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Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates Database for Alternate Repair Limits: Addendum 7

Non Proprietary Version

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PRODUCT DESCRIPTION

This Addendum 7 report updates EPRI Technical Report 1011456, Addendum 6 to NP-7480-L database report for outside diameter stress corrosion cracking (ODSCC) at tube support plates (TSPs). Addendum 7 is an update of Addendum 6 and remains a self-standing document for data and methods changes since the release of Addendum 1 and NRC Generic Letter 95-05.

Results and Findings

This report extends the database for outside diameter stress corrosion cracking at tube support plates. Pulled tube data from one plant for 7/8 inch tubing is added to the database. The alternate repair criteria (ARC) correlation probability of leakage for 7/8 inch tubing is updated to reflect this additional data. The ARC correlations for burst pressure and steam line break (SLB) leak rate for 7/8 inch tubing are unchanged. The ARC correlations for burst pressure, probability of leakage, and SLB leak rate for 3/4 inch tubing are unchanged from Addendum 6.

The report presents an update to the Addendum 6 probability of prior cycle detection (POPCD) as a function of bobbin voltage. The database formats have been revised. The updated POPCD includes forty-six inspections from thirteen plants.

Challenges and Objective(s)

Utilities with an NRC approved alternate repair criteria for outside diameter stress corrosion cracking at tube support plates are required to use the correlations in this report in their condition monitoring and operational assessment reports.

Applications, Values, and Use

This addendum will be updated with future tube pull data from plants implementing the alternate repair criteria.

Approach

Since Addendum 5, the overall content of the addenda has been significantly extended to incorporate essentially all applicable prior information on updates to NDE techniques, ARC analysis methods, and ARC programmatic information. Addendum 7 continues this approach. The intent is to maintain the addendum as a self-standing document for data and methods changes since the release of Addendum 1 and NRC Generic Letter 95-05. Sections 5 and 6 include all data and correlations even if not revised from a prior addendum

Keywords

Axial
ODSCC
TSP
POPCD

CONTENTS

1 INTRODUCTION 1-1

1.1 References 1-2

2 SUMMARY AND CONCLUSIONS 2-1

2.1 Database and Correlations for 3/4 Inch Diameter Tubing 2-1

2.2 Updated Database and Correlations for 7/8 Inch Diameter Tubing 2-1

2.3 Supplemental Test Data 2-1

2.4 Recommended Probability of Detection (POD) 2-2

2.5 NDE, Analysis Methods and Program Updates 2-2

2.6 References 2-2

3 EVALUATION OF PULLED TUBE DATA FOR ¾ INCH DIAMETER TUBING 3-1

4 EVALUATION OF PULLED TUBE DATA FOR 7/8 INCH DIAMETER TUBING 4-1

4.1 Plant W-2 2006 Pulled Tube 4-1

4.1.1 Tube Examination Summary 4-1

4.1.1.1 Non Destructive Examination 4-1

4.1.1.2 Destructive Examination Preparation 4-1

4.1.2 Plant W-2 Pulled Tube Evaluation for ARC Applications 4-2

4.1.2.1 Destructive Exam (DE) Depth Profiles 4-2

4.1.2.2 Corrections to DE Depth Profiles for Uncorroded Ligaments 4-3

4.1.2.3 Burst Pressure Analysis Results 4-3

4.1.2.4 SLB Leak Rate Analysis Results 4-4

4.2 References 4-5

5 UPDATED ARC DATABASES 5-1

5.1 3/4" Data 5-1

5.2 7/8" Data 5-1

5.3 Data for Burst inside the TSP 5-2

5.4 Data for Axial Tensile Tearing 5-2
5.5 Summary of Field NDD Data 5-2
5.6 References 5-2

6 UPDATED ARC CORRELATIONS 6-1
6.1 3/4" Diameter Tubes Data Analysis 6-2
6.1.1 Free Span Burst Correlation for 3/4" Tubes 6-2
6.1.2 Probability of Leak Correlation for 3/4" Tubes 6-2
6.1.3 Free Span SLB Leak Rate Correlation for 3/4" Tubes 6-2
6.2 7/8" Diameter Tubes Data Analysis 6-2
6.2.1 Free Span Burst Correlation for 7/8" Tubes 6-3
6.2.2 Probability of Leak Correlation 6-3
6.2.3 Free Span SLB Leak Rate Correlation for 7/8" Tubes 6-4
6.3 Axial Tensile Tearing Correlation 6-4
6.4 Summary/Conclusions 6-4
6.5 References 6-5

7 PROBABILITY OF PRIOR CYCLE DETECTION (POPCD) 7-1
7.1 Introduction 7-1
7.2 POPCD Definition and Classification of Indications 7-2
7.2.1 POPCD Definition 7-2
7.2.2 Classification of Indications and Assignment for POPCD Analyses 7-3
7.3 Calculation of the POPCD Distribution Including Uncertainties 7-5
7.3.1 Log-logistic Fitting 7-5
7.3.2 Monte Carlo Techniques 7-5
7.4 Growth Rate Considerations for POPCD Applications 7-8
7.4.1 Provision for Outlier Growth Rates 7-8
7.4.2 Development of Growth Rate Distributions 7-8
7.5 Noise Considerations for POPCD Applications 7-9
7.6 Benchmarking of POPCD 7-10
7.7 POPCD Evaluation for the Industry Database 7-11
7.7.1 Industry POPCD Distribution 7-11
7.7.2 Effect of Uncertainties in the Upper Voltage Range 7-12
7.7.3 Comparisons of Industry POPCD with ANL POD from Round Robin Testing and EPRI POD from Multiple Analyst Testing 7-13

7.8 Option for Developing Plant Specific POPCD Distributions 7-14
7.8.1 Minimum Number of Inspections for Plant Specific POPCD Application 7-14
7.8.2 Minimum Total Number of Indications for Plant Specific POPCD Application 7-14
7.8.3 Minimum Number of Detected and RPC Confirmed Indications in Upper Voltage Range 7-14
7.9 Continuing Assessment and Reporting for POPCD 7-15
7.10 Conclusions 7-16
7.11 References 7-17

8 RECOMMENDED NEW UPDATES TO NDE, ANALYSIS METHODS AND PROGRAMS 8-1

9 NRC APPROVED REVISIONS TO ARC PROGRAM, DATABASES, AND ANALYSIS METHODS 9-1
9.1 NRC/Industry SGDSM Database Protocol 9-1
9.2 Requirements for Pulling Tubes in Support of the Voltage Based Repair Limits 9-2
9.2.1 Description of the Issue 9-2
9.2.2 Bases for Tube Removal Guidelines 9-3
9.2.3 Criteria for Tube Removal and Examination/Testing 9-4
9.2.3.1 Number and Frequency of Tube Pulls 9-4
9.2.3.2 Tube Removal Selection Criteria 9-5
9.2.3.3 Pulled Tube Examination and Testing 9-5
9.3 Data Exclusion Criteria 9-6
9.3.1 Introduction 9-6
9.3.2 Data Exclusion Criteria 9-6
9.3.2.1 Criterion 1. Invalid or Inadequate Test 9-7
9.3.2.2 Criterion 2. Morphology Related Criteria 9-8
9.3.2.3 Criterion 3. Probable Test Error in Leakage Measurement 9-9
Basis for Criterion 3a 9-9
9.4 Exclusion of the French Data from the ARC Database 9-10
9.5 Revisions to Leak Rate Analysis Methods 9-11
9.6 References 9-12

10 PRIOR INDUSTRY RECOMMENDED UPDATES TO ARC ANALYSIS METHODS AND DATA APPLICATIONS 10-1
10.1 Determination of Bobbin Voltages for Indications Detected Only by RPC Inspection 10-1

10.1.1 Background 10-1
10.1.2 Bobbin Voltages Obtained from Flaw Identification at Single Frequencies Such as 200kHz 10-2
10.1.3 Bobbin Voltages Inferred from Correlation of Bobbin Voltage to RPC Voltage 10-2
10.1.3.1 Description of a Prior Plant-Specific Analysis 10-3
10.1.3.2 Uncertainties in the Predicted Bobbin Voltage 10-5
10.1.3.3 Application of Regression Correlation 10-5
10.1.3.4 Recommendations 10-5
10.1.3.5 Application to Dents ≤ 5 Volts and Mixed Residuals 10-6
10.1.3.6 Application to Dents > 5 Volts 10-6
10.2 NDE Technique for Cross Calibration of ASME Standards to the Reference Standard 10-7
10.2.1 Background 10-7
10.2.2 Theoretical Critique of the Four Methods 10-8
10.2.3 Experimental Study 10-8
10.2.4 Results 10-9
10.2.5 Recommendations 10-9
10.3 Voltage Dependent Growth Rate Methods 10-10
10.3.1 Introduction 10-10
10.3.2 Piecewise Linear Regression Analysis 10-12
10.3.3 Discussion of Growth Plotting 10-12
10.3.4 Analysis 10-13
10.3.4.1 Upper Range Number of Data 10-14
10.3.4.2 Bilinear Regression 10-14
10.3.4.3 Trilinear Regression 10-15
10.3.4.4 Quadrilinear Regression 10-16
10.3.5 Example Application to Plant DCPP Data 10-16
10.3.5.1 SG 2-4 Cycle 11 Growth Data 10-16
10.3.5.2 SG 2-4 Cycle 10 Growth Data 10-17
10.3.6 Discussion 10-18
10.3.7 Summary 10-19
10.4 Growth Rate in Deplugged Tubes Returned to Service 10-20
10.4.1 Introduction 10-20
10.4.2 Selection of a Bounding Growth Distribution for Deplugged Tubes 10-21

10.4.3 Method of Combining Active and Deplugged Tube Growth Data 10-21
10.4.4 Comparison of Leak and Burst Projections Considering Increased Deplugged Tube Growth with those Based on Actual Voltages 10-22
10.4.5 Conclusions 10-26
10.5 Extreme Values of ODSCC ARC Indications or Growth 10-27
10.5.1 Introduction 10-27
10.5.2 Regulatory Topics of Interest 10-30
10.5.2.1 Function of the Analysis 10-30
10.5.2.2 The "Fractional Flaw Paradox" 10-31
10.5.2.3 Extreme Growth of Indications at V. C. Summer 10-33
10.5.3 Objective of the Analyses 10-33
10.5.4 Distribution of ODSCC ARC Growth Rates 10-35
10.5.4.1 Analysis of SG Data 10-35
10.5.4.2 Generic Letter Requirements 10-35
10.5.4.3 Root Cause of Extreme Growth 10-36
10.5.4.4 Growth Rate Predictions 10-37
10.5.5 Potential Approaches 10-38
10.5.6 Insertion of Random Extreme Values 10-38
10.5.6.1 Factors Affecting Growth 10-38
10.5.6.1.1 Maturity of the Population of Indications 10-39
10.5.6.1.2 Number of Indications in the SG 10-39
10.5.6.1.3 Chemistry of the Secondary Side 10-39
10.5.6.1.4 Temperature of Operation 10-39
10.5.6.1.5 Normal Operation Differential Pressure 10-40
10.5.6.1.6 Adjustment of Voltage Growth 10-40
10.5.6.2 Simulation Approach Based on SG ARC Applications 10-40
10.5.6.3 Simulations Based on the Total Number of Indications 10-42
10.5.7 Summary/Recommendation 10-45
10.6 Noise Requirements for Voltage Based ARC 10-46
10.6.1 Introduction 10-46
10.6.2 Considerations for Noise at TSP Intersections 10-47
10.6.3 Tube Repair Requirements for Indications Found by RPC at Noisy TSP Intersections 10-49
10.6.3.1 Bobbin Voltage Sizing for Indications Found by RPC 10-49

10.6.3.2 Tube Repair Requirements for Indications Found by RPC at Noisy TSP Intersections 10-49
10.6.4 RPC Inspection Requirements for Noise at TSP Intersections 10-50
10.6.5 Conclusions 10-52
10.7 ARC Guidelines for Preventive Repair of Large +Point Indications 10-53
10.7.1 Introduction 10-53
10.7.2 Background Information 10-54
10.7.3 Guidelines for Preventive Repair 10-55
10.7.4 Guidelines for Supplemental RPC Inspection 10-57
10.7.5 Conclusions 10-57
10.8 References 10-58

