be acceptable for Unit 2 in terms of probability of RG 1.121 exceedances.

5.3 ADDITIONAL UNIT 2 STUDIES

Additional studies were performed to investigate the effects of imposed pressure load, and operating interval on the probability of tube rupture during the period of operation between U2R5 and U2R6. These included a series of cases run with sequentially decreasing final cycle times for both 3800 PSID (RG 1.121) and 2400 PSID (SLB) loadings. An additional case was run for a 12 month operating period under normal operating pressure loading to assess the probability of tube rupture during normal operation.

5.3.1 Probability of Tube Rupture Under Steam Line Break Conditions

The base case was modified for steam line break conditions by imposing a 2400 PSID pressure loading in place of the 3810 PSID loading used in the Regulatory Guide analysis. As expected, the reduced loading results in a lower probability of tube rupture during the proposed 12 month U2R5-U2M6 period of operation. The probability of tube rupture from steam line break pressure loading is approximately 0.018.

5.3.2 Effect of U2R5-U2R6 Operating Period

The effects of reduced operating period were studied using a modified base case in which the final period of operation was reduced by 30 day intervals for both RG 1.121 and steam line break (SLB) operating conditions. The results for Unit 2 are given in Figures 5.12 and 5.13.

5.3.3 Probability of Tube Rupture under Normal Operating Conditions

An addition case was run under normal operating conditions to assess the probability of tube rupture with normal loadings. For an operating period of 12 months, the probability of tube rupture was 2.7×10^{-3} at the U2R6 degradation state.

5.4 BENCHMARKING OF PROBABILISTIC MODEL

The present implementation of the probabilistic model has a significant amount of internal benchmarking, particularly with respect to the combined effects of crack initiation, growth, and detection. The modelling of four previous inspections provides a robust basis for the comparison of simulated and actual crack evolution in the Palo Verde Unit 2 steam generators giving confidence in the U2R6 projections. As can be seen from Figure 5.4 and 5.7, the comparison between simulated numbers of cracks and observed values is nearly exact.

Other benchmarks are facilitated by the mechanistic nature of the model in which critical elements such as crack growth rate, crack length, material property and probability of detection (POD) distributions are each individually benchmarked.

Perhaps the most important benchmark for the Unit 2 probabilistic model is contained in the normal operating condition case described in Section 5.3.3 The first inspection modelled in this case is U2R4 which is coincidentally the inspection immediately following the Unit 2 tube rupture during normal operation. The model predicts a "best estimate" of between 2 and 3 tubes degraded to the point of burst at normal operating pressure for the U2R4 inspection. This particular benchmark lends credence to the combined effects of growth rate and initiation models in terms of resulting in accurate estimates of historical risk. These elements of the Unit 2 probabilistic model were never calibrated with this benchmark in mind.

It can be concluded that the Unit 2 probabilistic model is thoroughly benchmarked in terms of:

- Individual models - crack growth rate
  - burst pressure
  - crack length
  - material properties
- Combinational effects - observable crack evolution
- Tube Rupture Risk - normal operating conditions