LIST OF FIGURES

Figure 4-1 Corrosion Depth Profile and Ligament Size for 01H 180° Crack 4-8
Figure 4-2 Corrosion Depth Profile and Ligament Size for 01H 110° Crack 4-9
Figure 4-3 Corrosion Depth Profile and Ligament Size for 02H 180° Crack 4-9
Figure 4-4 Addendum 6 Burst Pressure vs. Volts for 7/8" OD Alloy 600 SG Tubes 4-10
Figure 4-5 ANL Ligament Tearing Pressures vs. Crack Depth Alloy 600 MA SG Tubes with Part-Throughwall Axial Cracks 4-10
Figure 4-6 SLB Leak Rate (2405 psi) vs. Bobbin Amplitude 4-11
Figure 6-1 3/4" Burst Pressure Correlation 6-12
Figure 6-2 3/4" Burst Probability 6-12
Figure 6-3 3/4" Probability of Leak 6-13
Figure 6-4 3/4" SLB Leak Rate at 2560 psi 6-13
Figure 6-5 3/4" SLB Leak Rate at 2405 psi 6-14
Figure 6-6 7/8" Burst Pressure Correlation Tolerance Bounds 6-14
Figure 6-7 7/8" Probability of Burst at 2560 psi 6-15
Figure 6-8 7/8" Probability of Burst at 2405 psi 6-15
Figure 6-9 7/8" Probability of Leak 6-16
Figure 6-10 7/8" POL Comparison 6-16
Figure 6-11 7/8" Ratio of POLs 6-17
Figure 6-12 7/8" Leak Rate for 2405 psi 6-17
Figure 7-1 7/8" Tubes POPCD as Function of Bobbin Amplitude (Weighted Generalized Linear Model Log-logistic Solution) 7-36
Figure 7-2 Generic Industry POPCD as Function of Bobbin Amplitude 3/4" Tubing (Weighted Generalized Linear Model Log-logistic Solution) 7-36
Figure 7-3 Bobbin Drilled Hole TSP Database TSP Center P1 Mix Vvmax Noise Distributions 7-37
Figure 7-4 Comparison of POPCD Curves 7-37
Figure 7-5 Average of Resolution Analysts, Percentage of Correct TSP BC Calls as a Function of Bobbin Coil voltage for TSP cracks (POD evaluated for ODSCC at the TSP) 7-38
Figure 7-6 Average of Resolution Analysts for Percentage of Correct TSP BC Calls, (POD) Logistic Fit Curves for BC POD as a Function of Voltage for Axial ODSCC and IDSCC in TSP 7-38
Figure 10-1 Bobbin to RPC Voltage Correlation for an Example Case Bobbin Volts vs. 80 mil Mid Range Pancake RPC Volts 10-82

Figure 10-2 Bobbin to RPC Voltage Correlation for an Example Case Scatter Plot of Residuals – Linear Bobbin vs. Linear RPC 10-82
Figure 10-3 Bobbin to RPC Voltage Correlation for an Example Case Normal Plot of Residuals – Linear Bobbin vs. Linear RPC 10-83
Figure 10-4 Plot of Average Errors 10-83
Figure 10-5 Bilinear Regression Line Illustration 10-84
Figure 10-6 Trilinear Regression Line Illustration 10-84
Figure 10-7 Quadrilinear Regression Line Illustration 10-85
Figure 10-8 Excel Screen for Bilinear Regression Analysis 10-85
Figure 10-9 Excel Solver Screen for Bilinear Regression Analysis 10-86
Figure 10-10 Bilinear Regression Lines for SG 2-4 Cycle 11 Growth Data 10-86
Figure 10-11 Excel Screen for Trilinear Regression Analysis 10-87
Figure 10-12 Excel Solver Screen for Trilinear Regression Analysis 10-87
Figure 10-13 Trilinear Regression Lines for SG 2-4 Cycle 11 Growth Data 10-88
Figure 10-14 Excel Screen for Quadrilinear Regression Analysis 10-88
Figure 10-15 Excel Solver Screen for Quadrilinear Regression Analysis 10-89
Figure 10-16 Quadrilinear Regression of SG 2-4 Cycle 11 Growth Data 10-89
Figure 10-17 Excel Screen for SG 2 4 Cycle 10 Growth Data 10-90
Figure 10-18 Quadrilinear Regression without a Data Limit on Piece 3 10-90
Figure 10-19 Trilinear Regression of SG 2-4 Cycle 10 Growth Data (Illustration of an unsatisfactory analysis result) 10-91
Figure 10-20 Quadrilinear Regression with a Data Limit on Piece 3 10-91
Figure 10-21 Quadrilinear Regression of SG 2-4 Cycle 10 Growth Data 10-92
Figure 10-22 Growth Rates for Deplugged Tubes in the First Cycle After Return to Service Composite of Data from All SGs in a Plant Cumulative Probability Distributions for Growth on an EFPY Basis 10-93
Figure 10-23 Composite Growth Distribution Based on Active and Deplugged Tube Growth Distributions 10-93
Figure 10-24 Voltage Growth vs. BOC Voltage Deplugged Tube Data is for First Cycle of Operation After Tubes Deplugged 10-94
Figure 10-25 Limiting Growth Distribution Recommended for Deplugged Tube Indications Growth Considered Dependent of BOC Voltage 10-94
Figure 10-26 Probability of Leak for 7/8" Diameter Tubes 10-95
Figure 10-27 Distribution of Amplitude Growth for Cycle 11 10-95
Figure 10-28 Amplitude Growth CDF vs. Lognormal CDF 10-96
Figure 10-29 Normal Distribution Plot of Logarithm Residuals 10-96
Figure 10-30 Flaw and Mix Residual (400/100 Mix) for Plant A-1 Pulled Tube R27C54-1H 10-97
Figure 10-31 Upper and Lower TSP Noise Signals for Plant A-1 R27C54-1H (Center 1/3 of TSP Cannot be Evaluated Due to Flaw Signal) 10-97

Figure 10-32 Mix Residual and Center, Upper and Lower 1/3 TSP Noise Signals (400/100 kHz Mix) for Plant A-1 R27C54 at 2H 10-98

Figure 10-33 Plant P-1: TSP ODSCC 400/100 to 200 kHz Bobbin Voltage Ratios: Comparison of Ratios from Normal Resolution Process with Ratios Inferred from 200 kHz Mix Residual Analysis 10-99

Figure 10-34 Comparison of Bobbin Flow Mix Volts for Reported DSIs and DSIs Inferred from 200 kHz Mix Residual Analysis vs. 200 kHz +Point Volts 10-99

Figure 10-35 POD as Function of Mix P1 S/N (Flaw Vpp/Noise Vpp) (Generalized Linear Model Log-logistic Solution) 10-100

Figure 10-36 TSP Bobbin P1 Mix Peak-to-Peak Amplitude Noise Distributions Preliminary ETSS Data and Plant DW Data 10-100

Figure 10-37 +Point Amplitude Sizing Correlation for Estimating Depths Based on Amplitude (Logarithmic Fit to 2.5 Volts at 100% Depth and 0.1 Volt at 40% Depth).... 10-101

Figure 10-38 +Point DW +Point Volts versus Bobbin Coil Volts 10-101

Figure 10-39 Plant P-1 1R15: +Point versus Bobbin Volts, Axial ODSCC at TSP Intersections 10-102

Figure 10-40 DCPP-2 All SGs, 2R11: +Point to Bobbin Voltage Comparison for ODSCC at TSPs 10-102

LIST OF TABLES

Table 4-1 Summary of Plant W-2 2006 Pulled Tube Eddy Current Results 4-6
Table 4-2 Plant W-2 2006 Pulled Tube Data For ARC Applications 4-6
Table 4-3 Ligament Sizing Results 4-7
Table 4-4 R22C70 Calculated Burst Pressures from 01H and 02H 180° Crack Destructive Exam Profiles 4-8
Table 5-1 3/4 Inch Diameter Pulled and Model Boiler Tube Leak Rate and Burst Pressure Measurements 5-3
Table 5-2 7/8 Inch Diameter Pulled and Model Boiler Tube Leak Rate and Burst Pressure Measurements 5-11
Table 5-3 Burst Capability for Indications within the TSP 5-21
Table 5-4 Database for Correlating Axial Rupture Strength of Cellular ODSCC Specimens with Bobbin Amplitude 5-22
Table 5-5 Pulled Tubes with Field Bobbin NDD Indications 5-23
Table 6-1 Burst Pressure versus Bobbin Amplitude Correlation 3/4" Tube Data 6-6
Table 6-2 Probability of Leak Correlation 3/4" Tubes 6-7
Table 6-3 Leak Rate vs. Bobbin Amplitude Correlation (2560 & 2405 psi) 3/4" Tubes 6-8
Table 6-4 Burst Pressure versus Bobbin Amplitude Correlation 7/8" Tube Data 6-9
Table 6-5 Effect of Additional Data on the 7/8" Tube Probability of Leak Correlation 6-10
Table 6-6 Leak Rate vs. Bobbin Amplitude Correlation (2560 & 2405 psi) 7/8" Tubes 6-11
Table 7-1 Data Table for Tracking Indications between EOCn and EOCn+1 7-19
Table 7-2 7/8" Plant Data Summary Evaluation for POPCD (Data through 2007) 7-20
Table 7-3 3/4" Plant Data Summary Evaluation for POPCD (Data through 2007) 7-26
Table 7-4 7/8 and 3/4 Inch POPCD Log Logistic Distribution Parameters 7-34
Table 7-5 Source of Data for 7/8 Inch Tubing POPCD 7-35
Table 7-6 Source of Data for 3/4 inch Tubing POPCD 7-35
Table 9-1 NRC/Industry SGDSM Database Protocol 9-14
Table 9-2 Summary of Current (November 2007) Number and Target Number for Pulled Tube Intersections with Leakage – Excludes French Data 9-15
Table 9-3 Results of Comparisons of Burst Pressure Regression Analysis Models Copy of Table 1 of Reference 9-15 9-16
Table 9-4 Kolmogorov-Smirnov Test of Equality of EdF and US POL Data Distributions Copy of Table 5 of Reference 9-15 9-17

Table 10-1 Summary of Alternate Bobbin to RPC Voltage Correlations 80 mil Pancake Coil RPC Data 10-61
Table 10-2 Bobbin to RPC Voltage Correlation Sensitivity Analysis on Data Range 10-61
Table 10-3 Sample Information 10-62
Table 10-4 Percentage Variation in Mix Measurements Relative to the APC Reference Standard 10-63
Table 10-5 Bilinear Regression Sample Data 10-64
Table 10-6 Cycle 10 Data Added to Cycle 11 10-65
Table 10-7 Recommended Limiting Growth Distribution for Indications in Deplugged Tubes During First Cycle of Operation 10-66
Table 10-8 Combining Growth Data for Active and Deplugged Tubes Indications Using Recommended Method 10-67
Table 10-9 Comparison of Leak and Burst Results for a Cycle in which Deplugged Tubes are Returned to Service – Plant A-2 10-68
Table 10-10 New Indications during First Year of Operation in Deplugged Tubes Returned to Service 10-69
Table 10-11 Recommended Limiting Growth Distribution during First Cycle of Operation for Indications in Deplugged Tubes Growth Dependent on BOC Voltage 10-70
Table 10-12 Data Used to Obtain Recommended Limiting Growth Distribution for Indications in Deplugged Tubes 10-71
Table 10-13 Comparison of Leak and Burst Results for a Cycle in which Deplugged Tubes are Returned to Service – Plant P 10-72
Table 10-14 Listing of Extreme Growth Values (Data Through Spring 2004, M = 115,179 Total Bobbin Indications) 10-73
Table 10-15 Summary of Large V. C. Summer Indications (FDB Elevation, 1993) 10-75
Table 10-16 List of Extreme Growth Values, Volts/EFPY Adjusted to 610°F 10-76
Table 10-17 Probability of Large Extremes for Two Sample Sizes 10-77
Table 10-18 Total Expected Number of Extremes 10-78
Table 10-19 Plant P-1: Successive Cycle +Point Data for Highest Bobbin Volts, +Point Volts and Ratio of +Point to Bobbin Volts 10-79
Table 10-20 Plant Y-1: Successive Cycle +Point Data for Highest Bobbin Volts, +Point Volts and Ratio of +Point to Bobbin Volts 10-80
Table 10-21 Plant Y-2: Successive Cycle +Point Data for Highest Bobbin Volts, +Point Volts and Ratio of +Point to Bobbin Volts 10-81

1
INTRODUCTION

This addendum provides a 2007 update to the NP-7480-L Addendum 6 database report (2004) (Reference 1-1) for outside diameter stress corrosion cracking at tube support plates. Specifically, the database for 7/8 inch tubing is updated by this Addendum 7. Inspection results since Addendum 6 are included in an update of POPCD for 7/8 inch tubing.

Pulled tube data from one plant with 7/8 inch tubes is added to the database (Sections 4 and 5). Based on this data, two bobbin indications are added to the 7/8 inch database. Due to damage of the tube during the pulling process, burst and leakage tests could not be reliably performed. Therefore, burst pressure and leakage were assessed by analysis. One of these new indications was determined to exhibit leakage at SLB conditions by analysis. No new test results have been obtained for the forces required for axial tensile tearing of cellular indications, and the correlations of Addendum 2 (Reference 1-2) remain applicable for axial tensile tearing.

The revised database is used to update the ARC correlations (Section 6) for probability of leakage for 7/8 inch diameter tubing. The ARC correlations for burst pressure and SLB leak rate as a function of bobbin coil voltage for 7/8 inch diameter tubing are unchanged. The ARC correlations for burst pressure, probability of burst, and SLB leak rate as a function of bobbin coil voltage for 3/4 inch diameter tubing are unchanged. The new correlation for 7/8 inch tubing should be implemented in all new ARC analyses beginning with the spring 2008 outages.

An update to the Addendum 6 probability of prior cycle detection (POPCD) for 7/8 inch tubing as a function of bobbin voltage is developed in Section 7 for use in ARC supporting analyses for end of cycle voltage distribution projections. Implementation of the POPCD methods for ARC operational assessments requires NRC approval, which is not yet obtained for general applications. The recommended POD is developed from field inspection results since 1994 for inspections implementing the ARC for ODSCC at TSP intersections. The POPCD development uses results of one inspection to evaluate the POD at the prior inspection. The updated POD includes forty-six inspections from thirteen plants in contrast to Addendum 6 which included forty-one inspections.

For Addendum 5 (Reference 1-3), the overall content of the addenda was significantly extended to incorporate essentially all applicable prior information on updates to NDE techniques, ARC analysis methods and ARC programmatic information. Addendum 7 continues this approach. The intent is to maintain the addenda as a self-standing document for data and methods changes since the release of Addendum 1 and NRC Generic Letter 95-05. Sections 5 and 6 include all data and correlations even if not revised from a prior addendum.

1.1 References

1.1 *Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates Database for Alternate Repair Limits*, Update 2004, EPRI, Palo Alto, CA: 2005, 1011456.

1.2 NP-7480-L, Addendum 2, *Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates Database for Alternate Repair Limits, 1998 Database Update*, EPRI, Palo Alto, CA (April, 1998), 1007660.

1.3 NP-7480-L, Addendum 5, *Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates Database for Alternate Repair Limits, 2002 Database Update*, EPRI, Palo Alto, CA (November, 2002), 1007660.

2
SUMMARY AND CONCLUSIONS

2.1 Database and Correlations for 3/4 Inch Diameter Tubing

The database and correlations for 3/4 inch diameter tubing are unchanged from Addendum 6 of NP 7480-L (Reference 2-1) because no new data became available.

2.2 Updated Database and Correlations for 7/8 Inch Diameter Tubing

This report updates the database for 7/8 inch diameter tubing given in Addendum 6 of NP 7480-L (Reference 2-1). One tube was pulled in 2006 from Plant W-2.

2.3 Supplemental Test Data

The pulled tube did not have an intersection that had no reportable degradation (NDD) in the field inspection. Therefore no additional NDD data is added to the Addendum 6 database. No additional data have been obtained since Addendum 2 (Reference 2-2) to update pulled tube test data for the forces required for axial tensile rupture of cellular ODSCC indications or for burst data on indications pressurized inside a TSP. The available data from prior addenda are included in Section 5 for complete documentation of the EPRI database.

2.4 Recommended Probability of Detection (POD)

The industry POPCD is updated from Addendum 6. The tabular format for reporting the detection data is revised in this report. The recommended POD as a function of bobbin voltage is updated based on evaluation of five additional inspection results from plants implementing the ARC for ODSCC at TSP intersections. This POD development utilizes extensive experience integrated over forty-six (increased from forty-one in Addendum 6) ARC inspections and thus uses historical ARC operating experience as the basis for the recommended POD. The development uses the POPCD based on the ratio of indications reported at the prior inspection to the total indications (reported as prior cycle plus new indications) found at the subsequent inspection. The revised method and additional data do not significantly change the POPCD distribution reported in Addendum 6. The recommended POD is in good agreement with an EPRI POD developed using multiple analysts to evaluate a large number of field indications with "truth" for indications based on "expert" opinion.

2.5 NDE, Analysis Methods and Program Updates

For Addendum 5 (Reference 2-3), the overall content of the addenda was significantly extended to incorporate essentially all applicable prior information on updates to NDE techniques, ARC analysis methods and ARC programmatic information. The intent is to maintain the addenda as a self-standing document for data and methods changes since the release of Addendum 1 (Reference 2-4) and NRC Generic Letter 95-05. Section 8 provides new methods supporting ARC applications. However, no new methods were proposed since Addendum 6. Section 9 documents NRC approved changes to the ARC databases, analysis methods and program, and Section 10 includes industry recommended changes to the ARC databases, analysis methods and program that are either details below the level required for NRC approval or recommended only for sensitivity analyses.

There are no changes from Addendum 6 for Section 9 for NRC approved methods updates. This section includes the protocol for updating the ARC correlations, the tube removal requirements, the EPRI data exclusion criteria, changes to the database such as excluding the French data and revisions to the analysis methods such as techniques for leak rate analyses.

The industry recommendations in Section 10 below the level requiring NRC approval are methods for obtaining bobbin voltages for indications found by RPC, techniques for cross calibrating NDE standards against the reference standard, voltage dependent growth rate methods and growth rate data for deplugged tube indications returned to service.

2.6 References

2-1 *Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates Database for Alternate Repair Limits, Update 2004*, EPRI, Palo Alto, CA: 2005, 1011456.

2-2 NP 7480 L, Addendum 2, *Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates Database for Alternate Repair Limits 1998 Database Update*, EPRI, Palo Alto, CA (April, 1998).

2-3 NP 7480-L, Addendum 5, *Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates Database for Alternate Repair Limits, 2002 Database Update*, EPRI, Palo Alto, CA (November, 2002), 1007660.

2-4 NP 7480 L, Addendum 1, *Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates Database for Alternate Repair Limits 1996 Database Update*, EPRI, Palo Alto, CA (November, 1996).

3
EVALUATION OF PULLED TUBE DATA FOR ¾ INCH DIAMETER TUBING

No 3/4" tubes were pulled for examination since the publication of Addendum 6.

4

EVALUATION OF PULLED TUBE DATA FOR 7/8 INCH DIAMETER TUBING

This section provides an update of the database for 7/8" diameter tubing based on pulled tube examinations completed since the preparation of Addendum 6 of this report. Additional pulled tube data were obtained from Plant W-2 for which one tube was pulled and two intersections were destructively examined.

4.1 Plant W-2 2006 Pulled Tube

4.1.1 Tube Examination Summary

A section of hot leg tube was removed from Plant W-2, R22C70, SG 4 in 2006. The tube cut was located below the 03H support, thus the 01H and 02H intersections were removed for examination. Both intersections had field-reported bobbin DSI indications. The principal results of the tube examination (Reference 4-1) are described in this section.

4.1.1.1 Non Destructive Examination

4.1.1.2 Destructive Examination Preparation

4.1.2 Plant W-2 Pulled Tube Evaluation for ARC Applications

Due to distortion of tube R22C70 from the tube pulling operations, the indications at 01H and 02H could not be burst and leak tested with any confidence that the test results would yield meaningful results. To assess whether the burst pressures and leak rates for these flaws would be consistent with the ODSCC ARC correlations, analyses were performed based on the destructive examination depth profiles from the pulled tube exam. This section describes the results of these analyses.

4.1.2.1 Destructive Exam (DE) Depth Profiles

4.1.2.2 Corrections to DE Depth Profiles for Uncorroded Ligaments

4.1.2.3 Burst Pressure Analysis Results

4.1.2.4 SLB Leak Rate Analysis Results

The pulled tube examination results were evaluated for application to the EPRI database for ARC applications. The data for incorporation into the EPRI database were then defined and reviewed against the EPRI data exclusion criteria to provide acceptability for the database.

4.2 References

4-1 SG-CDME-07-21-NP, Rev. 0, "Examination of a Steam Generator Tube Removed from Sequoyah Unit 2", Westinghouse Electric Company, September 2007.

4-2 *Steam Generator Degradation Specific Management Flaw Handbook*, EPRI, Palo Alto, CA: 2001. 1001191.

4-3 *Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates Database for Alternate Repair Limits, Update 2004*, EPRI, Palo Alto, CA: 2005, 1011456.

4-4 WCAP-15128, Rev. 2, "Depth Based SG Tube Repair Criteria for Axial PWSCC at Dented TSP Intersections," February, 2003.

Table 4-1
Summary of Plant W-2 2006 Pulled Tube Eddy Current Results

Table 4-2
Plant W-2 2006 Pulled Tube Data For ARC Applications

Table 4-3
Ligament Sizing Results

Table 4-4
R22C70 Calculated Burst Pressures from 01H and 02H 180° Crack Destructive Exam Profiles

Figure 4-1
Corrosion Depth Profile and Ligament Size for 01H 180° Crack

Figure 4-2
Corrosion Depth Profile and Ligament Size for 01H 110° Crack

Figure 4-3
Corrosion Depth Profile and Ligament Size for 02H 180° Crack

Figure 4-4
Addendum 6 Burst Pressure vs. Volts for 7/8" OD Alloy 600 SG Tubes

Figure 4-5
ANL Ligament Tearing Pressures vs. Crack Depth
Alloy 600 MA SG Tubes with Part-Throughwall Axial Cracks

Figure 4-6
SLB Leak Rate (2405 psi) vs. Bobbin Amplitude

5
UPDATED ARC DATABASES

This section presents updated databases obtained by adding the 7/8" pulled tube specimen data obtained in 2006 to the Addendum 6 database presented in Reference 5-1. The database for 3/4" diameter tubes is unchanged. The Addendum 6 database is repeated here for completeness. The new data added to the 7/8" diameter database are described in detail in Section 4. The updated database presented has been utilized to develop the updated ARC correlation for probability of leakage presented in the next section (Section 6).

The database shows adjusted leak rates corresponding to two Δpsi: 2405 psi and 2560 psi. The data at 2405 psi Δp are applicable to a plant whose Tech Spec allows credit for operability of SG power operated relief valve (PORV) under accident conditions in accordance with GL 95-05. As in the past data, leak rates at 2560 psi Δp are applicable when no credit can be taken for SG PORV operability.

5.1 3/4" Data

The database for 3/4" diameter tubes is unchanged from Addendum 6. The database shown in Table 5-1 includes adjusted leak rates at two accident condition pressure differentials of 2405 psi and 2560 psi. The leak rate values were obtained using the same leak rate adjustment procedure as described in Reference 5-2. Leak rate data at 2405 psi Δp are applicable to plants for which credit can be taken for operability of SG PORV in the design-basis accident analyses.

5.2 7/8" Data

The database for 7/8" diameter tubes has been revised to include the Plant W-2, 2006. The new data included in the database for 7/8" diameter tubes are described in detail in Section 4.

The revised database is presented in Table 5-2. Table 5-2 identifies that the French data for Plants J-1, J-2, BA-1 and BB-4 have been excluded from the ARC database as discussed in Section 9.4.

The database for 7/8" diameter tubes, shown in Table 5-2, shows adjusted leak rate data at two accident condition pressure differentials including 2405 psi and 2560 psi. Leak rate adjustments were made in accordance with the procedure for 7/8" diameter tubes in Reference 5-3. Leak rate data at 2405 psi Δp are applicable to plants for which credit can be taken for operability of SG PORV under accident conditions in accordance with GL 95-05.

5.3 Data for Burst inside the TSP

No new tests have performed since 1995 to measure burst pressure for crack indications inside the TSP. Therefore, no changes are needed to the current version of this database since Addendum 1, Reference 5-2. The data from Addendum 1 are included as Table 5-3.

5.4 Data for Axial Tensile Tearing

No new data have become available for axial tensile tearing of cellular corrosion at TSP intersections. A summary of all of the applicable data through Addendum 6 (Reference 5-1) is provided in Table 5-4.

5.5 Summary of Field NDD Data

No new indications that were called NDD in the field have been obtained since Addendum 6. The database for field NDD indications is included as Table 5-5. The total number of indications in the database is 262. The maximum crack depth for the database is 62%, and the lowest measured burst pressure in the database is 9,063 psi. The database strongly supports the conclusion that ODSCC indications at TSP intersections not detected by the bobbin inspection are not structurally significant and would not contribute to SLB leakage or burst probability.

5.6 References

5-1 *Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates Database for Alternate Repair Limits*, EPRI, Palo Alto, CA: 2005. 1011456.

5-2 NP 7480 L, Addendum 1, *Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates Database for Alternate Repair Limits 1996 Database Update*, EPRI, Palo Alto, CA (November, 1996).

5-3 *Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates – Database for Alternate Repair Limits, Volume 1: 7/8 Inch Diameter Tubing*, NP-7480-L, Volume 1, Revision 2 (August 1996).