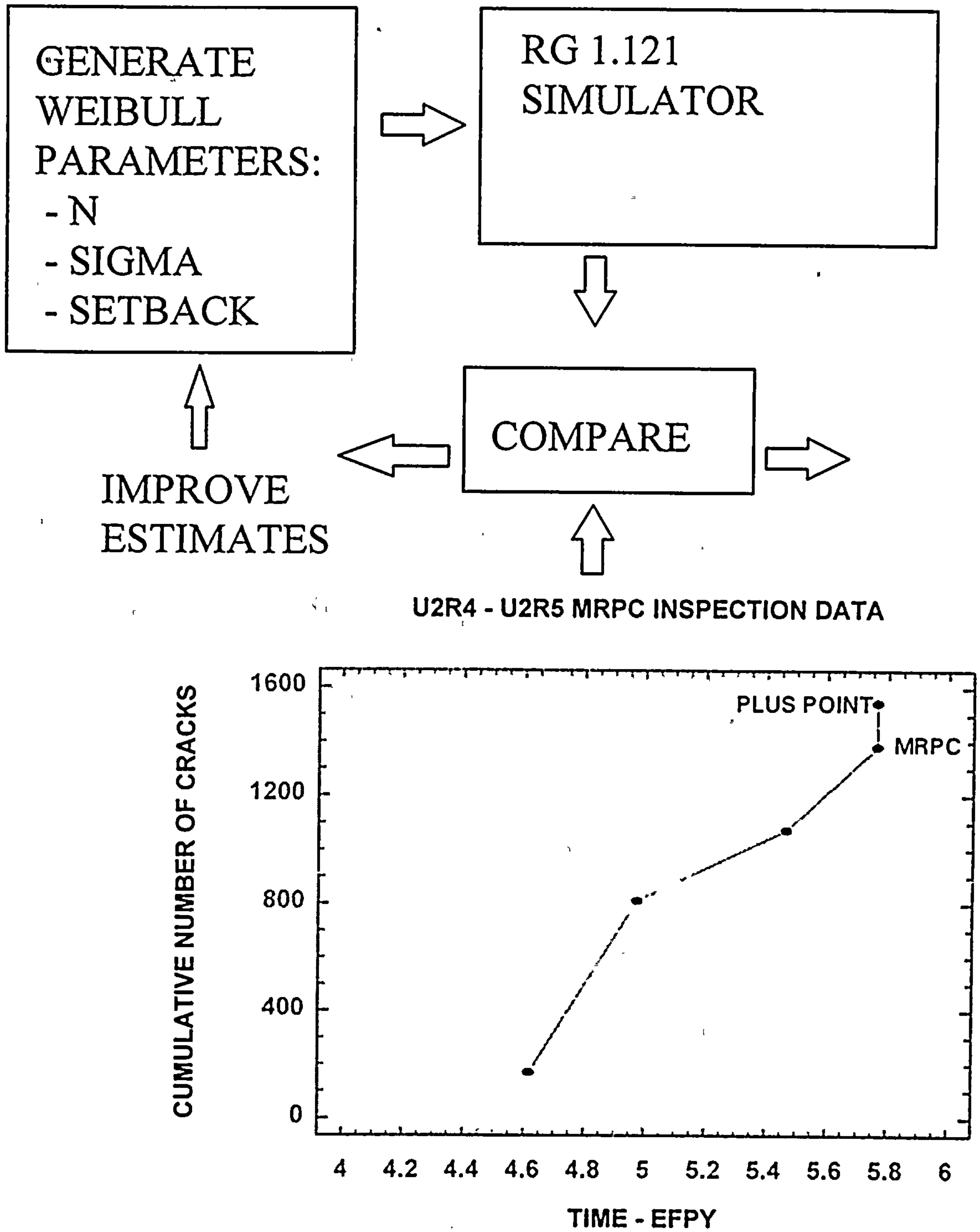


Figure 5.1 INITIATION MODEL OPTIMIZATION

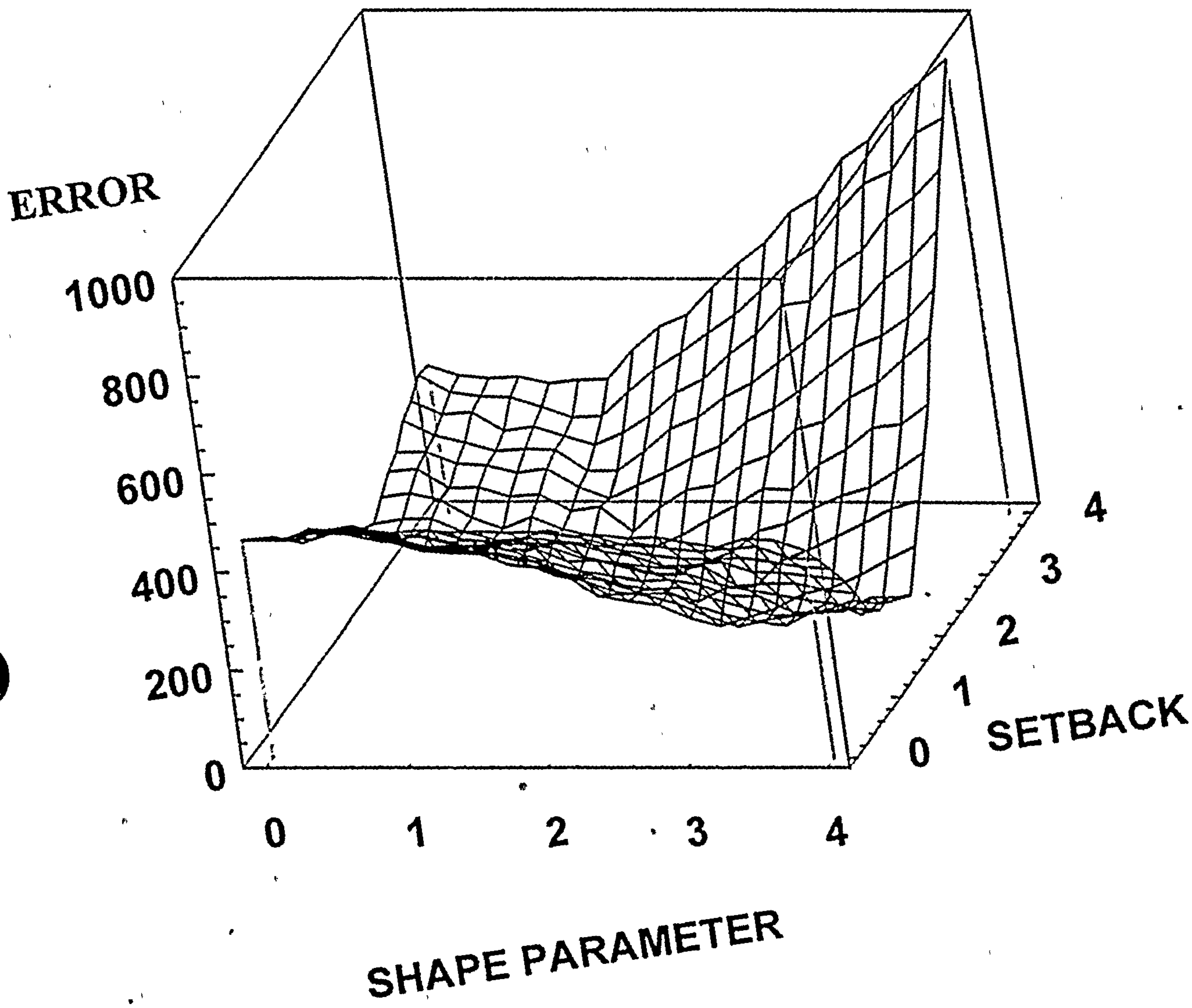


Figure 5.2 TYPICAL OPTIMIZATION SURFACE FOR INITIATION

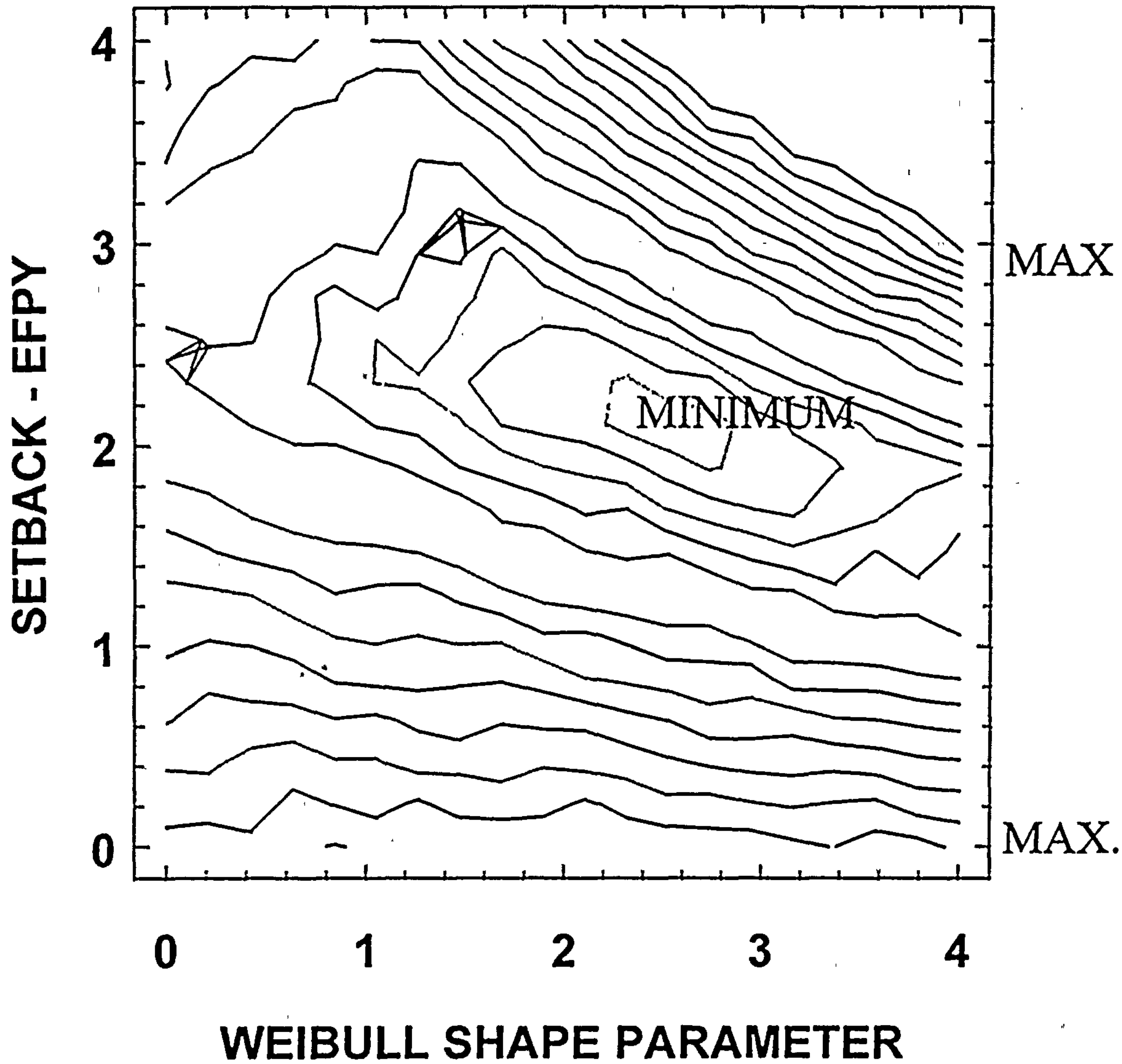


Figure 5.3 TYPICAL CONTOUR PLOT FOR INITIATION MODEL OPTIMIZATION

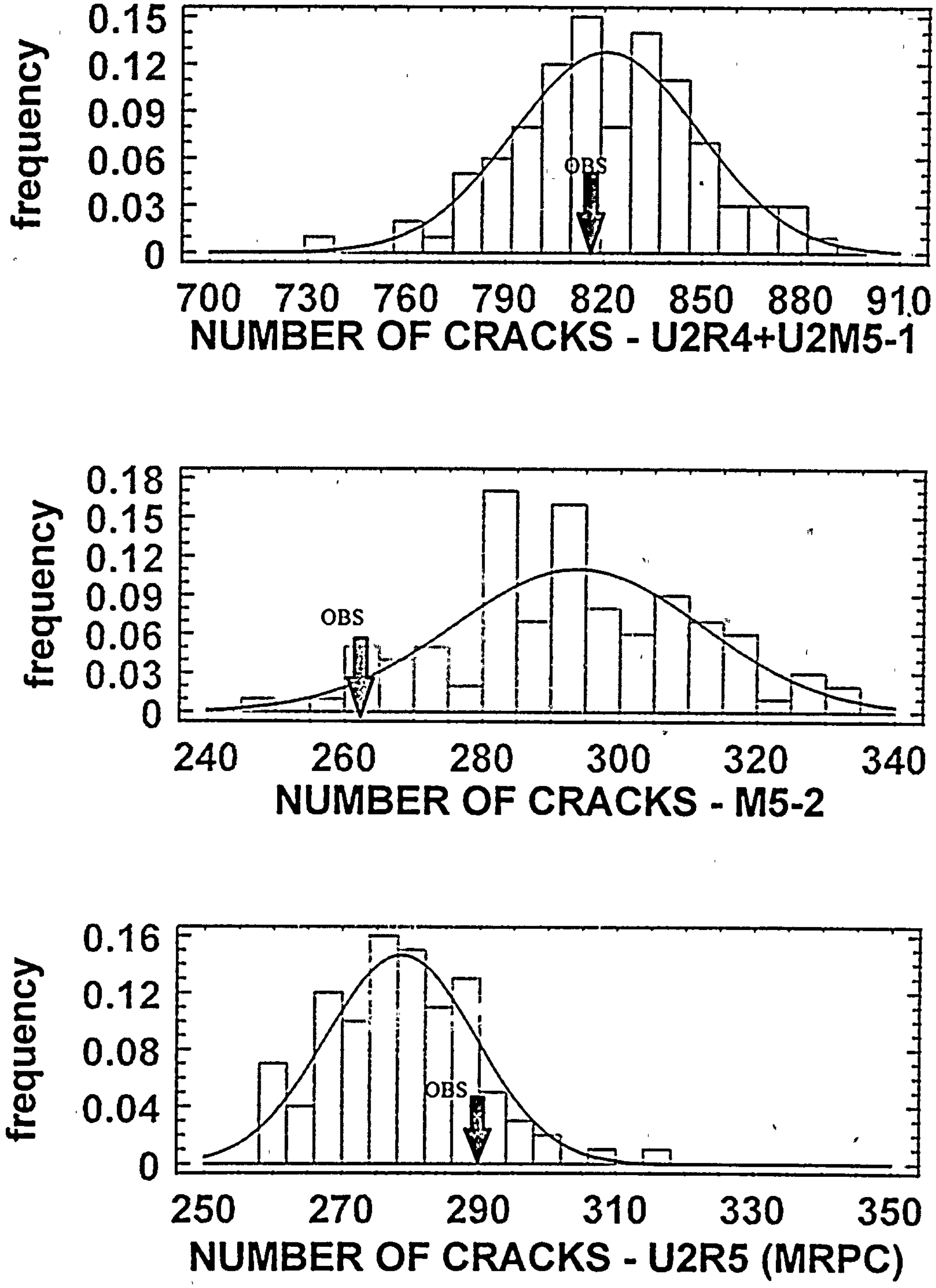


Figure 5.4 PROJECTIONS FOR MRPC INSPECTIONS

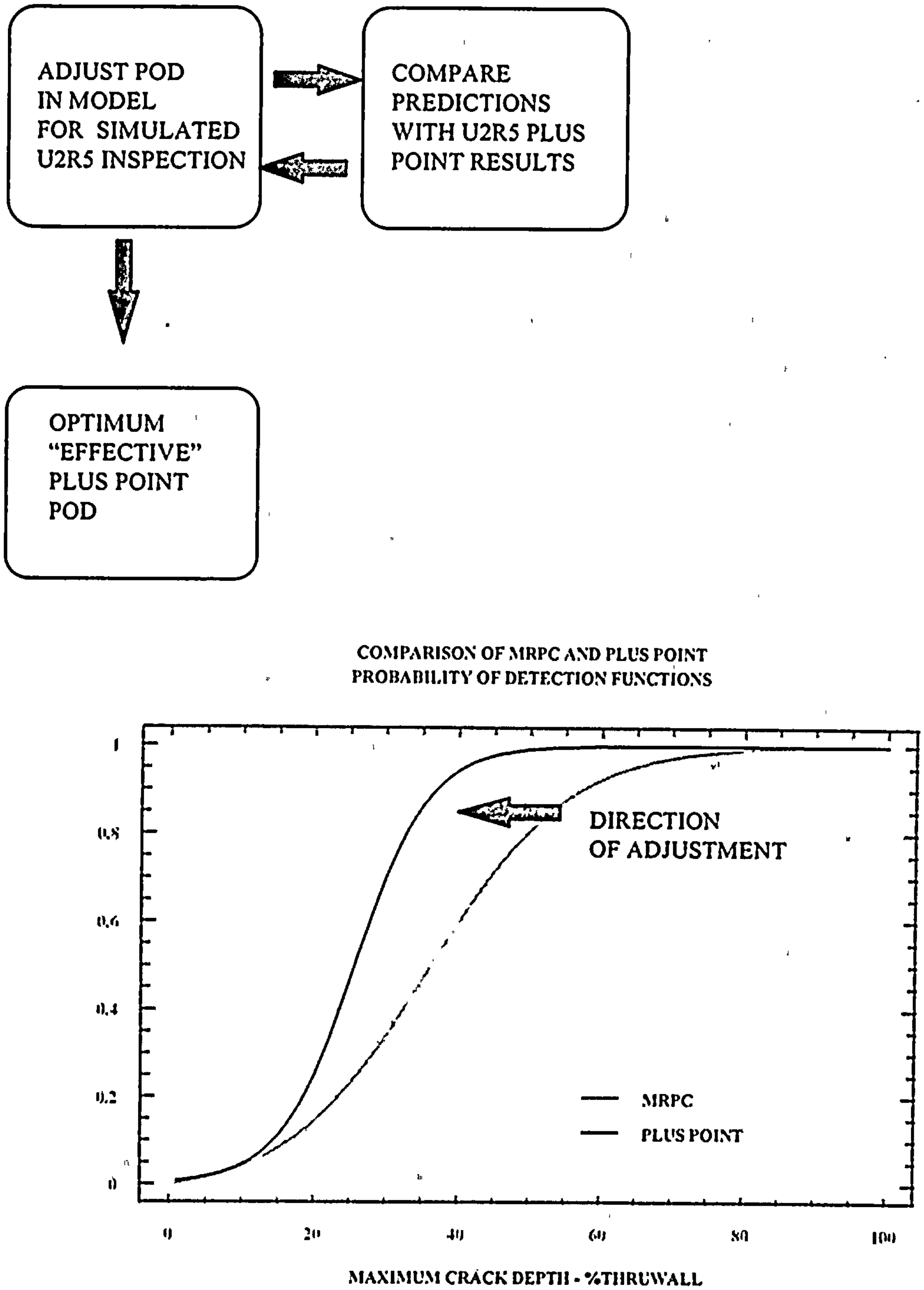


Figure 5.5 SCHEMATIC OF PLUS POINT POD OPTIMIZATION PROCESS

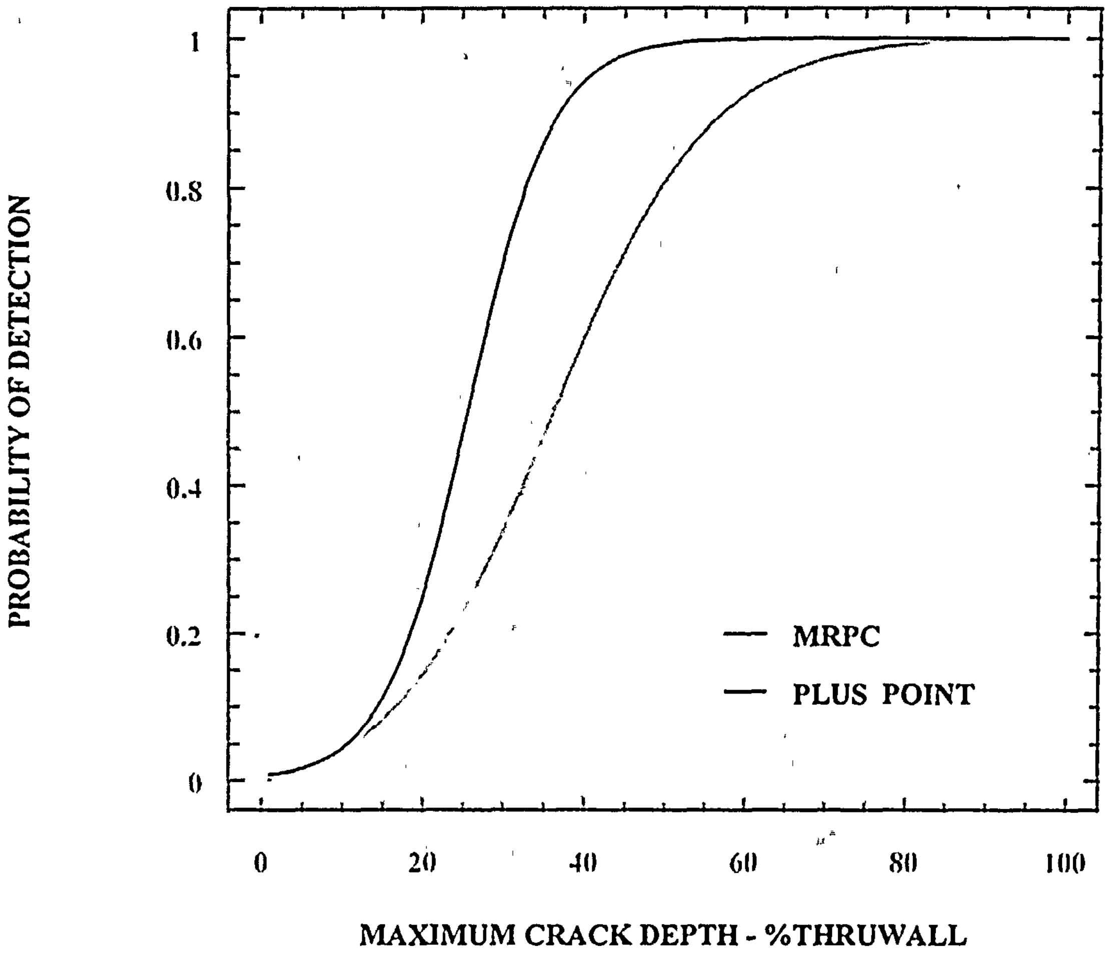
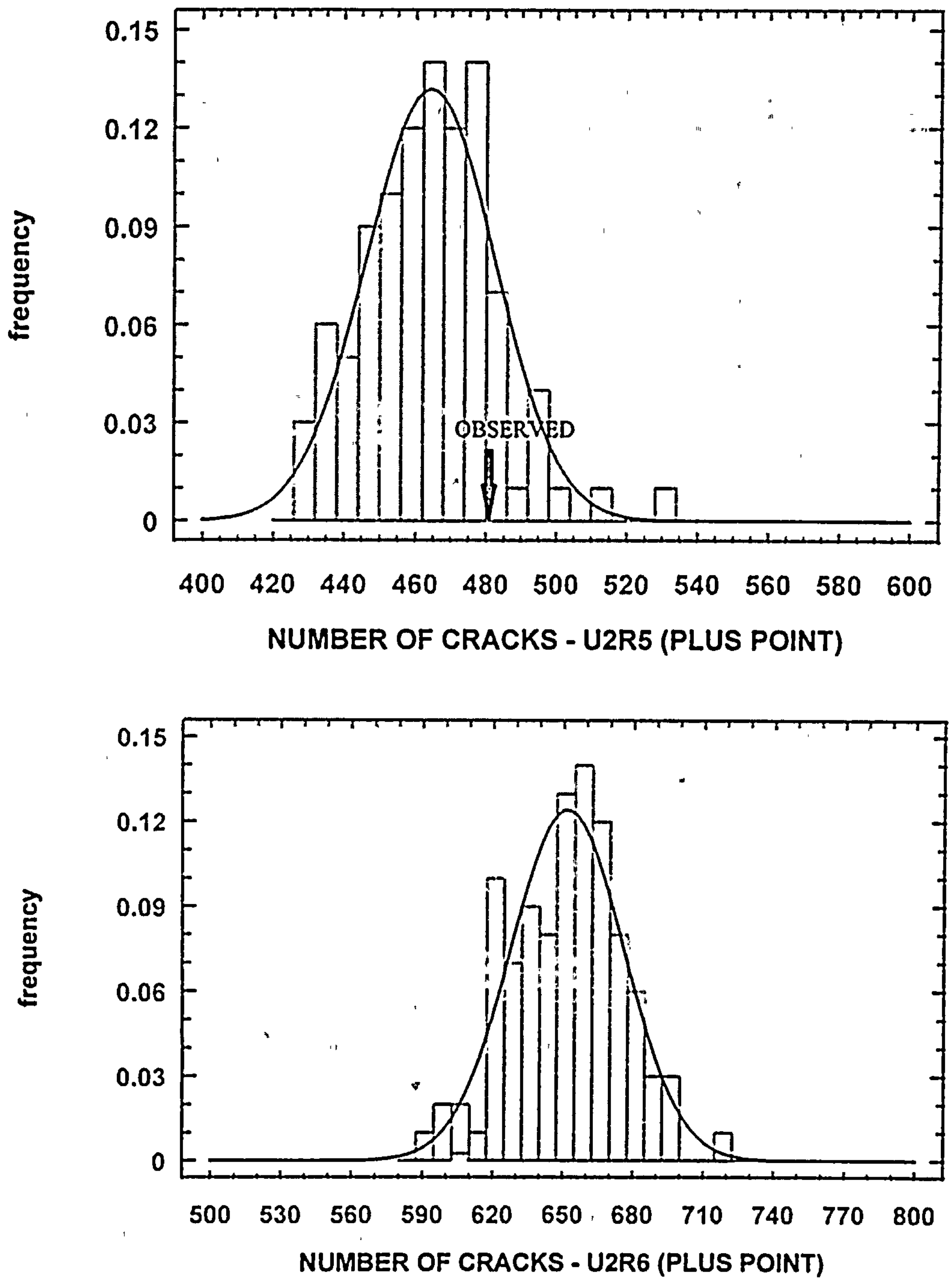