Table 5-1
3/4 Inch Diameter Pulled and Model Boiler Tube Leak Rate and Burst Pressure Measurements

Table 5-1 (continued)
3/4 Inch Diameter Pulled and Model Boiler Tube Leak Rate and Burst Pressure Measurements

Table 5-1 (continued)
3/4 Inch Diameter Pulled and Model Boiler Tube Leak Rate and Burst Pressure Measurements

Table 5-1 (continued)
3/4 Inch Diameter Pulled and Model Boiler Tube Leak Rate and Burst Pressure Measurements

Table 5-1 (continued)
3/4 Inch Diameter Pulled and Model Boiler Tube Leak Rate and Burst Pressure Measurements

Table 5-1 (continued)
3/4 Inch Diameter Pulled and Model Boiler Tube Leak Rate and Burst Pressure Measurements

Table 5-1 (continued)
3/4 Inch Diameter Pulled and Model Boiler Tube Leak Rate and Burst Pressure Measurements

Table 5-1 (continued)
3/4 Inch Diameter Pulled and Model Boiler Tube Leak Rate and Burst Pressure Measurements

Table 5-2
7/8 Inch Diameter Pulled and Model Boiler Tube Leak Rate and Burst Pressure Measurements

Table 5-2 (continued)
7/8 Inch Diameter Pulled and Model Boiler Tube Leak Rate and Burst Pressure Measurements

Table 5-2 (continued)
7/8 Inch Diameter Pulled and Model Boiler Tube Leak Rate and Burst Pressure Measurements

Table 5-2 (continued)
7/8 Inch Diameter Pulled and Model Boiler Tube Leak Rate and Burst Pressure Measurements

Table 5-2 (continued)
7/8 Inch Diameter Pulled and Model Boiler Tube Leak Rate and Burst Pressure Measurements

Table 5-2 (continued)
7/8 Inch Diameter Pulled and Model Boiler Tube Leak Rate and Burst Pressure Measurements

Table 5-2 (continued)
7/8 Inch Diameter Pulled and Model Boiler Tube Leak Rate and Burst Pressure Measurements

Table 5-2 (continued)
7/8 Inch Diameter Pulled and Model Boiler Tube Leak Rate and Burst Pressure Measurements

Table 5-2 (continued)
7/8 Inch Diameter Pulled and Model Boiler Tube Leak Rate and Burst Pressure Measurements

Table 5-2 (continued)
7/8 Inch Diameter Pulled and Model Boiler Tube Leak Rate and Burst Pressure Measurements

Table 5-3
Burst Capability for Indications within the TSP

Table 5-4
Database for Correlating Axial Rupture Strength of Cellular ODSCC Specimens with Bobbin Amplitude

Table 5-5
Pulled Tubes with Field Bobbin NDD Indications

Table 5-5 (continued)
Pulled Tubes with Field Bobbin NDD Indications

Table 5-5 (continued)
Pulled Tubes with Field Bobbin NDD Indications

Table 5-5 (continued)
Pulled Tubes with Field Bobbin NDD Indications

6
UPDATED ARC CORRELATIONS

This section reports on evaluations performed of results obtained from leak rate and burst testing of tubes removed from operating SGs at utility sites after the publication of Addendum 6 to the ARC database in 2004. The original database for the structural and leak analyses of ODSCC indications was documented in References 6-1 and 6-2 for 7/8" and 3/4" diameter SG tubes respectively. Modifications and additions to the database for both sizes of tubes were reported in References 6-3, -4, -5, -6, -7 and -8 (Addenda 1, 2, 3, 4, 5 and 6), and further in Sections 4 and 5 of this report. The specific use of the data is also delineated in Section 5 of this report. Only one additional pulled tube has been obtained since Addendum 6 of this report was issued in 2004. In summary, separate correlations were developed for Westinghouse designed SGs with drilled hole TSPs which employ 3/4 and 7/8" nominal diameter tubes which relate the burst pressure, the probability of leak (POL), and the leak rate to the bobbin inspection amplitude for ODSCC at locations where degradation has occurred. It has also been postulated that axial tensile tearing of the tube could be of concern if the extent of the degradation were to become extreme in the circumferential direction. For this reason, a correlation was developed between the axial tensile tearing strength and the magnitude of the bobbin amplitude (no new data have been added since the preparation of Addendum 2). Each of the correlations is discussed in the following sections.

Reference Database for 3/4" Diameter SG Tubes

No additional data for 3/4" diameter tubes has been obtained since Addendum 6 of this report. The reference database for 3/4" diameter SG tubes is given in Section 5 and is unchanged from Addendum 6. The parameters for the regression correlation equations are unchanged from Addendum 6, but are restated as Addendum 7 in this section for clarity.

Reference Database for 7/8" Diameter SG Tubes

A discussion of the additional data for 7/8" diameter tubes is provided in Section 4 of this report. The reference database for 7/8" diameter SG tubes is that of Addendum 6, Reference 6-8. Additional data were obtained from tests conducted on tube sections removed from Plant W-2. The results from the destructive examinations are provided in Section 4 of this report, and the data values to be used in the analyses are summarized in Section 5. Because of the condition of the pulled tube, the burst and leak rate correlations are unchanged from Addendum 6 so these correlations are restated as Addendum 7 in this section for clarity. The probability of leakage is updated with the two new data points in this section.

Reference Database for Axial Tensile Tearing

The database has not been changed from that which was documented in Addendum 2 to References 6-1 and 6-2 as no additional data have been obtained since then. Therefore, the axial, or tensile, tearing correlation reported in Addendum 2 remains valid.

6.1 3/4" Diameter Tubes Data Analysis

No additional data for 3/4" diameter tubes has been obtained since Addendum 6 of this report. The parameters for the regression correlation equations are unchanged from Addendum 6, but are restated as Addendum 7 in this section for clarity.

6.1.1 Free Span Burst Correlation for 3/4" Tubes

The burst pressure correlation is given in Table 6-1 and illustrated in Figure 6-1. Predicted values of the probability of burst of a single indication as a function of the bobbin amplitude are illustrated on Figure 6-2. These results are unchanged from Addendum 6.

6.1.2 Probability of Leak Correlation for 3/4" Tubes

The probability of leak correlation is given in Table 6-2 and illustrated in Figure 6-3. These results are unchanged from Addendum 6.

6.1.3 Free Span SLB Leak Rate Correlation for 3/4" Tubes

The correlation parameters of the log-leak rate to log bobbin voltage are listed in Table 6-3 for differential pressures of 2560 and 2405 psi respectively. The leak rate correlations are illustrated in Figure 6-4 and Figure 6-5 for differential pressures of 2560 and 2405 psi respectively. These results are unchanged from Addendum 6.

6.2 7/8" Diameter Tubes Data Analysis

This section reports on the evaluations of data obtained from leak and burst testing of Alloy 600 MA SG tubes with a nominal diameter of 0.875" and a nominal thickness of 0.050".

Due to damage to the flaws in the W-2 pulled tube sample as a result of the tube pulling operation, the crack indications could not be meaningfully burst and leak tested. To assess consistency with the ODSCC database of Addendum 6 based on test results, calculations of the burst pressure and SLB leak rates were performed as discussed in Section 4.

6.2.1 Free Span Burst Correlation for 7/8" Tubes

Predicted values of the probability of burst of a single indication as a function of the bobbin amplitude are illustrated on Figures 6-7 and 6-8 for differential pressures of 2560 and 2405 psi respectively. The burst correlation parameters which are given in Table 6-4 are unchanged from Addendum 6, but are restated as Addendum 7 for clarity.

6.2.2 Probability of Leak Correlation

In order to assess the quantitative effect of the new data on the correlation curve, the database was expanded to include the W2 data points and a *Generalized Linear Model* regression of the POL on the common logarithm of the bobbin amplitude was repeated. A comparison of the regression parameters with those for the reference database is shown in Table 6-5. These results indicate:

6.2.3 Free Span SLB Leak Rate Correlation for 7/8" Tubes

Figure 6-12 compares the predicted SLB leak rate with the ODSCC ARC Addendum 6 leak rate correlation.

The leakage correlation parameters which are given in Table 6-6 are unchanged from Addendum 6, but are restated as Addendum 7 for clarity.

6.3 Axial Tensile Tearing Correlation

Section 6.3 of Addendum 2, Reference 6-4, presents axial strength information for cellular corrosion based on a correlation of the remaining cross section area (CSA) of the tube as a function of the bobbin amplitude of the TSP ODSCC. There have been no additional tests performed since the Addendum 2 report was issued and no changes to the analysis of the Addendum 2 data.

6.4 Summary/Conclusions

The 3/4" tube leak rate correlations are unchanged because no new data became available. The 7/8" tube probability of leak correlation was updated with the calculated data from the tube pull at W-2. The burst and leak rate correlations for 7/8" tubes are unchanged.

6.5 References

6-1 NP-7480-L, Volume 1, Revision 2, *Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates – Database for Alternate Repair Limits, Volume 1: 7/8 Inch Diameter Tubing*, Prepared for EPRI by Westinghouse (August, 1996).

6-2 NP-7480-L, Volume 2, Revision 1, *Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates – Database for Alternate Repair Limits, Volume 2: 3/4 Inch Diameter Tubing*, Prepared for EPRI by Westinghouse (August, 1996).

6-3 NP-7480-L, Addendum 1, *Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates Database for Alternate Repair Limits, 1996 Database Update*, EPRI, Palo Alto, CA (November, 1996).

6-4 NP-7480-L, Addendum 2, *Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates Database for Alternate Repair Limits, 1998 Database Update*, EPRI, Palo Alto, CA (April, 1998).

6-5 NP-7480-L, Addendum 3, *Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates Database for Alternate Repair Limits, 1999 Database Update*, EPRI, Palo Alto, CA (November, 1999).

6-6 NP-7480-L, Addendum 4, *Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates Database for Alternate Repair Limits, Update 2001*, EPRI, Palo Alto, CA (August, 2001).

6-7 NP-7480-L, Addendum 5, *Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates Database for Alternate Repair Limits,2002 Database Update*, EPRI, Palo Alto, CA (November, 2002), 1007660.

6-8 *Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates Database for Alternate Repair Limits*, EPRI, Palo Alto, CA: 2005, 1011456.

Table 6-1
Burst Pressure versus Bobbin Amplitude Correlation 3/4" Tube Data

Table 6-2
Probability of Leak Correlation 3/4" Tubes

Table 6-3
Leak Rate vs. Bobbin Amplitude Correlation (2560 & 2405 psi) 3/4" Tubes

Table 6-4
Burst Pressure versus Bobbin Amplitude Correlation 7/8" Tube Data

Table 6-5
Effect of Additional Data on the 7/8" Tube Probability of Leak Correlation

Table 6-6
Leak Rate vs. Bobbin Amplitude Correlation (2560 & 2405 psi) 7/8" Tubes

Figure 6-1
3/4" Burst Pressure Correlation

Figure 6-2
3/4" Burst Probability

Figure 6-3
3/4" Probability of Leak

Figure 6-4
3/4" SLB Leak Rate at 2560 psi

Figure 6-5
3/4" SLB Leak Rate at 2405 psi

Note: R22C70 points are Addendum 7 calculations.

Figure 6-6
7/8" Burst Pressure Correlation Tolerance Bounds

Figure 6-7
7/8" Probability of Burst at 2560 psi

Figure 6-8
7/8" Probability of Burst at 2405 psi

Note: W2 data are Addendum 7 data.

Figure 6-9
7/8" Probability of Leak

Figure 6-10
7/8" POL Comparison

Figure 6-11
7/8" Ratio of POLs

Bobbin Amplitude, V (Volts)

Note: R22C70-1H point is Addendum 7 calculation.

Figure 6-12
7/8" Leak Rate for 2405 psi

7
PROBABILITY OF PRIOR CYCLE DETECTION (POPCD)

This section provides a minor revision to Section 7 of Addendum 6 (Reference 7-2). The methods for defining the Probability of Prior Cycle Detection (POPCD) and for calculating the resulting POD distribution have been revised based on interactions with the NRC in support of licensing POPCD for Diablo Canyon Units 1 and 2 ARC analyses. All references to 7/8 inch POPCD include industry 7/8 inch tubing data through 2007 outages. All references to 3/4 inch POPCD include industry 3/4 inch tubing data through 2003 outages, and are unchanged from Addendum 6.

The methods of this section are the same as described in Addendum 6 with the exception that bobbin indications that were found to be NDD by RPC are treated as bobbin undetected for POPCD calculations. Since this requirement was approved since Addendum 6 was issued, the new definition has been applied retroactively to those plants which have developed a plant specific POPCD, and incrementally to one plant that has been replaced. The specific plant outages for which data is included in the summary POPCD is provided.

7.1 Introduction

This report provides guidelines for developing steam generator (SG) detection probabilities based on the Probability of Prior Cycle Detection (POPCD). The POPCD method was initially described in Reference 7-1 with the latest update to the data provided in Reference 7-2 and was developed for application with the NRC GL 95-05 (Reference 7-3) voltage based repair criteria. GL 95-05 requires NRC approval for implementing POPCD. This report provides POPCD guidelines and results supporting a generic industry POPCD submittal for NRC approval, and includes an option for applying a plant specific POPCD when adequate data is available on a plant specific basis. NRC approval of a permanent POPCD for DCPP Units 1 and 2 was provided in Reference 7-4. The POPCD guidelines and data of this report reflect changes to References 7-1 and 7-2 based on the NRC review reflected in the DCPP approval of Reference 7-4.

POPCD is defined in Section 7.2 including the classification of indications for POPCD analyses. Methods for calculating POPCD distributions including uncertainties are given in Section 7.3. Growth rate and noise considerations for POPCD applications are provided in Sections 7.4 and 7.5. Section 7.6 summarizes benchmarking results for industry wide POPCD applications. Section 7.7 provides the POPCD evaluation for the industry database with Section 7.8 defining requirements for applying plant specific POPCD distributions. Section 7.9 provides reporting requirements for POPCD applications and conclusions of the report. References are provided in Section 7.11.

7.2 POPCD Definition and Classification of Indications

7.2.1 POPCD Definition

POPCD is calculated as the ratio of indications reported at the prior inspection to the total indications found at the subsequent inspection (all indications reported in the prior cycle plus new indications). POPCD for the EOC_n inspection (EOC_n) is defined as:

This definition of POPCD is based on the premise that all indications that can contribute significantly to burst and leakage for voltage-based repair criteria application can be confirmed by rotating pancake coil (RPC) inspections. The term RPC is meant to include an RPC probe or equivalent, which includes a +Point coil. The POPCD definition that is used for ODSCC ARC analyses is based on RPC confirmed indications plus indications not RPC inspected.