Figure 5.6 COMPARISON OF MRPC AND PLUS POINT PROBABILITY OF DETECTION FUNCTIONS



PROJECTED FOR 12 MONTH RUN TIME

Figure 5.7 PROJECTED NUMBER OF CRACKS FOR PLUS POINT INSPECTIONS

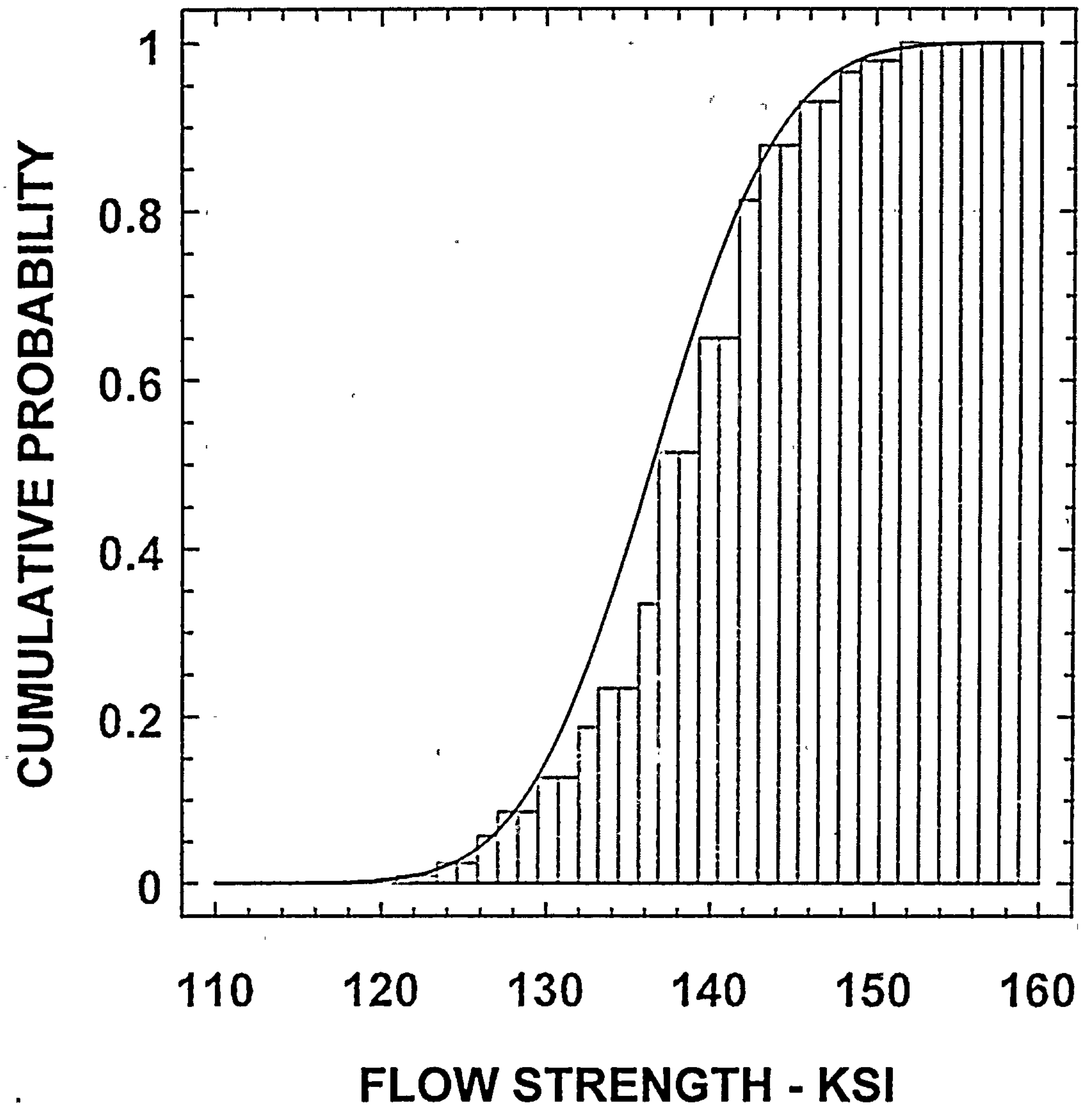


Figure 5.8 TUBE FLOW STRENGTH DISTRIBUTION FOR UNIT 2 ANALYSIS

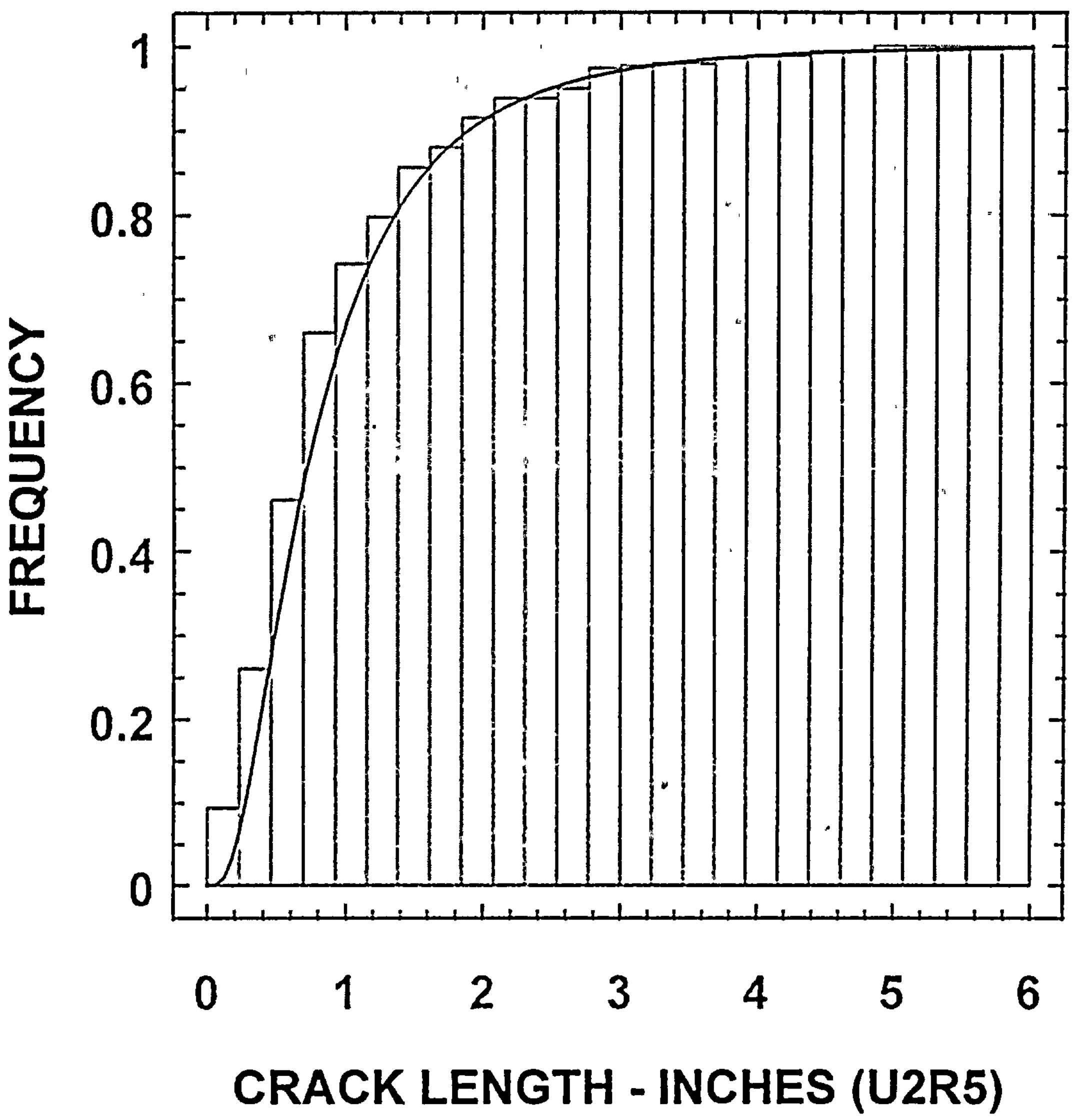


Figure 5.9 DISTRIBUTION OF U2R5 CRACK LENGTHS

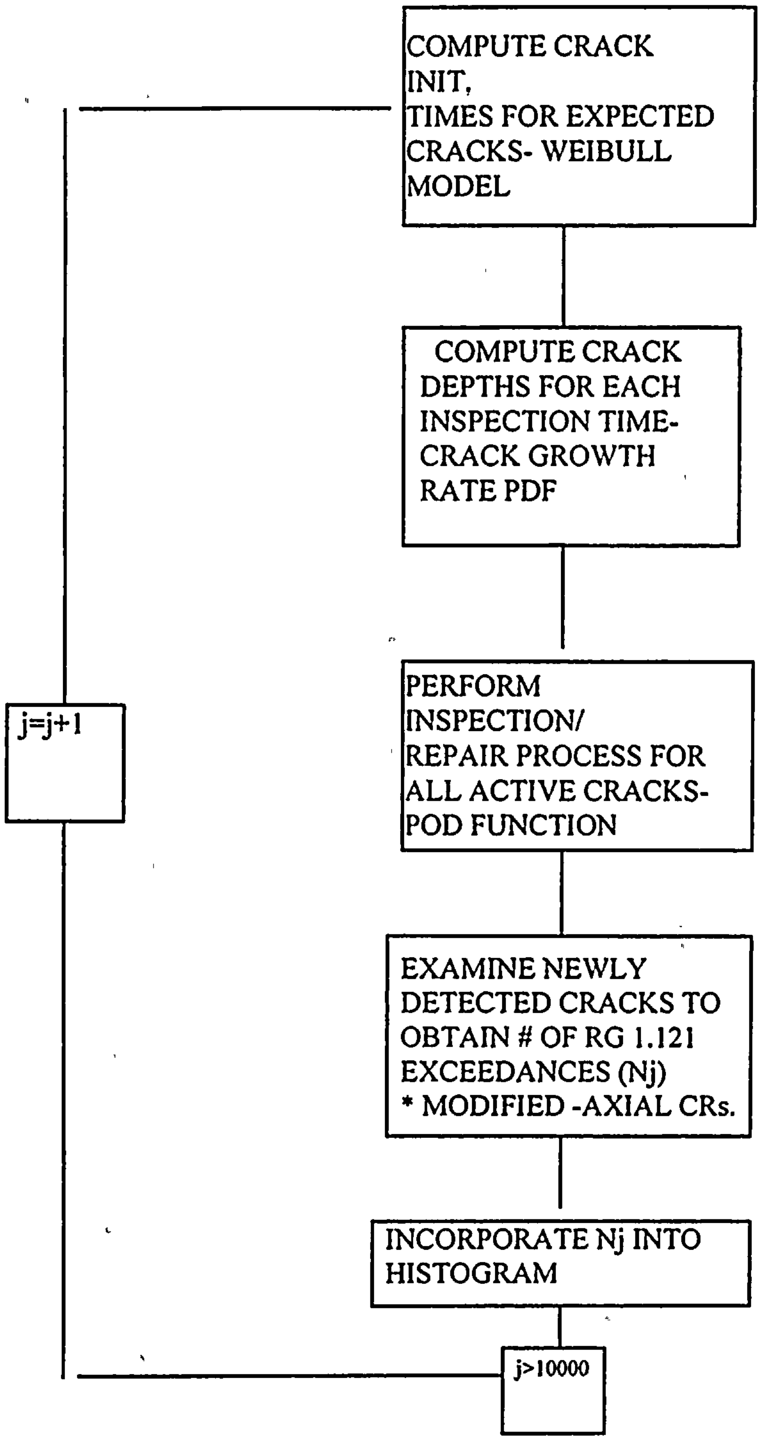


Figure 5.10 SIMULATION SCHEMATIC FOR PROBABILISTIC MODEL - ALL MECHANISMS

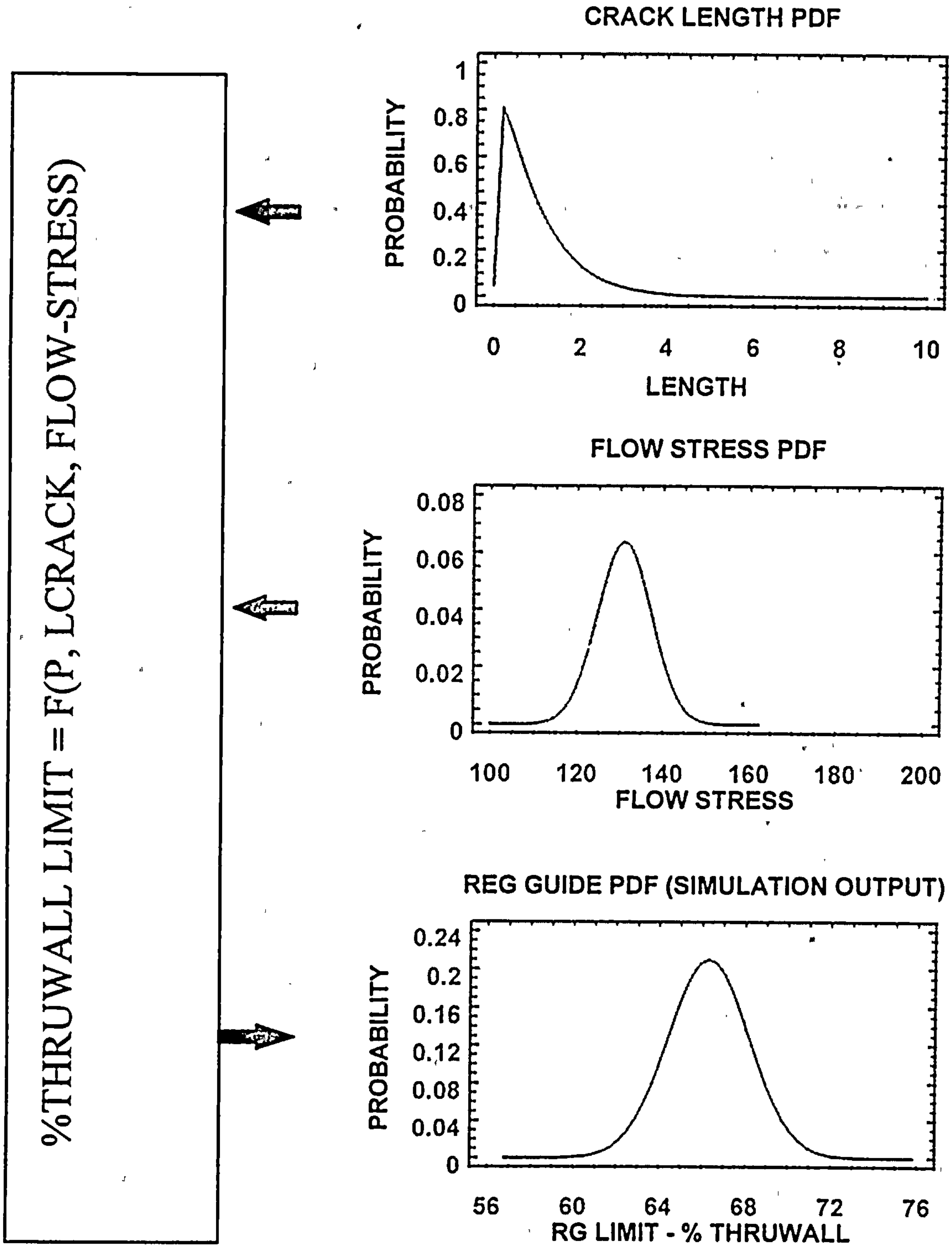


Figure 5.11 REG GUIDE LIMIT SIMULATION

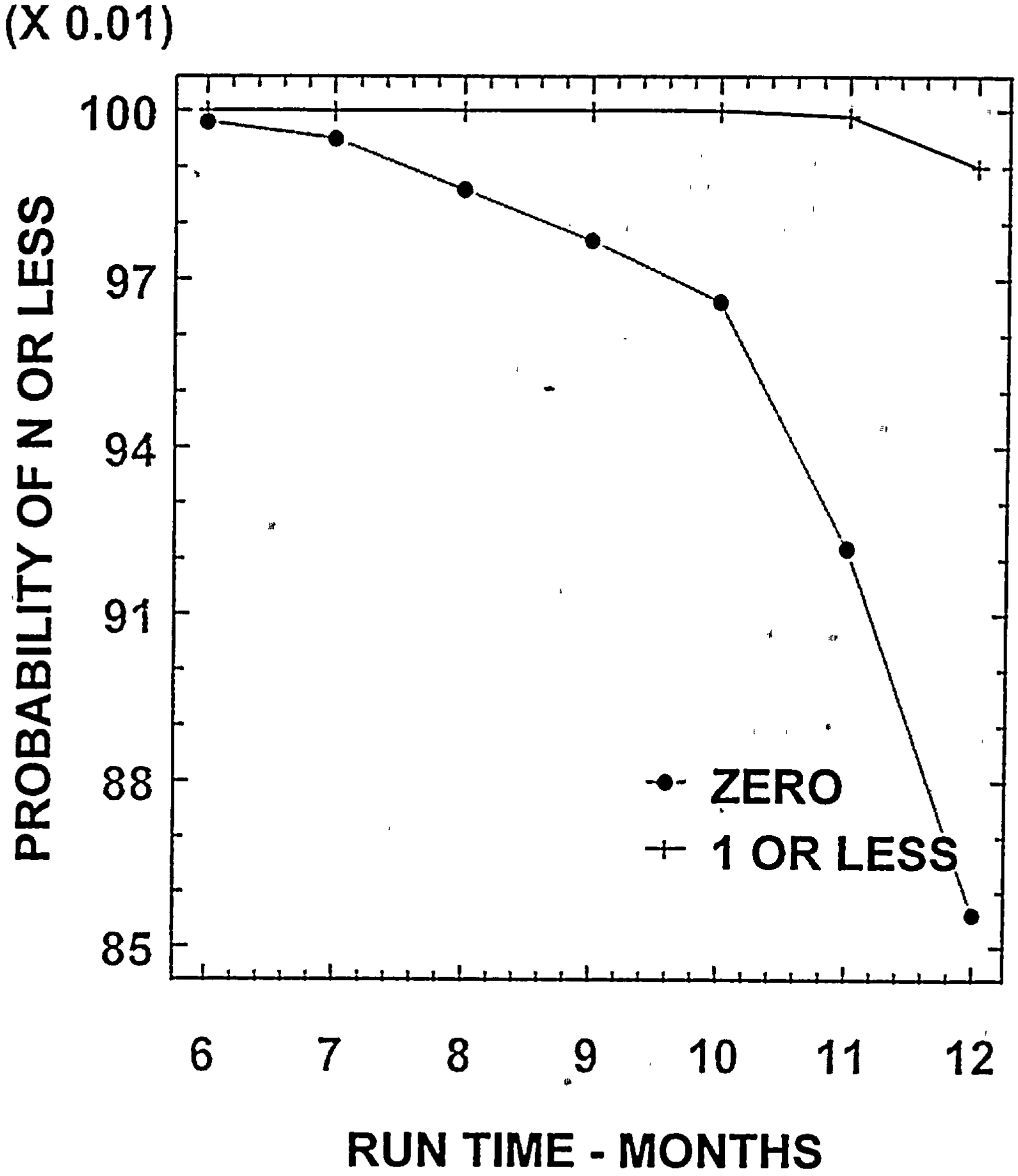


Figure 5.12 PROBABILITY OF N OR LESS RG 1.121 EXCEEDANCES AT U2R6 VS. RUN TIME

midcycle outages. During the downpower, contaminant hideout return is quantified and characterized to ascertain the effects of the operating period's chemistry control. Elevated levels of the insoluble species which typify tube deposit environments, such as sulfate, silica and calcium are observed. Hideout return of sodium, a soluble species more typical of crevice environments has been very minimal.

4. Boric Acid Treatment

Boric acid treatment was initiated in Unit 2 during U2M5-1 as a remedial step for caustic crevice environments. The reasoning behind boric acid's effectiveness is threefold:

1) Boric acid reduces the pH of alkaline environments by reaction with NaOH to form borate.

2) Boric acid dilutes the OH^- concentration, thereby lowering the chemical activity and reducing the probability that OH^- is present at the actively corroding grain boundary.

3) Boric acid forms a passive borate layer on Alloy 600 tubing, protecting the metal by restricting the movement of the OH^- ion.

Crevice flushes with 2000 ppm boron were performed on both steam generators at 290 °F during Mode 4. The 07H through 09H support regions were targeted during a series of eleven flushes per steam generator. A low power soak at 300 ppm boron commenced following the crevice flushes and was maintained to power ascension. Boron concentrations during operations have been maintained in the
5 - 10 ppm boron range.

During the U2M5-2 outage a 300 ppm low power soak was successfully completed. and during the U2R5 outage, the 2000 ppm boric acid crevice flush was performed on SG 22 only. A 300 ppm low power soak was successfully completed on both steam generators.

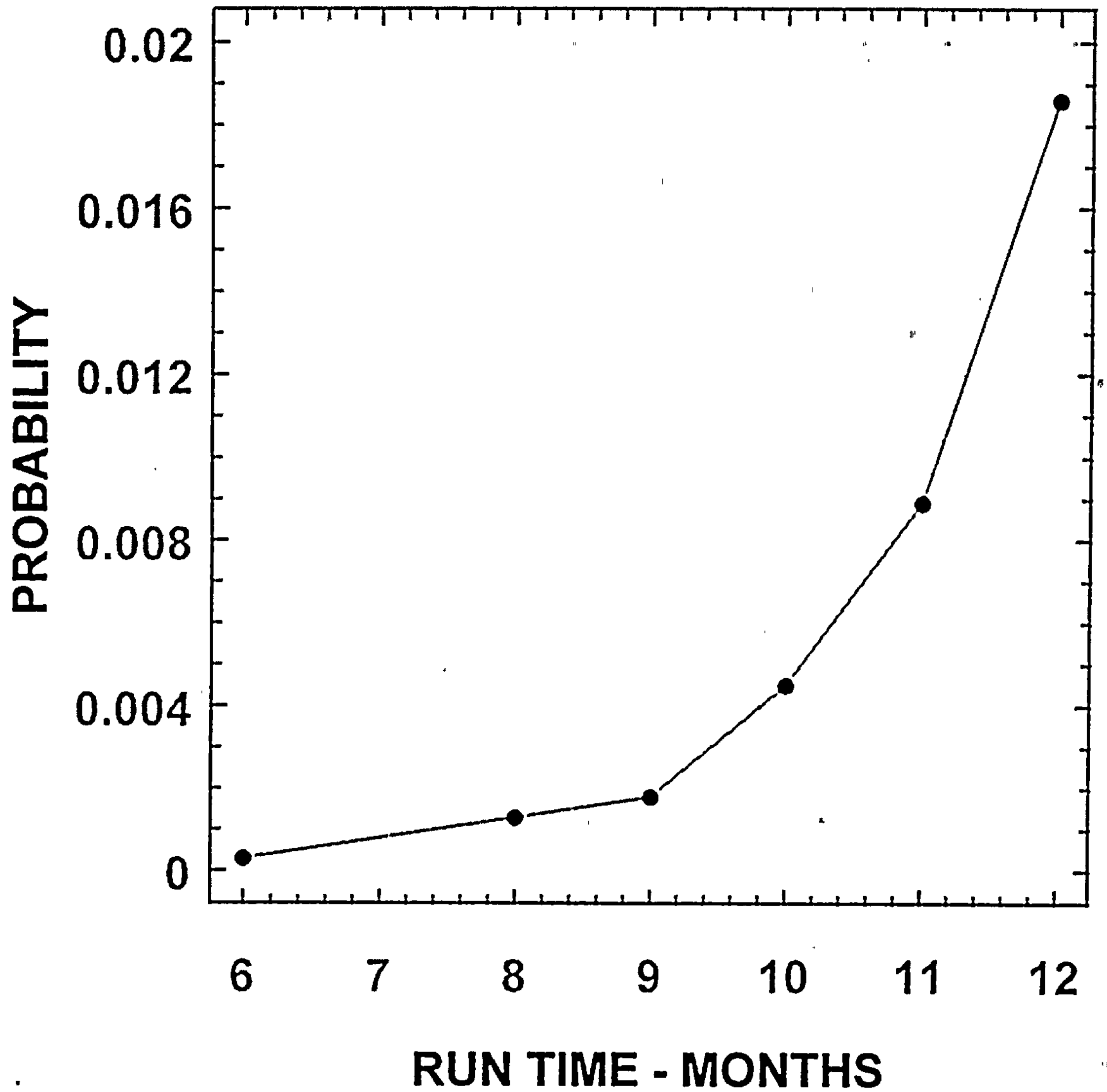


Figure 5.13 PROBABILITY OF TUBE RUPTURE UNDER STEAM LINE BREAK DIFFERENTIAL PRESSURE LOAD

chemistry, as reported to INPO for all operations above 30% power, is presented in Table C-2.

Table C-2

Chloride ppb	Sodium ppb	Sulfate ppb	Iron ppb	Oxygen ppb	Molar Ratio
4.60	2.63	2.88	5.23	5.34	1.02

Molar ratio control was significantly improved by the injection of ammonium chloride during the cycle. Results of the EPRI MULTEQ code predictions indicate that this chemistry program significantly improved crevice pH. The predictions are 8.6 for U2M5-1, 6.4 for U2M5-2 and 5.95 for U2R5 (neutral pH is approximately 5.0). Additionally the shutdown chemistry approached neutral pH crevice environments during operation, and the quantity of caustic species hideout was reduced.

3. Reducing Dryout Region Effects

PVNGS has consistently operated within EPRI guidelines for steam generator sodium and sulfate contamination. As reported in the "Status of PVNGS Steam Generator Activities", August 1994, Palo Verde implemented stricter specifications for these two species. The requirement to reduce power to, or maintain power at 86% power at levels as low as 20 ppb sodium or sulfate, mitigates the effects of the upper bundle dryout. The requirement was also adhered to following each downpower event ensuring chemistry control was acceptable prior to increasing power above 86% power. EPRI specification guidelines allow 7 days operation at 20 ppb sodium or sulfate prior to taking action versus Palo Verde's requirement to downpower within 8 hours.

In addition to the specification requirement to maintain power at 86% in the event of elevated sodium or sulfate, whether due to source term ingress during operation or hideout return due to a downpower, Unit 2 completed a planned downpower to 70% power in order to re-wet the upper bundle dryout region. This course of action was completed approximately six weeks after startup from the refueling outage. Two forced shutdowns occurred for the

- Changes in the normal and abnormal blowdown schemes to enhance ionic impurity removal.

- Establishment of a Water Treatment Department responsible for improving secondary chemistry control.

- Improvements in condensate polisher design and operations to reduce resin cross contamination, sodium and sulfate throw.

2. Chemical Cleaning Effects

The Unit 2 steam generator chemical cleaning was performed during February 1994 (U2M5-1). Details of the process application are described in Reference 17. The process effectively removed 5910 pounds of iron from SG 21 (including 300 pounds from sludge lance) and 5402 pounds from SG 22(including 390 pounds from sludge lance). As expected, the amount of copper removed from each SG was minimal (less than 10 pounds). This is consistent with a nearly copper-free facility (the condenser tubesheet is composed of aluminum-bronze).

During U2R5, the steam generators were sludge lanced. Approximately 234 pounds of iron was removed from SG 21 and 221 pounds removed from SG 22. A sludge sample was analyzed with the results listed in Table C-1.

Table C-1

	Fe_3O_4 %	PbO ppm	Cr_2O_3 ppm	NiO %
SG 21	100.8	72	558	1.2
SG 22	99.8	71	515	1.3

After completion of chemical cleaning, it was anticipated that typical operating chemistry values would be elevated due to the lack of crevice regions and fouling which would act as host sites for hideout. The average Cycle 5

ensure the cross contamination of cation and anion resin meets acceptance criteria. Additional tests for qualifying the condition of the resin are performed by the Central Chemistry Laboratory located on site.

A significant reduction in sodium throw has been accomplished by completion of several design modifications to the polishers and by reducing the concentration of caustic (sodium hydroxide) used to regenerate the anion resin by one half. The modifications have resulted in enhanced control of the resin separation process. Installation of hand indicating controllers (throttle valves for flow separation control) have optimized control of the cation/anion resin interface during separation resulting in optimized resin separation and minimized cross contamination. The separation process was further optimized by installing an anion resin drawoff header.

In order to further reduce the potential for sulfate ingress, all resin retention elements and resin traps were inspected and repaired as required. Testing has been completed and Unit 2 has installed 45 micron resin traps downstream of all polisher vessels. The 45 micron size is roughly ten times smaller than the previous traps which were designed to contain a catastrophic failure of a retention element within the polisher vessel.

Through a combination of source term identification and reduction, condensate polisher design modifications and condensate polisher regeneration enhancements, the Unit 2 chemistry reported to INPO was significantly improved as shown in Table C- 2.

Unit 2 Cycle 5 Operating Chemistry

1. Introduction

APS has reviewed the Unit 2 Cycle 5 operating chemistry experience to determine if the current program has been optimized to mitigate the predominant types of tube degradation observed to date at Palo Verde. The current program has been designed to address the key chemistry-related contributors to the Unit 2 ARC region ODSCC: caustic-sulfate environment, freespan crevice formation and the dry-out region contaminant concentration effects. Elements of the program will also have a similar benefit on the circumferential cracking at the tubesheet. The results of this review, and a description of the current chemistry program in Unit 2 will be presented in the following sections. The following topics highlight this review.

- Steam generator chemical cleaning and the subsequent effects on operating and shutdown chemistry trends. Steam generator sludge lancing and sludge analysis.