This application of the RPC results is applied to exclude from POPCD the probable false bobbin calls that would not contribute to tube integrity concerns at EOC_{n+1} for both previously reported and new indications. The use of RPC confirmation provides a measure of confidence that irrelevant prior and new bobbin calls are not allowed to influence the POD either as an increase or a decrease in the POD. The intent is that the EOC_{n+1} RPC should define the significance of the bobbin indication for POD considerations such that the insignificant RPC NDD indications are excluded from the POPCD method for both previously reported and new bobbin indications. EOC_n bobbin calls that were RPC no detectable degradation (NDD) at EOC_n but were either bobbin or RPC detected or not RPC inspected at EOC_{n+1} are included in POPCD as bobbin undetected indications at EOC_n.

7.2.2 Classification of Indications and Assignment for POPCD Analyses

Table 7-1 identifies all potential classifications for tracking bobbin coil indications between EOC_n and EOC_{n+1}. The classification of an indication is dependent upon whether the indication is bobbin detected at each cycle and whether the indication is confirmed by RPC inspection or not RPC inspected. The letters in the columns of Table 7-1 reflect the column for entering data in the Table 7-2 reporting format for POPCD data results. The Table 7-2 format for reporting POPCD data, is revised from that of the NP 7480-L Addendum 6 POPCD table format due to differences in evaluating EOC_n RPC NDD indications. Table 7-2 is constructed as follows.

Data from Addendum 6 was retained for all cases except three plants that have developed plant specific POPCD using the Table 7-1 format. The POPCD for the last outage for one plant was also developed using Table 7-1 format, and added to its Addendum 6 data. Therefore the Table 7-2 Column G contains all historic data for three plants and one outage of data from a fourth plant. Thus Column G contains data extracted from about 49% of all of the indications in Table 7-2.

The format for reporting POPCD data in Table 7-2 is used to develop the POPCD distributions following the guidelines described in this subsection. The upper rows of each column in Table 7-2 provide the source of input data based on bobbin and RPC detection at EOC_n and EOC_{n+1}. Guidelines for assigning bobbin voltages to bobbin NDD indications are provided at the end of this subsection. The rows show the voltage bin widths of 0.1 volt .

The following indications are considered to be false bobbin coil calls and are not included in the POPCD analyses. The numbers are tabulated in column H in Table 7-2.

The following guidelines are to be applied for determination of detection and bobbin voltages for the POPCD analyses:

7.3 Calculation of the POPCD Distribution Including Uncertainties

7.3.1 Loglogistic Fitting

The preferred approach to simulating the POD is to fit a loglogistic cumulative distribution function to the empirical data. The statistically based POD distribution such as the loglogistic provides uncertainties in the POD distribution. The POD uncertainties are included in Monte Carlo analyses as described below. This allows for an analytical simulation of the POD analogous to the simulation of the probability of leak for ODSCC indications at TSPs. The simulation of the probability of leak for ODSCC indications at TSPs is discussed in several documents pertaining to the application of the ODSCC ARC. The functional form of the loglogistic equation is,

where P is the POD, V is the bobbin amplitude, and b0 and b1 are parameters obtained by performing a regression analysis of the empirical POD data. The equation can be easily rearranged into the log-odds form as,

where the ratio in the parentheses is the odds of detection, i.e., the ratio of the POD to the probability of nondetection.

For application to POPCD analyses, the data are sorted into 0.1 volt bins representing various voltage levels, and the POPCD distributions used for ARC analyses are developed using fits to weighted binary data (hit/miss = 1/0), where weighting is based on the number of indications in each bin. The fitting parameters developed from Table 7-2 and 7-3 for 7/8 inch tubing and ¾ inch tubing respectively are given in Table 7-4.

7.3.2 Monte Carlo Techniques

The following is a description of the Monte Carlo techniques that are used to apply POPCD curves. The Monte Carlo analysis consists of simulating all of the indications in a SG several

thousand times. Each simulation of all of the indications in a SG is referred to as one simulation of the SG. If POD uncertainties are needed for the ARC analysis, each simulation of a SG calculates a set of random possible parameters for the POD equation (the intercept, slope and error standard deviation) that are applied to all of the detected indications to establish a population of detected and undetected indications. For a given POD, P, the number of indications that remain in service, N, in a given bin is given by,

where N_D is the number of indications detected and N_P is the number of indications plugged.

Because the POD is a decimal value, the fraction in the above equation will not return an integer number of indications. The result is truncated to an integer value and a random draw from a uniform distribution is used to determine if an additional indication should be added to the total. If the value obtained from the uniform distribution is greater than the value of the fractional indication, an indication representing the fractional indication is not present. Likewise, if the value is less than the fractional indication value then a whole indication representing the fractional indication is present and is included in the analysis to determine the probability of burst and potential total leak rate for that simulation of the SG. The application of this approach results in one additional indication being present in the prediction bin for a fraction of the SG simulations that matches the average value of the predicted fractional indication. For example, 10 indications in a bin with a POD of 0.33 gives rise to predicting that 30.3 indications were originally present. If the random draw from a uniform distribution is less than or equal to 0.3 the indication is present. If the number drawn is greater than 0.3 the indication is not present.

For each of the Monte Carlo simulations of a SG, the elements of the population variance covariance matrix for the parameters of the loglogistic equation are found using the estimated values from the regression analysis and a random value from the Chi-Square distribution corresponding to the degrees of freedom associated with the regression analysis. Once the population values for the variance-covariance matrix have been calculated, population parameters of the POD equation, β_0 and β_1 corresponding to b_0 and b_1, can be calculated using two random values from the standardized normal distribution based on the assumption that they are bivariate normally distributed. Given the population parameters, the POD for any indication voltage, V_i, associated with a bin can be calculated as,

where the β values are the estimated population parameters corresponding to the regression parameters b_0 and b_1. For each bin of indications found during the current outage, the number of indications present that gave rise to finding the number reported for that bin is found by substituting the calculated P_i values into Equation 3.

The methodology to employ an analytic form for the POD is essentially identical to that used to simulate indications for evaluating the probability of burst and leak. If POD uncertainties are included in the Monte Carlo analysis, the process is repeated so that each simulation of all of the indications in a SG is independent of the other simulations of all of the indications in the SG. In

this manner, thousands of variations of the possible levels of degradation within the SG can be considered. The determination of the POB and the potential leak rate during a postulated steam line break event proceeds according to the methodology outlined in GL 95-05.

POPCD uncertainties can be addressed by either applying POPCD at the lower 95% confidence level or including an uncertainty analysis for POD in the operational assessment. The industry POPCD uncertainties are small at 95/50 confidence (See Figures 7-2 and 7-3) due to the large number of indications in the database. Sampling of POD uncertainties leads to the same number of simulations with more than or less than the average number of indications for the mean POD. Due to the small uncertainties and the trend for the Monte Carlo results to converge to that obtained for the average number of indications, the effects of including POD uncertainties in the Monte Carlo process are negligible. It can also be noted that when the POD uncertainties are significant, the Monte Carlo sampling process leads to changes in the mean POD distribution near 0% and 100% POD. The latter results change since applying uncertainties near 0% POD are cutoff at 0% (smaller uncertainties applied below the mean POD than above the mean POD) with a resulting increase in the mean POD near the 0% value. Near 100% POD, the uncertainties are cutoff at 100% above the mean POD but not below the mean POD with a resulting decrease in the mean POD near the 100% value. These effects are found when Monte Carlo sampling a POD distribution with uncertainties and comparing the mean POD after sampling with the input mean POD. These cutoff effects would be negligible due to the small POD uncertainties.

The p-value from the POPCD regression analysis is the probability of observing a value of χ^2 as small as the one calculated from the data. If the p-value is found to be greater than 5 percent (i.e., the probability of randomly observing a value as small as the one calculated would be greater than 5 percent) a default value of POD of 0.6 will be applied. The associated implication would be that there could be sufficient noise at the location of the indications to interfere with the detection of the indications. For regression results shown in Table 7-4, the p-values were calculated to be effectively zero.

Single-cycle POPCD distributions can be expected to change from cycle-to-cycle dependent upon the number and size of indications in a given inspection. For inspections with a large number of indications spanning up to at least 5 volts, the differences between a single-cycle POPCD and a combined cycle POPCD would be expected to be modest. Multi-cycle POPCD distributions are applied for ARC applications. The integrated inspection experience is then included in POPCD to represent the history of undetected indications. For example, if the last inspection resulted in the largest undetected voltage indication, the last inspection results do not imply similar occurrences for the next cycle and the overall integrated history would be the best estimate for the next cycle. This conclusion is applicable as long as SG conditions at TSP intersections do not significantly degrade with operating time, which is typical of operating times after the first one or two cycles during which the residual signals form at TSP intersections.

7.4 Growth Rate Considerations for POPCD Applications

7.4.1 Provision for Outlier Growth Rates

Calculations applying POPCD or 0.6 as the POD will not predict flaws which result from voltage growth rates which are higher than previously seen (e.g. the R44C45-2H flaw which was detected as a 21.5-volt flaw at DCPP in the 2R11 inspection and was detected as a 2.0-volt flaw in 2R10 and left in service per the ODSCC ARC repair criteria) and both POD methods lead to underestimates of the 2R11 maximum flaw size, burst probability, and leak rate. The overly conservative and arbitrary application of a POD of 0.6 has not changed any assessments for corrective actions following identification of a large growth rate indication. For smaller growth rate under predictions, the application of a POD of 0.6 can mask a real growth rate issue by leading to artificially high burst and leakage predictions with an associated conclusion that no corrective action is necessary.

If the NRC approves the methods described in Reference 7-5 for an outlier growth rate, the methods will be included in the ARC operational assessments upon NRC approval of the generic industry POPCD for ARC applications.

7.4.2 Development of Growth Rate Distributions

Conservative growth rates should be used in the operational assessments for ARC analyses. The outlier growth method noted above, as required for POPCD applications, is one technique for adding conservatism to the growth distributions. GL 95-05 requires the use of the most limiting of the two previous growth rate distributions for the next operating cycle.

GL 95-05 notes that a single growth distribution in terms of ΔV rather than percent ΔV can be used provided the conservatism of this approach continues to be supported by operational experience. This requires an assessment for the potential onset of voltage dependent growth (VDG). The onset of VDG can generally be seen from plots of voltage growth versus BOC voltage. The occurrence of a higher frequency of large growths or increased growth rates with increased BOC voltage is an indication of the presence of VDG. Methods for calculating voltage dependent growth rate distributions are described in Section 10.3 and Reference 7-6. These methods define techniques for determining break points in voltage bins with each bin defining a separate growth distribution. When applying POPCD, the assessment for the onset of VDG

should be performed and the methods of Section 10.3 applied when growth rates show a dependence on the BOC voltage.

7.5 Noise Considerations for POPCD Applications

The POPCD approach to detection probabilities considers the potential for missing indications that might challenge structural or leakage integrity. The database includes successive inspections such as five consecutive inspections for one of the units in the industry database with high noise levels. If a large indication was missed in one inspection, it would continue to grow until finally detected in a later inspection. The POPCD methodology includes all new indications as assumed missed indications and large new indications found in an inspection are reevaluated at the prior outage to define the undetected indication voltages for a POPCD cycle.

The two units dominating the missed indications above 1.6 volts had high noise levels at TSP intersections compared to the currently operating SGs. Although not numerically demonstrated by noise analyses, the noise levels for the industry POPCD database can be expected to bracket current ARC applications. Evaluations of noise levels for the extensive industry POPCD database would be a major task that is not warranted based on the detection experience cited above. The ARC pulled tube database is a representative sample of the overall POPCD database since the number of pulled tubes from a given plant reflects the number of cycles for which the ARC has been implemented and the detection data included in the POPCD database. Consequently, noise levels for the pulled tube database can be adequately applied to represent the POPCD database.

Based on work performed under the EPRI Tools for Tube Integrity Program (Reference 7-9), noise analyses for tube integrity applications are based on maximum noise voltage amplitudes at the area of interest for detection. TSP ODSCC indications are dominantly located near the center of the TSP or span the center of the TSP. Thus, the area of interest for noise analyses is the center 1/3 of the TSP thickness. For application of ETSS PODs to be developed from performance testing of multiple analysis teams under the EPRI tools program, the plant noise distribution must be shown to be bounded by the ETSS noise distributions based on applying the Kolmogorov-Smirnov (KS) two sample test for compatible distributions. For TSP indications, the bobbin mix vertical maximum amplitude at the center 1/3 of the TSP is the appropriate noise measurement for assessing POD applicability.

The noise requirement to apply the industry POPCD on a plant specific basis is that the plant bobbin vertical maximum noise amplitude at the TSP center be bounded by the pulled tube noise distribution as demonstrated by passing the one-sided (pulled tubes bound plant) KS test at a 5%

probability level. Figure 7-3 provides an example of this application for Plant DW. As expected, the noise levels for the pulled tube data base, which includes data from replaced SGs with higher noise levels than active SGs, bounds the plant noise distribution for Plant DW.

With regard to the presence of mix residuals and the influence of the mix residuals on sizing the indications, it must be emphasized that all TSP intersections have mix residuals after the first one or two cycles of operation. After about two cycles, the mix residuals generally do not change with operating time. The dominant voltage for the mix residual signals is not affected by the mixing used to analyze the bobbin data so the mix residual signal amplitude does not vary with operating time or nondestructive examination (NDE) analyst. Frequently, a significant part of the mix residual signal is present in bobbin data obtained without a TSP for pulled tubes examined in the laboratory. Some of the model boiler specimens show mix residuals although generally smaller than field data due to the shorter time at temperature. The bobbin response apparently includes an effect of the time at temperature at a TSP on the magnetic properties of the tube. Metallography was performed on a pulled tube to attempt to identify the cause for the signal, but was not successful in identifying any physical change to the tube or grain structure.

Many of the pulled tubes in the ARC database (and the POPCD database) have mix residual signals larger than typically found in currently operating SGs. Whatever influence the mix residuals may have on voltage sizing for TSP indications is built into the ARC database by the pulled tubes. The mix residuals may be more easily understood as TSP noise. The noise may distort the flaw signal particularly when the two phase responses are similar. The mix residual voltage is not being used in current assessments (e.g., noise distributions described above) of the influence of noise on detection or sizing. For signal to noise evaluations, the noise is being evaluated as the peak vertical amplitude response over one third sections of the TSP to reflect the larger noise near the edges of the TSP. The noise differences between the center and edge of a TSP affect detectability of short, low voltage indications located at the edges of the TSP. The short indications at the TSP edges must grow to the center of the TSP to become structurally significant and the lower noise levels at the TSP center provide for detection of even low voltage indications. It is not feasible or necessary to attempt to define bobbin voltages that are not affected by the TSP noise or mix residuals. All indications have a range of noise influence on voltage sizing, and the ARC database includes many indications with larger noise levels than DCPP and other plant active SGs.

7.6 Benchmarking of POPCD

In a letter dated January 24, 1997 (Reference 7-10), the NRC issued a request for additional information to the Nuclear Energy Institute (NEI) requesting supplemental information in support of NP 7480-L, Addendum 1. Question 9, Part 2 requested an assessment of the ability of the POPCD approach to conservatively project the EOC voltage distribution. The NEI response to this request for additional information dated September 14, 1998, provided extensive benchmarking of POPCD analyses as summarized below. In addition, the DCPP POPCD distribution for the last operating cycle has been benchmarked against the inspection results at DCPP 2R11 as described below.

The NEI letter to the NRC dated September 14, 1998 (Reference 7-11), provided a response to an NRC request for additional information on benchmarking OA using POPCD for the POD

rather than a POD of 0.6. The response included Monte Carlo analyses for 32 cases including 18 SGs with 7/8 inch tubing and 14 SGs with 3/4 inch tubing together with an additional 17 sensitivity cases. The analyses compared EOC voltages with the projected values in addition to comparisons of burst probabilities and leak rates based on projected and actual (inspection results) voltage distributions.

Benchmarking analyses were also performed by DCPP to show the adequacy of using a DCPP POPCD distribution (Reference 7-7). Monte Carlo POB and leak rate projections were performed for multiple cycles using the DCPP POPCD. The results of these analyses indicate that the methodology used to predict EOC conditions were generally although not always, conservative. The underpredictions were not significant relative to the as-found inspection results.

Under predictions when applying POPCD are more likely to be due to growth rate uncertainties than POPCD uncertainties. The above benchmarking results support the adequacy of the POPCD methodology for ARC applications.

7.7 POPCD Evaluation for the Industry Database

7.7.1 Industry POPCD Distribution

The POPCD industry database was updated in EPRI Topical Report NP 7480-L, Addendum 6. The industry POPCD data were reevaluated for this report to provide the data consistent with the new format of Table 7-2. The POPCD data were obtained from 33 inspections in plants with 7/8" tubing and from 12 inspections in plants with 3/4 inch tubing. The POPCD data include results from inspections through 2007 outages. Tables 7-2 and 7-3 provide the resulting POPCD database for 7/8" tubes, 3/4" tubes, respectively. Table 7-3 for 3/4" tubes in unchanged from Addendum 6. The plants and inspections which provided the data for these tables are listed in Table 7-5 and Table 7-6.

The bin mid-range voltages of the POPCD data tables are used to develop the loglogistic POPCD distribution. The general linear model (GLM) regression analyses of the data are based on weighted binary input as described in Section 7.3.1.

Figure 7-1 and Figure 7-2 show the POPCD log-logistic fits to the 7/8" and 3/4" data including the lower 95% confidence bounds on the POPCD distributions. The lower 95% confidence bounds show only a small reduction relative to the nominal regression fits, which supports small uncertainties for the industry POPCD distributions based on the large databases available. The uncertainties in the upper voltage range above about 3 volts are further discussed below.

Figure 7-4 compares the 7/8" and 3/4" POPCD distributions together with the POPCD obtained by combining the two datasets. The 3/4" POPCD is slightly lower than that obtained from the 7/8" data, although the differences are insignificant above about 2 volts. This POPCD difference results from the larger number of new indications below one volt for 3/4" tubing. Above one volt, the bin average POPCD values for 3/4" tubing in Table 7-3 are generally higher than that for 3/4" tubing in Table 7-2.

7.7.2 Effect of Uncertainties in the Upper Voltage Range

7.7.3 Comparisons of Industry POPCD with ANL POD from Round Robin Testing and EPRI POD from Multiple Analyst Testing

As discussed above, substantial industry benchmarking has been performed to support POPCD applications. An independent POD assessment that supports the POPCD results and elimination of the 0.6 POD for ARC applications is described in the ANL study contained in NUREG/CR-6791 (Reference 7-8) under work sponsored by the NRC. The ANL POD results were obtained from round-robin NDE analyses of data from a SG mock-up. The ANL results discussed in this section were obtained from Figures 2.54 and 2.55 of NUREG/CR-6791, which are based on test results for axial ODSCC at TSP intersections. POD distributions as a function of bobbin coil voltage are described in the report. The NUREG/CR-6791 figures are shown in Figure 7-5 and Figure 7-6 of this report.

Based on the methods applied in this report, the ANL logistic fit shown in Figure 7-6 appears to represent too high a POD distribution for the data shown in Figure 7-5. For example, the nominal fit approaches unity near 2 volts where the data indicate about a 0.9 POD. To permit an equivalent comparison of POD curves between the DCPP and ANL data, the ANL bin data from Figure 7-5 were processed in the same manner as the industry POPCD data described previously, except for using fractional data rather than weighted binary data, to obtain a log-logistic fit to the ANL data. Figure 7-4 compares the Industry and ANL log-logistic nominal PODs. The comparisons show that the Industry POPCD results are significantly higher than the ANL results and both are near unity above 5 volts. The ANL data are based exclusively on laboratory specimens, which may have morphology differences from pulled tubes that lead to the differences in the PODs. The trends of POD with increasing voltage are essentially the same for all distributions.

EPRI also conducted blind testing of NDE analysts to develop a POD versus voltage curve. The resulting POD distribution is reported in NP 7480-L, Addendum 5, as the EPRI POD curve. For this evaluation, the EPRI POD data were reevaluated by applying a weighted GLM analysis to the data for 1363 indications evaluated by 12 NDE analysts. Figure 7-4 provides a comparison of the 3/4" and 7/8" industry POPCDs, ANL, and EPRI POD curves. The comparison shows consistent high detectability for bobbin indications above one volt at TSP intersections independent of the methods used to develop the POD distributions. Below about two volts, the ANL results show a lower POD than POPCD and the EPRI POD. The POPCD results are based on the conservative assumption that all new indications in the inspection outage were not detected in the prior outage. For POPCD, "truth" as an indication is defined as inspection results for RPC confirmed plus not RPC inspected indications. The EPRI POD is based on testing analysts against field data for about 5726 TSP intersections from three plants with 3/4 inch tubing. The definition of "truth" (flaws in the population) for the EPRI POD is based on 890 indications confirmed by RPC, 222 indications not confirmed by RPC or not RPC inspected and 251 added indications based on expert opinion. The results shown in Figure 7-4 clearly demonstrate the inadequacy of a POD of 0.6 to represent the strong dependence of POD on voltage, and the results support the consistency of the POPCD results. The differences in POPCD are primarily dependent on the number of new indications found below about 1 volt.

7.8 Option for Developing Plant Specific POPCD Distributions

Application of a plant specific POPCD requires satisfaction of minimum data requirements for which guidelines are described below. If a plant does not meet the minimum data requirements, the industry POPCD distribution must be applied unless it is shown that the plant specific POPCD distribution for ARC analyses yields a uniformly lower POD above 1.0 volt and has a POD less than the industry POPCD in the range of 0.1 to 0.2 volt. Alternately, a plant specific POPCD can be constructed by applying the lower of the plant specific and industry POPCD distribution above 1 volt and the lower of the two distributions below 1.0 volt, particularly near about 0.2 volt. The latter may require changes to Monte Carlo analysis codes to accommodate differences in POPCD uncertainties below and above 1.0 volt. These options permit application of conservative POPCD distributions while the plant specific database is increased to meet the guidelines for applying a plant specific POPCD distribution.

Guidelines for applying a plant specific POPCD distribution are:

7.9 Continuing Assessment and Reporting for POPCD

Upon implementation of POPCD, if the EOC conditional SLB burst probability, the projected SLB leak rate or number of indications are under predicted by the previous cycle operational assessment (using the actual cycle length), the following guidelines will be applied to assess the need for methods adjustments:

Historically, there have been no ARC cases where undetected indications (POD effects) have led to a challenge to structural or leakage integrity. These cases have been associated with under predictions in growth rates. It is expected that growth rates would be the first potential cause examined for ARC under predictions. Potential POD effects as the cause for under predictions would also be assessed if the probable cause for the low predictions is a larger than anticipated undetected indication or due to cumulative numbers of indications above about 1 volt. The 90-day report will document any recommended changes to POD or growth methodology indicated by the assessments.

Upon implementation of POPCD, the following additional information shall be included in the 90 day report:

- To assess POPCD for potential changes over time, the 90-day report should compare the multi-cycle POPCD distribution applied for the last operational assessment with the POPCD distribution obtained for only the last operating cycle. Differences in the two POPCD distributions should be assessed relative to the potential for significant changes in detection capability.

- For RPC confirmed indications at EOC_n that are RPC NDD at EOC_{n+1}, an assessment is required for the cause for the "disappearing flaws" if the RPC (+Point or pancake coil)

voltage is greater than 0.5 volt. If there are a significant number of occurrences (such as more than three occurrences in any one SG) of these "disappearing flaws", the cause should be evaluated independent of the +Point voltage.

- The POPCD data reported in the 90 day report shall include the plant specific historical results and the last cycle results reported in the format of Table 7-1.

- In support of this evaluation, Table 7-1 requires an RPC inspection at EOC_{n+1} for RPC confirmed indications at EOC_n (either bobbin detected or bobbin NDD) that are bobbin NDD at EOC_{n+1}. This inspection is necessary to ensure that all known ODSCC indications are included in the condition monitoring and operational assessments as well as properly categorized for the POPCD evaluation.

- For plants that assign bobbin voltages to ODSCC confirmed by RPC but are NDD by bobbin, assess these assigned bobbin voltages to verify they are conservative. That is, for prior cycle NDD indications that become detectable by bobbin, the review should assess the prior cycle assigned bobbin voltages, the current cycle actual bobbin voltages, and growth rates.

7.10 Conclusions

The current licensed ARC methodology of using a uniform POD value of 0.6, based on GL 95-05, results in an overly conservative and counter intuitive estimate of the number and severity of indications remaining in the SGs following the inspection.

POPCD distributions are developed based on fitting the inspection results used to define POPCD by loglogistic functions, which are commonly applied in tube integrity analyses for POD distributions. Uncertainties in the resulting POD distributions are obtained from the analyses. In addition, the industry POPCD results for bobbin coil detection are shown to be in good agreement with POD results obtained from ANL round-robin test results in NUREG/CR-6791, and an EPRI POD obtained from blind testing of analysts.

Based on industry and plant specific bobbin detection data for ODSCC within the SG TSP region, large voltage bobbin indications that can individually challenge structural or leakage integrity can be detected with near 100 percent certainty and would not be left in service. These large voltage indications should not be included in the BOC voltage distribution, other than as inferred from the voltage dependent POD, for the purpose of the operational assessment. The POPCD approach to probability of detection considers the potential for missing indications that might challenge structural or leakage integrity by applying the POPCD data from successive

inspections. The database used to develop the POPCD values includes data from successive inspections. If a large indication was missed in one inspection, it would continue to grow until finally detected in a later inspection. Therefore, the use of the POPCD method to determine the BOC voltage distribution will improve EOC projections and lead to appropriate estimates of the margin in SG tube structural and leakage integrity.

7.11 References

7-1 NP-7480-L, Addendum 1, *Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates Database for Alternate Repair Limits 1996 Database Update*, EPRI, Palo Alto, CA (November, 1996).

7-2 *Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates Database for Alternate Repair Limits, Update 2004, Interim Report (Addendum 6)*, EPRI, Palo Alto, CA (January, 2005).