- Continuation of planned downpowers, and incorporation of more restrictive chemistry specifications to reduce the effects of the dryout region.

- Initiation of a comprehensive boric acid treatment program to neutralize steam generator crevice pHs.

- Initiation of ammonium chloride injection to neutralize steam generator crevice pHs.

- Initiation of ethanolamine treatment to reduce iron transport.

- Continuation of elevated hydrazine for electrochemical potential minimization and iron oxide ratio control.

- Initiation of nitrogen sparging to reduce condensate dissolved oxygen and iron transport.

APPENDIX B

Unit 2
Operating Chemistry
Summary
Cycle 5

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7.0 REFERENCES

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wide basis. Early results are encouraging. Work toward developing growth rate distributions using phase angle crack profiles is in progress.

A highly refined probabilistic model was used to evaluate the structural integrity of steam generator tubing in PVNGS Unit 2 which is subject to upper bundle, axial, OD IGA/IGSCC. The approach is well benchmarked with the past corrosion performance of the steam generators. The probability of exceeding Regulatory Guide 1.121 structural margins has been computed as a function of run time in Cycle 6. After 12 months of operation the probability of more than one exceedance would be less than 0.01. At this same point in time, the conditional probability of tube burst given the occurrence of a main steam line break is 0.018. With regard to leakage, there is less than a 10% chance of wall penetration if a steam line break occurs after 12 months of operation.

TABLE 5-1

INSPECTION	CRACKS	TIME (EFPY)	TEMPERATURE (Prior Operation)	COMMENTS
U2R4	170	4.62	621°F	.080 RPC probe, pre-chemical cleaning (questionable)
U2M5-1	653	4.97	609°F	.115 RPC probe, post-chemical cleaning (inspection transient)
U2M5-2	261	5.47	613°F	.115 RPC probe, partial inspection with RPC (at and above BW1)
U2R5	483*	5.76	613°F	.115 RPC probe, full inspection, first use of plus point probe for U2 (inspection transient)

*Approximately 290 cracks detectable by MRPC

6.0 SUMMARY

An analysis was performed of the effect of upper bundle, axial, IGA/IGSCC on the structural integrity of steam generator tubing in Palo Verde Unit 2. The analysis was fully probabilistic. Using a statistical approach which has been continuously refined over the past two years, the processes of initiation of IGA/IGSCC, growth and eddy current inspection were modelled. Hence, the past performance of Unit 2 was simulated and used as a benchmark to project the progression of upper bundle corrosion degradation during Cycle 6. Predictions of the number of NDE indications versus run time closely match past observations. The distribution of observed changes in RPC eddy current probe voltages also matches predicted values. This serves to validate the initiation, growth and eddy current probe probability of detection functions. After completion of the model and computation of corrosion degradation as a function of run time, a final benchmark was evaluated. In agreement with past experience, the simulation model correctly indicated a high probability of a tube burst event at normal operating pressure at the end of Cycle 4.

The Plus Point eddy current probe was used in the last inspection in addition to the standard RPC probe. The improved detection sensitivity of the Plus Point probe led to an inspection transient in terms of a larger number of NDE indications relative to projections based on use of the standard probe. This inspection transient provided input to derive a probability of detection curve for the Plus Point probe. Use of the Plus Point probe was found to be of significant benefit in terms of structural margins as a function of run time in Cycle 6.

Considerably refined statistical techniques were used to develop a degradation growth rate distribution from observations of RPC probe voltage changes. Consistent parameters were developed using three independent techniques. The degradation growth rate distribution was evaluated in terms of predictions versus observations of RPC voltage changes, laboratory data, pulled tube corrosion morphology and field experience with variations in time to failure. The degradation growth rate distribution interacts with the initiation function and eddy current probability of detection curve to affect predictions of both the numbers of NDE indications and the severity of degradation relative to structural integrity. Hence good correspondence of predictions with observations of the number and severity of cracks provides another measure of validating the degradation growth rate distribution. Additional means of developing growth data are being pursued. Crack profiles can be generated from RPC phase angle information as the probe repeatedly traverses a crack along its length. This technique is being evaluated on an industry

changed to a cyclic program, where normal and abnormal blowdown modes are cycled on each steam generator while the other steam generator is in the opposite mode. Previously only the normal

10. Water Treatment Department

In order to meet the secondary chemistry improvement goals established by the site, the Water Treatment Department was established during August 1994. The department, reporting to the Director of Operations, established a single point of contact across the site to address secondary chemistry control and radwaste processing issues including the following.

- Condensate polisher and blowdown demineralizer operation, maintenance and design modifications.
- Chemical feed system operation.
- Contaminant ingress minimization.
- Radwaste processing.

The department staff includes dedicated polisher operators, as well as chemistry, engineering and project management personnel. Details of improvements in polisher design and operation are presented in the following section.

11. Condensate Polisher Improvements

Improvements in condensate polisher and blowdown demineralizer design and operation continue to focus on monitoring and reducing the ingress of resin fragments, sodium and sulfate.

In order to improve monitoring capabilities, the site installed an ion chromatograph with the capability of performing on-line low level sensitivity analyses of each polisher beds outlet. The data will be used to improve the quality of regenerations and to determine precisely when a polisher bed should be removed from service. In addition to monitoring bed effluent chemistry, the site has established a resin testing program. Resin tests for cross contamination are performed by operators during each regeneration to

7. Elevated Hydrazine

In accordance with the EPRI PWR Secondary Water Chemistry Guidelines, Palo Verde increased the feedwater hydrazine concentration to greater than 100 ppb in January 1993. Unit 2 has maintained elevated hydrazine throughout the cycle while on-line testing of electrochemical potential (ECP) is was conducted in Unit 1 between January 1995 and April 1995 to determine baseline ECP under current chemistry control. The recommended increase in hydrazine was based upon industry data indicating that increased hydrazine concentrations promoted a reduction in ECP. A reducing environment in the steam generator, as indicated by ECP, can significantly reduce the rate of intergranular attack. The ECP baseline results are approximately -560 mV standard hydrogen electrode (SHE) corrected for Alloy 600. The ECP test results in Unit 1 indicate the final feedwater dissolved oxygen concentrations are significantly less than 1 ppb, and are not impacted by reductions in hydrazine feedrate or fluctuations of 1 to 7 ppb dissolved oxygen concentrations in the condensate. Similarly, the ECP is not impacted by hydrazine feed rate or condensate oxygen fluctuations of 1 to 7 ppb. Additional testing is currently being conducted to provide metal oxidation state data (hematite to magnetite ratios) with varying hydrazine concentrations. The oxide state data will determine how the hydrazine concentration impacts the ratio of hematite to magnetite in the final feedwater. Hematite can raise the ECP by + 100 mV and can therefore have an impact on intergranular attack. Upon completion of the oxide state analyses, a final determination for hydrazine concentration will be made.

8. Nitrogen Sparging

Nitrogen sparging was introduced to Unit 2 following the start of Cycle 6 April 1995. Condensate dissolved oxygen is controlled to approximately 1 to 2 ppb. Preliminary data indicates an additional reduction in iron transport since the implementation of nitrogen sparging.

9. Blowdown Changes

In order to further reduce operating contaminant concentrations of soluble ionic species such as sodium and sulfate the blowdown scheme has been

5. Ammonium Chloride Injection

Ammonium chloride injection was initiated in Unit 2 following the U2M5-1 outage, May 1994, in order to control steam generator crevice pHs within a near-neutral range. Sodium reduction methods have been concurrently pursued to minimize the quantity of ammonium chloride required for injection. The objective of molar ratio control is to promote a near-neutral crevice pH environment by developing a relationship between bulk water chemistry and crevice chemistry which can be monitored and controlled on a daily basis. Palo Verde determined an initial control range of 0.2 - 0.6 (equivalents of sodium divided by chloride) was appropriate to achieve a neutral shutdown molar ratio target of 1.0. Based upon the hideout return observed during three shutdowns during the cycle, the initial target range remains appropriate. The midcycle outage MULTEQ predictions indicated near-neutral conditions as stated earlier, and the shutdown molar ratios were only slightly higher than the 1.0 target. Average molar ratio for the cycle with ammonium chloride injection was 0.57 as compared to ratios ranging from 1.13 to 2.1 without injection prior to U2R5.

Unit 2 will continue to operate within the 0.2 - 0.6 band with the optimum target at the low end of the band.

6. Ethanolamine pH Control

In June 1994, Unit 2 converted from ammonia to ethanolamine (ETA) for secondary system pH control with the goal of reducing corrosion product to the steam generators. ETA successfully reduced iron transport as evidenced by the comparisons prior to the implementation of ETA when ammonia was utilized, iron transport averaged 6.0 ppb (during elevated ammonia and condensate demineralizer bypass operation). Following the implementation of ETA the iron transport values typically averaged 4.4 ppb

With ETA operation, the unit has the highest degree of flexibility in operating with or without condensate polishers. This flexibility is desired due to the potential for condenser tube leaks which would necessitate operation with full flow condensate polishing. With ammonia, the site specific upper pH which Palo Verde could operate and maintain full flow condensate polishing was 9.15. Under those conditions, iron transport was typically 10 ppb. ETA was adopted to reduce iron transport rates to less than the 5 ppb EPRI specification without having an adverse affect on the polishers.

REVIEW OF U2R5 ARC REGION DEFECTS - VOLTAGE GROWTH

UNIT	SG	ROW	LINE	LENGTH	LOCATION	R5VOLTS	R5rev	INITVOLTS	M2rev	INDOUT	DVDT
2	2	140	91	0.5	BW1+19.59	0.37		0.17		2	0.682
2	2	140	91	0.3	BW1+6.62	0.41		0.27		2	0.477
2	2	152	91	0.6	BW1+27.24	0.41		0.27		2	0.478
2	2	144	91	0.7	BW1+7.16	0.44		0.57		2	-0.44
2	2	136	91	1	bw1+5.56	0.47		0.32		2	0.511
2	2	130	91	1.1	bw1+7.51	0.74		0.45		2	0.989
2	2	144	91	1.7	BW1+20.67	0.96	1.14	0.53	1.2	2	1.468
2	2	145	92	2.2	BW1+7.80	0.2		0.24		2	-0.137
2	2	143	92	0.9	BW1+9.35	0.5		0.21		2	0.989
2	2	137	92	0.6	BW1+4.47	0.61		0.38		2	0.784
2	2	143	92	1.3	BW1+7.17	0.82	0.76	0.35	0.38	2	1.604
2	2	150	93	0.7	BW1+17.03	0.23		0.5		2	-0.92
2	2	136	93	0.7	BW1+18.99	0.4		0.27		2	0.443
2	2	130	93	0.5	BW1+8.83	0.44		0.24		2	0.682
2	2	142	93	0.5	BW1+7.83	0.45		0.3		2	0.511
2	2	149	94	1.7	BW1+19.45	0.41		0.26		2	0.511
2	2	133	94	0.6	BW1+8.00	0.78		0.16		2	2.116
2	1	124	95	1.5	BW1+5.7	0.26		0.3		2	-0.13
2	2	140	95	0.7	BW1+10.00	0.35		0.15		2	0.682
2	1	136	95	0.5	BW1+7.43	0.36		0.41		2	-0.17
2	2	136	95	1.7	BW1+22.28	0.68		0.33		2	1.194
2	2	149	96	1.5	BW1+20.01	0.34		0.46		2	-0.4
2	1	141	96	0.7	BW1+7.37	0.4		0.26		2	0.477
2	2	137	96	3	BW1+20.41	0.44		0.38		2	0.204
2	1	144	97	0.3	BW1+3.52	0.59		0.38		2	0.716
2	2	140	99	0.5	BW1+3.39	0.37		0.35		2	0.068
2	1	151	100	1.4	BW1+18.3	0.2		0.28		2	-0.27
2	2	127	100	0.9	BW1+7.71	0.21		0.24		2	-0.1
2	2	127	100	0.6	BW1+2.65	0.33		0.25		2	0.273
2	2	135	100	0.8	BW1-1.12	0.36		0.22		2	0.477
2	2	135	100	0.4	BW1+7.86	0.42		0.37		2	0.17
2	2	149	100	1.6	BW1+18.31	0.56		0.32		2	0.819
2	1	150	101	1.6	BW1+18.75	0.26		0.28		2	-0.06
2	2	154	101	1	BW1+24.63	0.43		0.28		2	0.511
2	2	133	102	0.4	BW1+6.34	0.27		0.38		2	-0.37
2	2	133	102	0.6	BW1+2.28	0.37		0.33		2	0.136
2	2	128	103	0.7	BW1+8.008	0.21		0.12		2	0.307
2	2	146	103	0.8	BW1-.22	0.23		0.11		2	0.409
2	2	146	103	0.4	BW1+9.45	0.37		0.2		2	0.58
2	2	132	103	1	BW1+2.7	0.42		0.29		2	0.443
2	2	132	103	2	BW1+6.59	0.61		0.46		2	0.511