7-3 Generic Letter 95-05, "Voltage-Based Repair Criteria for Westinghouse Steam Generator Tubes Affected by Outside Diameter Stress Corrosion Cracking," dated August 3, 1995.

7-4 NRC Letter, G. S. Shukla (NRC) to G. M. Rueger (PG&E), "Diablo Canyon Power Plant, Unit Nos. 1 and 2 – Issuance of Amendment Re: Permanently Revised Steam Generator Voltage-Based Repair Criteria Probability of Detection Method (TAC Nos. MC2313 and MC2314)," dated October 28, 2004.

7-5 Enclosure 1 ("Extreme Values of ODSCC ARC Indications Growth") to Nuclear Energy Institute Letter, Alex Marion (NEI) to Document Control Desk (NRC), "*Revision to ODSCC ARC Task Extreme Values of ODSCC ARC Growth*,"dated July 9, 2004.

7-6 Enclosure 3 ("Voltage Dependent Growth Break Point Determination") to Nuclear Energy Institute Letter, Alex Marion (NEI) to Document Control Desk (NRC), "Generic Letter 95-05 Alternate Repair Criteria Methodology Updates," dated June 2, 2004.

7-7 Letter from Lawrence F. Womack, PG&E, to the NRC, "Diablo Canyon Unit 2, PG&E Response to NRC Questions on 2R11 Steam Generator Tube Inspections," dated September 30, 2003, letter DCL-03-121.

7-8 NUREG/CR-6791, ANL-02/07, "Evaluation Current Reliability Results from the Steam Generator Mock-Up Analysis Round-Robin," Published November 2002, Argonne National Laboratory.

7-9. *Update on the Tools for Integrity Assessment Project*. EPRI, Palo Alto, CA: 2007. 1014756.

7-10 Letter from S. L. Magruder, Nuclear Regulatory Commission, to D. Modeen, Nuclear Energy Institute, January 24, 1997.

7-11 Nuclear Energy Institute Letter, D. Modeen (NEI) to Document Control Desk (NRC), "Steam Generator Degradation Specific Management Database, Addendum 2 and Responses to NRC Requests for Additional Information (RAI)," dated September 14, 1998.

Table 7-1
Data Table for Tracking Indications between EOCn and EOCn+1

Table 7-2
7/8" Plant Data Summary Evaluation for POPCD (Data through 2007)

Table 7-2 (continued)
7/8" Plant Data Summary Evaluation for POPCD (Data through 2007)

Table 7-2 (continued)
7/8" Plant Data Summary Evaluation for POPCD (Data through 2007)

Table 7-2 (continued)
7/8" Plant Data Summary Evaluation for POPCD (Data through 2007)

Table 7-2 (continued)
7/8" Plant Data Summary Evaluation for POPCD (Data through 2007)

Table 7-2 (continued)
7/8" Plant Data Summary Evaluation for POPCD (Data through 2007)

Table 7-3
3/4" Plant Data Summary Evaluation for POPCD (Data through 2007)

Table 7-3 (continued)
3/4" Plant Data Summary Evaluation for POPCD (Data through 2007)

Table 7-3 (continued)
3/4" Plant Data Summary Evaluation for POPCD (Data through 2007)

Table 7-3 (continued)
3/4" Plant Data Summary Evaluation for POPCD (Data through 2007)

Table 7-3 (continued)
3/4" Plant Data Summary Evaluation for POPCD (Data through 2007)

Table 7-3 (continued)
3/4" Plant Data Summary Evaluation for POPCD (Data through 2007)

Table 7-3 (continued)
3/4" Plant Data Summary Evaluation for POPCD (Data through 2007)

Table 7-3 (continued)
3/4" Plant Data Summary Evaluation for POPCD (Data through 2007)

Table 7-3 (continued)
3/4" Plant Data Summary Evaluation for POPCD (Data through 2007)

Table 7-4
7/8 and 3/4 Inch POPCD Log Logistic Distribution Parameters

Table 7-5
Source of Data for 7/8 Inch Tubing POPCD

Table 7-6
Source of Data for 3/4 inch Tubing POPCD

Figure 7-1
7/8" Tubes POPCD as Function of Bobbin Amplitude
(Weighted Generalized Linear Model Log-logistic Solution)

Figure 7-2
Generic Industry POPCD as Function of Bobbin Amplitude 3/4" Tubing
(Weighted Generalized Linear Model Log-logistic Solution)

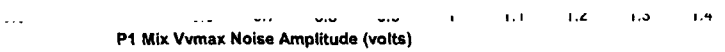

Figure 7-3
Bobbin Drilled Hole TSP Database TSP Center P1 Mix Vvmax Noise Distributions

Figure 7-4
Comparison of POPCD Curves

Figure 7-5
Average of Resolution Analysts, Percentage of Correct TSP BC Calls as a Function of Bobbin Coil voltage for TSP cracks (POD evaluated for ODSCC at the TSP)

Figure 7-6
Average of Resolution Analysts for Percentage of Correct TSP BC Calls, (POD) Logistic Fit Curves for BC POD as a Function of Voltage for Axial ODSCC and IDSCC in TSP

8
RECOMMENDED NEW UPDATES TO NDE, ANALYSIS METHODS AND PROGRAMS

In previous addendums, this section provided recommended new updates to NDE and analysis methods applied in applications of the ARC for ODSCC at TSP intersections. NRC approved updates are given in Section 9 of this report, and prior industry updates recommended for ARC implementation are included in Section 10 of this report.

9
NRC APPROVED REVISIONS TO ARC PROGRAM, DATABASES, AND ANALYSIS METHODS

This section documents NRC approved revisions to the ARC program requirements, databases and analysis methods applied in applications of the ARC for ODSCC at TSP intersections. The ARC program requirements include the protocol for updating the database and the tube pull requirements. ARC database changes included in Addendum 5 were the NRC approved EPRI data exclusion criteria and exclusion of the French data from the ARC database. Analysis methods updates in Addendum 5 included revisions to the leak rate analysis methods based on clarification of the confidence level required for a correlation and the methods for including the confidence level for a correlation in the leak rate analyses. There have been no new NRC approved revisions in Addendum 6 or this Addendum 7. The only change in this section from Addendum 6 is the update to Table 9-2 as described below.

The requirements for pulling tubes in Section 9.2 includes Table 9-2, which identifies the number of indications needed to complete voltage bins for the leak rate data. This table and related Section 9.2.2 are updated for this addendum to reflect the new pulled tube results described in Section 4 and will be further updated for future addenda. The remaining information in this section is not expected to change between addenda. Any future NRC approved changes will be added as additional subsections to this section.

9.1 NRC/Industry SGDSM Database Protocol

The NRC/industry SGDSM database protocol for updating the ARC database is given in Table 9-1. Items 1 and 2 were developed when annual updates to the database were anticipated. Due to the reduced number of plants implementing the ARC, the addenda updates are issued only when required due to additional pulled tubes. Item 2 should therefore be interpreted as plants in an outage season when a new addendum is issued have the option of using the prior addendum provided there is not a significant, non-conservative shift in the ARC correlations. Item 3 provides for requesting NRC approval of changes to the exclusion criteria of Section 9.3 or exclusions of data, such as described in Section 9.4. If issuing an addendum update to the correlations does not include any request for changes to the exclusion criteria or data exclusions, NRC approval of the updated correlations is not required for plant implementation. Item 4 provides for excluding data from the database only when applying the NRC approved data exclusion criteria given in Section 9.3. Item 5 provides the requirements for issuing interim ARC correlations in the event that new pulled data leads to significant non-conservative changes to the correlations.

Items 1 to 5 were submitted to the NRC by NEI in Reference 9-3 and items 1 to 4 were approved by the NRC in Reference 9-4. Item 5 was submitted by Reference 9-1 and approved by the NRC in Reference 9-2.

9.2 Requirements for Pulling Tubes in Support of the Voltage Based Repair Limits

The industry recommended requirements for pulling tubes were initially defined in Addendum 3 and updated to incorporate the NRC approval with comments in Reference 9-5. The NRC comments were incorporated and transmitted to the NRC in Reference 9-6. To maintain important documentation supporting the ARC, the NRC approved tube pull requirements are given below, as previously reported in Addendum 4.

9.2.1 Description of the Issue

The pulled tube database supporting the voltage based repair limits has been significantly increased since the issuance of GL 95-05, resulting in updated requirements for pulling tubes in support of the ARC. This section describes the current industry recommended and NRC approved requirements for pulling tubes.

Pulled tubes are required to characterize the crack morphology as dominantly axial ODSCC for consistency with that of the EPRI database and to increase the pulled tube database supporting the ARC. There have been no pulled tubes for which the ODSCC crack morphology differs from that found in the initial EPRI database prior to issuance of GL 95-05. The morphology is dominantly axial ODSCC with differences between pulled tubes being principally in the degree of cellular corrosion found at a given intersection. The cellular involvement can differ between TSP intersections on the same tube as much as differences between SGs or plants. The only morphology difference from the EPRI database found in the pulled tubes has been one case of combined local wall thinning with ODSCC, which was identified as a volumetric indication in the field inspection and was pulled to clarify the morphology of the indication. Tubes pulled with RPC axial ODSCC field calls have had morphologies consistent with the EPRI database. Consequently, removal of tubes specifically for morphology verification can be a low priority for tube removal. As a result of this consistent morphology experience, it is acceptable to delay the initial tube pull for morphology confirmation to the end of the first cycle following ARC implementation if this delay can improve the value of the pulled tube data to the database.

The principal objective for the tube pulls should be to support the database where the database has limited data. The burst pressure versus bobbin voltage correlation has not changed significantly with additional pulled tube data since before issuance of GL 95-05 in 1995. The additional data have resulted in changes in the structural limit by about half a volt or less. Changes in the leak rate versus voltage correlation have been more significant due to the smaller database on leaking tubes. Thus the primary objective for pulling tubes should be to increase the leak rate database. The tubes should have a large enough voltage to have a significant likelihood of leaking. The correlations of Section 6 show that to obtain a 30% probability of leakage, both the 3/4 inch and 7/8 inch (excluding French data) tubes should have bobbin voltages > 3.2 volts.

These considerations lead to emphasis on pulling tubes based on having large enough voltages to contribute to the leak rate database.

The GL 95-05 requirements for tube removal can be summarized as follows:

Number and Frequency of Tube Pulls

- Two pulled tubes with a minimum of four intersections should be obtained during the plant SG inspection outage implementing the ARC or a preceding outage.
- Additional tube pulls with a minimum of two intersections should be obtained at the refueling outage following accumulation of 34 EFPM of operation following the previous tube pull.

Selection Criteria

- The emphasis should be on removing tube intersections with large voltage indications
- Where possible, the removed intersections should cover a range of voltages, including intersections with no detectable degradation.
- Selected intersections should include a representative number of intersections with RPC signatures of a single dominant crack as compared to intersections with two or more dominant RPC signatures around the circumference.

The following provides the NRC approved changes to the above requirements for tube removal.

9.2.2 Bases for Tube Removal Guidelines

Based on the above considerations, the primary emphasis for pulled tubes should be to support the leak rate correlation, while also obtaining information on crack morphology. Table 9-2 summarizes the number of ODSCC indications pulled and destructively examined and the number of intersections that had leak rates contributing to the correlations for both 3/4 and 7/8 inch diameter tubing. Table 9-2 has been updated to the Addendum 7 database and will be updated with each future addendum update. It is seen that 137 out of a total of 190 indications (excluding the French data) had voltages less than 2 volts. This voltage range, which is typical of indications found during the first outage implementing the ARC, has more data than needed and emphasis for tube removal should be on higher voltage indications. In this low voltage region, crack morphology features typically are not well established and the data provide only OD cracking as a morphology confirmation. Therefore, the tube removal requirements should be defined to minimize the need for pulling low voltage indications.

For 3/4 inch tubing, indications greater than about 3 volts would have a 30% probability of leakage and would likely contribute to the leak rate correlation database. As seen in Table 9-2, the existing leak rate database for 3/4 inch tubing is extensive and only 4 indications are needed to complete a database of 2 indications in each one volt bin up to 12 volts. For 7/8 inch tubing, indications less than about 3 volts have a very low leakage probability with only 1 small leaking indication in 33 pulled tube indications between 1 and 3 volts. The probability of leakage correlation shows < 20% leakage potential at 3 volts. Therefore, indications > 3 volts are desirable to have a reasonable likelihood of contributing to the leak rate database. It is therefore

recommended that tube pulls be targeted toward obtaining a leak rate database of 2 indications in each one volt range above a minimum of 2 volts for 3/4 inch tubing and above 3 volts for 7/8 inch tubing.

9.2.3 Criteria for Tube Removal and Examination/Testing

Implementation of the voltage based repair criteria should include a program of tube removals for testing and examination as described below. The purposes of this program, in order of priority, are: 1) to provide additional data to enhance the conditional leak rate, burst pressure and probability of leakage correlations; 2) to verify axial ODSCC as the dominant degradation mechanism at or near the time of ARC implementation; 3) to assess inspection capability; and 4) to monitor the degradation mechanism over time.