REVIEW OF U2R5 ARC REGION DEFECTS - VOLTAGE GROWTH

UNIT	SG	ROW	LINE	LENGTH	LOCATION	R5VOLTS	R5rev	INITVOLTS	M2rev	INDOUT	DVDT
2	2	146	103	2	BW1+18.31	1.02	1.02	0.22	0.22	2	2.73
2	2	127	104	0.5	BW1+1.88	0.23		0.23		2	0
2	2	131	104	1	BW1+5.63	0.32		0.33		2	-0.03
2	1	115	104	0.8	BW1+3.09	0.32		0.58		2	-0.88
2	2	149	104	1.3	BW1+14.76	0.43		0.39		2	0.136
2	2	147	104	1.3	BW1+18.18	0.61		0.36		2	0.853
2	2	140	105	0.2	BW1+6.88	0.17		0.13		2	0.136
2	1	142	105	0.9	BW1+8.90	0.2		0.31		2	-0.37
2	1	145	106	0.3	BW1+1.7	0.2		0.22		2	-0.06
2	2	149	106	1.9	BW1+19.18	0.28		0.41		2	-0.44
2	1	145	106	0.8	BW1+18.51	0.3		0.66		2	-1.22
2	1	145	106	0.8	BW1+15.81	0.44		0.45		2	-0.03
2	2	140	107	0.8	BW1+7.15	0.1		0.28		2	-0.61
2	2	138	107	1.1	BW1+18.53	0.16		0.15		2	0.034
2	2	152	107	0.8	BW1+16.33	0.2		0.18		2	0.068
2	2	140	107	1.2	BW1+5.21	0.28		0.25		2	0.102
2	1	148	107	3.3	BW1+16.13	0.32		0.22		2	0.341
2	2	150	107	2	BW1+19.97	0.38		0.34		2	0.136
2	1	136	107	1	BW1+.65	0.47		0.44		2	0.102
2	2	140	107	1.7	BW1+18.73	0.57		0.44		2	0.443
2	2	143	108	1	BW1+3.68	0.41		0.46		2	-0.17
2	2	131	108	0.5	BW1+1.28	0.56		0.31		2	0.853
2	1	150	109	0.7	BW1+18.47	0.24		0.33		2	-0.3
2	2	146	109	0.4	BW1+.70	0.35		0.52		2	-0.58
2	2	142	109	1.1	BW1+7.31	0.79		0.47		2	1.092
2	2	145	110	1.9	BW1+4.65	0.81		0.51		2	1.023
2	1	150	111	4	BW1+17.15	0.35		0.52		2	-0.58
2	2	138	111	1.3	BW1+4.79	0.7		0.32		2	1.296
2	2	147	112	0.8	BW1-.10	0.22		0.18		2	0.136
2	2	145	112	1.2	BW1+6.24	0.49		0.45		2	0.136
2	2	137	112	1.8	BW1+7.84	0.55		0.78		2	-0.785
2	2	138	113	0.7	BW1+4.83	0.31		0.34		2	-0.1
2	2	144	113	0.8	BW1+5.78	0.34		0.26		2	0.273
2	1	148	113	1.4	BW1+15.37	0.39		0.83		2	-1.5
2	2	144	113	0.6	BW1+1.46	0.44		0.55		2	-0.37
2	1	147	114	1.9	BW1+16.08	0.29		0.31		2	-0.06
2	1	148	115	0.6	BW1+18.22	0.22		0.2		2	0.068
2	1	132	115	0.6	BW1+3.21	0.31		0.25		2	0.204
2	2	132	115	0.2	BW1+.64	0.4		0.26		2	0.477
2	2	139	116	0.1	BW1+3.59	0.18		0.29		2	-0.37
2	2	139	116	0.1	BW1+9.49	0.26		0.34		2	-0.27

REVIEW OF U2R5 ARC REGION DEFECTS - VOLTAGE GROWTH

UNIT	SG	ROW	LINE	LENGTH	LOCATION	R5VOLTS	R5rev	INITVOLTS	M2rev	INDOUT	DVDT
2	2	151	118	2	BW1+17.94	0.34		0.41		2	-0.23
2	2	137	118	0.3	BW1+.35	0.47		0.38		2	0.307
2	1	147	118	0.9	BW1+17.42	0.57		0.35		2	0.751
2	2	138	119	0.2	BW1+6.80	0.2		0.44		2	-0.819
2	1	147	120	1.1	BW1+17.89	0.48		0.42		2	0.204
2	2	138	121	0.5	BW1+5.45	0.22		0.23		2	-0.03
2	2	140	121	1.4	BW1+5.41	0.35		0.52		2	-0.58
2	2	144	121	3	BW1+6.32	0.45		0.63		2	-0.61
2	2	152	121	0.7	BW1+17.52	0.5		0.29		2	0.716
2	2	144	121	0.8	BW1-1.51	0.91		0.39		2	1.774
2	2	145	122	1.5	BW1+.49	0.56		0.44		2	0.409
2	2	138	123	0.7	BW1+7.36	0.31		0.76		2	-1.53
2	2	150	123	1.3	BW1+17.61	0.33		0.63		2	-1.02
2	2	149	124	1.6	BW1+17.51	0.35		0.2		2	0.511
2	2	150	125	0.4	BW1+17.10	0.47		0.27		2	0.682
2	2	138	127	0.7	BW1+6.02	0.43		0.32		2	0.375
2	1	142	127	2	BW1+18.03	0.68		1.07		2	-1.33
2	2	137	128	2.9	BW1+7.38	0.47		0.21		2	0.887
2	2	146	129	1.3	BW1+17.33	0.57		0.55		2	0.068
2	2	144	129	1.2	BW1+18.16	0.74		0.51		1	0.337
2	1	142	129	1.2	BW1+18.95	0.94	0.44	0.26	0.42	2	2.32
2	1	138	129	0.5	BW1+16.90	2.01	0.6	0.45	0.46	2	5.324
2	1	145	130	0.5	BW1+18.34	0.45		0.37		2	0.273
2	1	137	130	0.3	BW1+13.93	0.53		0.41		2	0.409
2	2	141	130	1.1	BW1+16.23	0.54		0.59		2	-0.17
2	1	136	131	1.6	BW1+16.32	0.28		0.27		2	0.034
2	1	138	131	1.5	BW1+18.13	0.52		0.56		2	-0.13
2	1	140	131	2.7	BW1+17.54	0.61		0.25		2	1.228
2	2	133	132	0.6	BW1-1.90	0.18		0.33		2	-0.51
2	2	133	132	0.6	BW1+1.30	0.24		0.3		2	-0.2
2	2	122	133	1.1	BW1+6.46	0.31		0.36		2	-0.17
2	2	138	133	1.4	BW1+15.93	0.49		0.26		2	0.784
2	2	140	133	0.5	BW1+18.84	0.57		0.34		2	0.784
2	2	125	134	0.2	BW1+.73	0.24		0.25		2	-0.034
2	2	125	134	1.5	BW1+6.89	0.46		0.25		2	0.716
2	1	125	134	1	BW1+4.79	0.65		0.53		2	0.409
2	2	114	135	0.4	BW1+.45	0.18		0.18		2	0
2	2	86	135	0.8	BW1+3.51	0.73		0.28		2	1.535
2	2	117	136	0.3	BW1+7.03	0.29		0.25		2	0.136
2	2	127	136	0.5	BW1+7.05	0.46		0.48		1	-0.02
2	2	132	137	0.3	BW1-1.38	0.3		0.27		2	0.102

REVIEW OF U2R5 ARC REGION DEFECTS - VOLTAGE GROWTH

UNIT	SG	ROW	LINE	LENGTH	LOCATION	R5VOLTS	R5rev	INITVOLTS	M2rev	INDOUT	DVDT
2	1	112	39	1	BW1+15.88	0.23		0.31		2	-0.27
2	2	122	39	0.8	BW1+17.77	0.5		0.49		2	0.034
2	1	117	40	0.8	BW1+21.89	0.66		0.7		2	-0.13
2	2	105	40	0.9	BW1+3.87	0.93		0.53		2	1.365
2	2	120	41	0.6	BW1+.53	0.38		0.24		2	0.477
2	2	120	41	1.3	BW1+10.52	0.61		0.3		2	1.058
2	2	120	41	4.5	BW1+13.63	0.81		0.43		2	1.296
2	1	111	42	0.4	BW1+4.5	0.25		0.33		2	-0.27
2	2	111	42	0.6	BW1+2.97	0.43		0.24		2	0.648
2	1	106	43	0.4	BW1+6.29	0.27		0.29		2	-0.06
2	1	106	43	0.7	BW1+7.51	0.4		0.6		2	-0.68
2	2	129	44	1.1	BW1+20.28	0.35		0.39		2	-0.137
2	2	127	44	5	BW1+20.22	0.99		0.4		2	2.013
2	2	122	45	0.5	BW1+2.01	0.17		0.37		2	-0.68
2	2	130	45	0.2	BW1+18.34	0.26		0.4		2	-0.47
2	2	130	45	0.8	BW1+17.12	0.33		0.24		2	0.307
2	1	112	45	0.2	BW1+.91	0.35		0.15		2	0.682
2	2	126	45	0.8	BW1+16.37	0.5		0.27		2	0.784
2	1	110	45	0.5	BW1+4.07	0.58		0.48		2	0.341
2	2	126	45	0.8	BW1+19.72	0.63		0.32		2	1.058
2	2	112	45	0.4	BW1+7.65	0.78		0.36		2	1,433
2	2	119	46	0.7	BW1+8.25	0.28		0.23		2	0.17
2	1	125	46	0.4	VS1+.05	0.48		0.62		2	-0.47
2	2	99	46	0.5	BW1+4.12	0.62		0.67		2	-0.17
2	2	127	46	1.1	BW1+11.92	0.67		0.48		2	0.648
2	2	127	46	2.2	BW1+17.53	0.69		0.56		2	0.443
2	2	121	46	3.1	BW1+.54	0.74		0.65		2	0.307
2	1	108	47	0.4	BW1+17.53	0.18		0.36		2	-0.61
2	2	98	47	0.5	BW1+8.62	0.32		0.42		2	-0.34
2	1	108	47	0.6	BW1+18.61	0.33		0.14		2	0.648
2	1	124	47	0.3	VS1+.81	0.46		0.51		2	-0.171
2	2	125	48	0.3	BW1-.5	0.32		0.4		2	-0.27
2	1	124	49	0.5	vs1+.66	0.47		0.29		2	0.614
2	2	122	49	3	bw1+7.56	0.79		0.46		2	1.126
2	2	131	50	0.4	bw1-.13	0.25		0.31		2	-0.2
2	2	115	50	0.6	bw1+8.01	0.41		0.42		2	-0.03
2	2	119	50	0.4	bw1+5.01	0.55		0.54		2	0.034
2	2	135	50	0.7	bw1+17.01	0.97		0.44		2	1.808
2	2	120	51	1.2	bw1+9.26	0.69		0.72		2	-0.1
2	2	100	51	0.5	bw1+3.87	0.87		0.63		2	0.819
2	2	100	51	0.7	bw1+5.37	1.15	1.15	0.67	0.7	2	1.638

REVIEW OF U2R5 ARC REGION DEFECTS - VOLTAGE GROWTH

UNIT	SG	ROW	LINE	LENGTH	LOCATION	R5VOLTS	R5rev	INITVOLTS	M2rev	INDOUT	DVDT
2	2	140	85	0.6	bw1+7.71	0.58		0.47		2	0.375
2	2	136	85	0.6	BW1+20.96	0.81		0.42		2	1.331
2	2	142	85	0.5	BW1+7.81	0.82		0.43		2	1.331
2	2	146	85	0.9	bw1+19.34	0.87		0.31		2	1.911
2	2	129	86	0.4	bw1+7.8	0.37		0.51		2	-0.47
2	2	129	86	0.7	bw1+8.84	0.43		0.43		2	0
2	2	141	86	0.8	bw1+12.88	0.52		0.7		2	-0.61
2	2	143	86	0.5	bw1+20.92	0.64		0.62		2	0.068
2	2	145	86	2.7	bw1+19.59	0.66		0.76		2	-0.34
2	2	143	86	1.3	bw1+22.73	0.76		0.62		2	0.477
2	2	132	87	0.7	bw1+3.07	0.1		0.17		2	-0.23
2	2	118	87	0.1	bw1+5.71	0.12		0.31		2	-0.648
2	2	148	87	1.1	bw1+20.90	0.32		0.15		2	0.58
2	2	128	87	2	bw1+3.78	0.49		0.38		2	0.375
2	2	138	87	2	bw1+20.42	0.49		0.55		2	-0.2
2	2	128	87	0.6	bw1+9.07	0.54		0.25		2	0.989
2	1	126	87	0.9	BW1+5.04	0.57		0.53		2	0.137
2	1	142	87	3.9	BW1+12.5	0.71		0.3		2	1.399
2	2	138	87	1.2	bw1+7.49	0.72		0.59		2	0.443
2	2	132	87	0.7	bw1+7.01	0.78		0.12		2	2.252
2	2	144	87	1.4	bw1+23.41	0.89		0.22		2	2.286
2	2	144	87	2	bw1+9.1	0.96		0.27		2	2.354
2	2	130	87	2.8	bw1+7.86	1.3		0.76		2	1.843
2	1	123	88	0.6	BW1+1.86	0.25		0.32		2	-0.23
2	2	123	88	0.6	bw1+3.59	0.31		0.22		2	0.307
2	2	131	88	0.7	bw1+6.53	0.56		0.29		2	0.921
2	2	131	88	1.1	bw1+8.79	0.59		0.23		2	1.228
2	2	135	88	0.4	bw1+15.25	0.86		0.28		2	1.979
2	2	127	88	0.6	bw1+5.78	0.92		0.48		2	1.501
2	1	142	89	2.7	BW1+10.57	0.33		0.33		2	0
2	2	130	89	0.4	bw1+7.59	0.46		0.36		2	0.341
2	2	149	90	0.2	BW1+17.42	0.19		0.17		2	0.068
2	2	149	90	0.3	BW1+18.35	0.22		0.16		2	0.204
2	2	141	90	0.4	bw1+17.64	0.46		0.2		2	0.887
2	2	141	90	0.8	bw1+6.79	0.47		0.24		2	0.784
2	2	135	90	0.5	bw1+19.86	0.5		0.22		2	0.956
2	2	141	90	0.3	bw1+4.97	0.57		0.28		2	0.989
2	2	141	90	0.6	bw1+3.36	0.58		0.31		2	0.921
2	2	123	90	1.7	bw1+4.15	0.69		0.53		2	0.546
2	2	149	90	0.6	bw1+9.57	0.73		0.36		2	1.262
2	2	136	91	1.3	BW1+14.82	0.3		0.43		2	-0.44

REVIEW OF U2R5 ARC REGION DEFECTS - VOLTAGE GROWTH

UNIT	SG	ROW	LINE	LENGTH	LOCATION	R5VOLTS	R5rev	INITVOLTS	M2rev	INDOUT	DVDT
2	2	124	53	1.4	BW1+8.83	0.9		0.41		2	1.672
2	2	120	53	1.2	BW1+4.83	0.95	0.95	0.36	999	2	2.013
2	1	131	54	0.3	bw1+4.33	0.5		0.52		2	-0.068
2	2	110	55	0.3	BW1-.8	0.39		0.31		2	0.273
2	2	124	55	0.9	BW1+8.22	0.4		0.43		2	-0.1
2	1	136	55	1.7	BW1+16.65	0.44		0.74		2	-1.02
2	2	127	56	4.4	BW1+7.75	1.06		0.35		2	2.423
2	2	114	57	0.5	BW1-2.08	0.25		0.31		2	-0.2
2	1	137	62	0.2	BW1+16.08	0.3		0.25		2	0.17
2	1	137	62	0.2	BW1+17.28	0.33		0.28		2	0.17
2	2	137	64	0.5	BW1+.22	0.3		0.36		2	-0.2
2	2	141	66	0.3	BW1+7.73	0.46		0.23		2	0.784
2	2	148	67	0.9	BW1+17.54	0.23		0.47		2	-0.81
2	2	140	67	0.7	BW1+3.69	0.7		0.44		2	0.887
2	2	138	67	3	BW1+8.23	0.78		0.55		2	0.785
2	1	124	67	0.2	VS1+.76	0.88		0.35		2	1.808
2	2	127	70	0.6	BW1+8.18	0.62		0.63		2	-0.03
2	1	125	70	0.7	VS1-.78	0.89		0.62		2	0.921
2	2	139	72	2.6	BW1+7.12	0.35		0.53		2	-0.61
2	2	145	72	0.7	BW1+18.36	0.46		0.55		2	-0.307
2	2	139	72	1.4	BW1+2.06	0.49		0.48		2	0.034
2	2	146	75	0.7	BW1+4.13	0.63		0.28		2	1.194
2	2	134	77	2	BW1+19.31	0.77		0.52		2	0.853
2	2	131	80	0.4	BW1+8.46	0.21		0.44		2	-0.78
2	2	147	82	0.2	BW1+19.3	0.21		0.22		2	-0.03
2	2	135	82	0.3	BW1+18.97	0.39		0.52		2	-0.44
2	2	152	83	0.6	BW1+23.80	0.25		0.2		2	0.17
2	2	132	83	0.7	BW1-1.77	0.3		0.25		2	0.17
2	2	152	83	0.4	BW1+24.85	0.31		0.27		2	0.136
2	2	132	83	0.6	BW1-1.18	0.31		0.28		2	0.102
2	2	130	83	0.8	BW1+1.44	0.43		0.31		2	0.409
2	2	146	83	1.3	BW1+23.12	0.8		0.32		2	1.638
2	2	136	83	5	BW1+17.64	0.93		0.41		2	1.774
2	2	125	84	0.4	BW1+3.04	0.45		0.22		2	0.784
2	2	145	84	1	BW1+10.47	0.97		0.26		2	2.423
2	2	152	85	0.8	bw1+30.53	0.11		0.26		2	-0.51
2	2	152	85	0.7	bw1+27.53	0.28		0.27		2	0.034
2	2	142	85	0.4	bw1+8.34	0.38		0.42		2	-0.13
2	2	152	85	0.5	bw1+29.14	0.38		0.42		2	-0.13
2	2	134	85	1	BW1+19.81	0.43		0.46		2	-0.1
2	2	142	85	1.8	BW1+4.81	0.49		0.31		2	0.614

APPENDIX C

Unit 2 Cycle 5
ECT Voltage Growth
Summary

REVIEW OF U2R5 ARC REGION DEFECTS - VOLTAGE GROWTH

UNIT	SG	ROW	LINE	LENGTH	LOCATION	R5VOLTS	R5rev	INITVOLTS	M2rev	INDOUT	DVDT
2	2	95	158	0.2	BW1 +2.37	0.43		0.5		2	-0.239
2	2	101	158	0.8	BW1 +.91	0.82		0.24		2	1.98
2	2	101	158	1	BW1 +5.87	0.99		0.29		2	2.389
2	2	101	158	1.2	BW1 +2.56	1.09	1.06	0.25	999	2	2.867

REVIEW OF U2R5 ARC REGION DEFECTS - VOLTAGE GROWTH

UNIT	SG	ROW	LINE	LENGTH	LOCATION	R5VOLTS	R5rev	INITVOLTS	M2rev	INDOUT	DVDT
2	2	130	137	0.2	BW1+.67	0.35		0.22		2	0.443
2	2	130	137	1.5	BW1+10.20	0.39		0.21		2	0.614
2	2	132	137	0.7	BW1-2.62	0.4		0.36		2	0.136
2	2	132	137	2.1	BW1+.34	0.41		0.39		2	0.068
2	2	130	137	0.4	BW1+1.09	0.51		0.44		2	0.238
2	2	132	137	3	BW1+16.21	0.65		0.24		2	1.399
2	2	121	138	0.2	BW1+1.46	0.15		0.23		2	-0.27
2	2	127	138	0.6	BW1+3.58	0.27		0.23		2	0.137
2	2	137	138	0.7	BW1+16.34	0.4		0.57		2	-0.58
2	2	131	138	0.6	BW1+1.96	0.44		0.33		2	0.375
2	2	133	138	0.2	BW1+16.17	0.58		0.33		2	0.853
2	2	133	138	0.2	BW1+2.92	0.59		0.31		2	0.956
2	2	132	139	1.4	BW1+17.62	0.24		0.17		2	0.239
2	2	136	139	1.1	BW1+18.86	0.27		0.38		2	-0.375
2	2	90	139	0.8	BW1+4.12	0.65		0.48		1	0.249
2	2	97	140	0.3	BW1+1.68	0.36		0.23		2	0.444
2	2	133	140	2.3	BW1+16.96	0.62		0.48		2	0.478
2	2	105	140	0.6	BW1+.63	0.77		0.76		2	0.034
2	2	124	141	0.6	BW1+9.97	0.2		0.2		2	0
2	2	136	141	1.6	BW1+18.56	0.51		0.27		2	0.819
2	2	123	142	0.6	BW1+1.26	0.31		0.31		2	0
2	2	127	142	0.2	BW1+4.38	0.38		0.26		2	0.41
2	2	133	142	1	BW1+18.32	0.4		0.28		2	0.41
2	1	115	142	0.4	BW1+3.8	0.41		0.33		2	0.273
2	2	123	142	0.2	BW1+7.46	0.45		0.46		2	-0.034
2	1	122	143	1	BW1+16.86	0.17		0.3		2	-0.44
2	2	121	144	0.2	BW1+1.17	0.36		0.3		2	0.205
2	1	130	145	1.1	BW1+20.65	0.5		0.3		2	0.682
2	2	121	146	0.5	BW1+1.17	0.34		0.52		2	-0.614
2	2	111	146	2.3	BW1+5.44	0.47		0.4		2	0.239
2	2	106	147	0.4	BW1+1.48	0.5		0.43		2	0.239
2	1	120	147	0.4	BW1+16.42	0.56		0.39		2	0.58
2	1	109	150	1.3	BW1+20.07	0.32		0.6		2	-0.95
2	2	105	150	0.6	BW1+2.64	0.43		0.24		2	0.648
2	2	111	150	2.2	BW1+8.35	0.94		0.37		2	1.945
2	2	114	151	1	BW1-.8	0.35		0.28		2	0.239
2	2	109	152	0.6	BW1+.63	0.28		0.32		2	-0.137
2	2	113	152	1.5	BW1-2.13	0.35		0.34		2	0.034
2	2	121	152	0.2	BW1+16.97	0.88	0.88	0.17	999	2	2.423
2	2	106	153	0.2	BW1-2.29	0.32		0.23		2	0.307
2	2	112	153	0.4	BW1+.26	0.95		0.6		2	1.195