The principal database goal to support the ARC correlations is to enhance the leak rate correlation. Table 9-2 identifies voltage ranges for additional leaking indications (target number) to work toward a leak rate database that includes at least two indications with leakage in one volt intervals for which leakage is reasonably expected. Tube removals should be targeted toward satisfying the target number of indications. As noted below, the required times for tube pulls may optionally (utility option) be delayed up to one fuel cycle if no pullable tube indications are found that satisfy the target indication voltage ranges. The data of Table 9-2, including target indications, shall be updated and included in the EPRI ARC database addenda so that the target indications reflect the latest available pulled tube results.

The following criteria for tube removal and examination shall be followed.

9.2.3.1 Number and Frequency of Tube Pulls

- Two pulled tube specimens with an objective of retrieving as many intersections as is practical (a minimum of four intersections) should be obtained for each plant either during the SG inspection outage that implements the voltage based repair criteria or during an inspection outage preceding initial application of these criteria. However, if no pullable tube indications are found in this inspection that would satisfy the industry database target indications, the tube removal may be delayed (utility option) to the next planned inspection with the goal of obtaining indications satisfying the database target. The tube pulls may not be delayed more than one planned outage following implementation of the repair criteria.
- On an ongoing basis, an additional (follow-up) pulled tube specimen with an objective of retrieving as many intersections as is practical (minimum of two intersections) should be obtained at the refueling outage following accumulation of three operating cycles following the previous tube pull. However, if no pullable tube indications are found in this inspection that would satisfy the industry database target indications, the tube removal may be delayed (utility option) to the next planned inspection with the goal of obtaining indications satisfying the database target. The tube pulls may not be delayed more than one planned outage following the required time for an additional pulled tube specimen. Consequently, the maximum interval between tube removals is four operating cycles to provide a periodic confirmation of crack morphology.

- If the above time requirements for a pulled tube specimen coincide with the plant's last scheduled outage before SG replacement, the requirement for a tube pull is waived. However, this waiver does not apply if the plant has not previously pulled tubes to support the ARC database. For example, if the last scheduled outage is the first or second outage implementing the ARC, the waiver does not apply where tube pull specimens have not been obtained during the plant SG inspection outage that implements the voltage based repair criteria or during an inspection outage preceding initial application of these criteria.
- If indications with unanticipated voltage levels substantially higher than the structural limit (for example, > 10 volts) from the burst correlation are found in an inspection, the indication should be considered for removal and destructive examination if the test results are likely to determine whether or not condition monitoring or operational assessment results would satisfy acceptance limits.

9.2.3.2 Tube Removal Selection Criteria

- The primary emphasis for selecting an intersection for removal should be an indication that satisfies the target indication voltages of Table 9-2. If the target voltage range cannot be satisfied, the emphasis should be on intersections with large voltage indications.
- Where possible, the removed tube intersections should cover a range of voltages, including intersections with no detectable degradation.
- For selection between indications of comparable voltage levels, the preference for removal should be intersections with RPC (or equivalent probe) signatures indicative of a single dominant crack as compared to intersections with RPC signatures indicative of two or more dominant cracks about the circumference.

9.2.3.3 Pulled Tube Examination and Testing

- Removed tube intersections should be subjected to leak and burst tests under simulated MSLB conditions to confirm that the failure mode is axial and to permit enhancement of the supporting data sets for the burst pressure and leakage correlations. The systems for leak testing should accommodate and permit measurements of leak rates as high as practical including leak rates that may be in the upper tail of the leak rate distribution for a given voltage. Leak rate data should be collected at temperature for the differential pressure loadings associated with the maximum postulated MSLB. When it is not practical to perform hot temperature leak tests, room temperature leak rate testing may be performed as an alternative. Burst testing may be performed at room temperature. The burst and leak rate correlations and/or data should be normalized to reflect the appropriate pressure and temperature assumptions for a postulated MSLB.
- Subsequent to burst testing, the intersections should be destructively examined to confirm that the degradation morphology is consistent with the EPRI database morphology for ODSCC at tube to TSP intersections. The destructive examination techniques should include techniques such as metallography and scanning electron microscope (SEM) fractography as necessary to characterize the degradation morphology (e.g., axial ODSCC, circumferential ODSCC, IGA involvement, cellular IGA and combinations thereof) and to characterize the largest crack networks with regard to their orientation, length, depth and ligaments. For

uncorroded ligaments, the following information should be reported: location within the elevation of the overall macrocrack; angular orientation (approximate degrees) relative to the primary direction of the macrocrack; and size of the ligament such as uncorroded ligament area. The purpose of these examinations is to verify that the degradation morphology is consistent with the assumptions made in NRC GL 95-05 as well as that included in the EPRI database.

9.3 Data Exclusion Criteria

9.3.1 Introduction

This section describes the criteria for excluding data from the Alternate Repair Criteria (ARC) database supporting the burst, probability of leakage and leak rate correlations. The criteria are applied to identify specimens to be excluded from the correlations. Exclusion Criteria 1 and 2 submitted by References 9-7 and 9-8 are consistent with NRC guidelines given in Paragraph 2.b.3(2) of Generic Letter 95-05. In addition, the NRC has accepted a modification to Criterion 3a as originally drafted in Reference 9-9. The NRC acceptance (References 9-10 and 9-11) of Criterion 3a is based on increasing the confidence level for application of this criterion from 95% to 99%. Criterion 3a then excludes leak rate data that is outside the lower 99% prediction interval on both the leak rate versus voltage and leak rate versus crack length correlations. In the NRC RAI of Reference 9-12, the NRC provided a staff position on exclusion Criterion 2a that this criterion should be applied to all data rather than the original criterion application to data that had high burst pressures. This change is included in Criterion 2a.

Reference 9-11 provided approval of the ARC database in Addendum 2 as an update to the database approved in GL 95-05. The approval of Criterion 3a led to exclusion from the leak rate database of model boiler specimens 598-3 and 604-2. Reference 9-11 also approved a revision of the SLB leak rate for Plant S Tube R28C41 from 2496 l/hr to 1250 l/hr as a revision to GL 95-05 Paragraph 2.b.3(2) requirements.

The complete data exclusion criteria, as approved by the NRC, are given in this section. Criterion 3b of Reference 9-9 was not accepted by the NRC and is not included in this section. Data resulting from application of these criteria form the database for the ARC correlations. Evaluations of new data against these exclusion criteria are given in Sections 3 and 4 of each ARC database addendum.

9.3.2 Data Exclusion Criteria

NRC guidelines for acceptance of data used in developing the correlations are based on accepting all data that do not satisfy specific criteria for exclusion from the database. The NRC's general guidelines for exclusion of data from the database are:

1. Data associated with an invalid test.
2. Data associated with atypical morphology must be based on morphology criteria which are rigorously defined and applied to all data.

3. Data exclusion criteria must be able to be unambiguously applied by an independent observer.
4. Data can be excluded if it results in conservatism associated with application of the affected correlation.

Specific criteria developed for exclusion of data following the above guidelines and approved by the NRC are:

9.3.2.1 Criterion 1. Invalid or Inadequate Test

An invalid test is associated with unacceptable test specimens or invalid test measurements as exemplified by one of the following situations:

1a. *Eddy current signal corruption.* This condition results in the data point not being used in any of the three correlations. Examples of this condition are tube specimens that have been severely damaged for reasons other than the operating corrosion, specimens exhibiting extraneous eddy current signal effects (e.g., due to proximity of the degradation to a specimen weld), both of which result in inappropriate or excessive eddy current voltage response.

1b. *Inadequate or inappropriate burst test.* This condition results in the data point not being used in the burst correlation. Examples of this condition are: tube specimens that did not attain a true burst condition (e.g., caused by the specimen's internal re-enforcing bladder leaking), a test fixture malfunction with inability to retest and specimens tested for other purposes (e.g., specimen burst tested inside a support plate).

1c. *Inadequate leak test.* This condition results in the data point not being used in the leak rate correlation. Examples of this condition are: insufficient test loop flow capacity to reach the specimen's leak rate for SLB conditions and test malfunction with inability to retest.

1d. *Tube damage from field induced tube pull forces.* This condition results in the data point not being used in the leak rate correlation. It may be used in the probability of leak correlation if justified by analysis. An example of this condition is radial ligament tearing as indicated by excessive post-pull measured voltage for the field obtained specimen and higher than expected leak rates at or below normal operating conditions. Supporting analyses must show that the uncorroded ligament would not have torn to increase the leak rate under SLB conditions.

1e. *Unavailable test information for estimating probability of leakage.* This condition results in the data point not being used in the probability and leak rate correlation. An example of this situation is a number of tube specimens for which no leak rate tests were performed and the specimens exhibit short throughwall crack lengths (less than 0.1") for which experience shows they do not leak. An

additional example is a specimen with no leak test and no destructive exam data to estimate whether or not the indication would leak at SLB conditions.

9.3.2.2 Criterion 2. Morphology Related Criteria

These criteria identify atypical degradation that if incorporated into the database would inappropriately bias the correlations over the range of interest. Pulled tube specimens with this atypical degradation do not invalidate the application of the correlations to the plants from which the tubes were pulled. The specific criteria are as follows:

2a. *Atypical degradation ligament morphology.* This condition results in the data not being used in any of the three correlations. The morphology for exclusion is defined to be degradation with less then or equal to 2 ligaments within the macrocrack and the maximum corrosion depth is less than 60%. This criterion is to be applied irregardless of the magnitude of the burst pressure (i.e., such as a high burst pressure) associated with the indication. Experience indicates that this degradation results in tubes exhibiting relative high bobbin voltages but maintaining relatively high burst pressures close to that of undegraded tubing. Such degradation is atypical of the dominant ODSCC degradation in the database for which the ARC correlations are developed and would be considered an inappropriate bias to the correlation if incorporated into the database. The correlation uncertainty distribution is associated with random effects (e.g., due to non-quantifiable changes in the degradation morphology) about the correlation mean. However, data for atypical degradation exhibits a non random effect that is physically definable and different from the dominant ODSCC morphology.

Removal of data under this criterion from the correlation's database results in a conservative shift of, for example, the mean of the burst correlation. Since the removed data are positioned in the tail of the correlation's uncertainty distribution, their removal from the database may decrease the distribution's variance. This effect is acceptable because scientific argument does not suggest that the existence of these data located on one side of the uncertainty distribution dictates an equal probability of some type of effect on the other side of the distribution.

2b. *Severe degradation.* This condition results in the data point not being used in any of the correlations. The condition is defined to be a data point that has a voltage measurement more than 20 volts higher than the next adjacent point located at the high voltage boundary of the data. Note that this criterion applies only to one side of the correlation, specifically to the high voltage region of the correlation. Such data is far removed from the voltage range of interest over which the correlation is applied. It is not appropriate to allow one data point, which represents an extreme form of degradation compared to the majority of the data, to have a significant influence on the linear regression correlation. If additional data is obtained in this very high voltage region, such that there is a more uniform distribution of data in this extreme voltage region, review of all data will be performed with consideration of incorporating data previously filtered from the correlation by this criterion. Exclusion of such data has a varied effect on the correlation mean. Its

effect is dependent on the voltage range of interest. Removal of the data point could for example, add conservatism in the high voltage region from which the data is excluded, with a reduction in conservatism in the low voltage region because of the linear nature of the regression.

9.3.2.3 Criterion 3. Probable Test Error in Leakage Measurement

Criterion 3 is intended to exclude leakage measurements exhibiting extreme behavior, such as a very low measurement, although the specific cause for the probable test measurement error cannot be identified. In the performance of leak tests, the crack can become plugged by deposits resulting in abnormally low leak rates or a measurement error (e.g., piping leakage between specimen and leakage collection tank, collection time error, etc.) could occur. For these cases, the cause for the measurement error is not as apparent as for Category 1 and the test results must be evaluated for probable errors. It is not appropriate to include the spread in leak rates resulting from plugging of cracks during leak tests in the leak rate correlation and each leak rate measurement should be evaluated against Criterion 3 before including the data in the database. Criterion 3a provides for excluding SLB leak rates much lower than expected for the throughwall crack length found by destructive examination.

3a. *Probable Test Error in Leakage Measurements.* Data with throughwall crack length measurements are excluded from the leak rate correlation if the measured leak rate is below the lower, one-sided 99% prediction interval from regression analyses for correlations of both SLB leak rate versus corrosion throughwall length and SLB leak rate versus bobbin voltage as obtained without including the suspect data point in the regression analysis. For application of this criterion, the throughwall crack length must have no remaining uncorroded ligaments over the throughwall length. Uncorroded ligaments, if present, could contribute to the lower than expected leak rate.

Basis for Criterion 3a

The potential for plugging of a crack due to deposits in a leak rate test has existed and will continue to exist in leak rate measurements. Prototypic borated primary water, as used in the earlier database tests, is being eliminated in future tests to reduce the potential for deposits in the cracks. Indications that have extremely low leakage, based on quantified lower 99% prediction intervals on the voltage correlation for leak rates are candidates for further evaluation. The leak rate versus voltage correlation, by itself, does not adequately identify probable deposits affecting the leak rate since the voltage could be influenced by crack morphologies or distortions in the bobbin response. Thus, when crack length measurements are available from destructive examination of the specimen, the indication must be a low outlier on both the voltage and the crack length correlations. The use of the 99% prediction interval conservatively exceeds other applications such as the burst correlation and acceptance levels for leak rates.

An increased physical insight into the potential for plugging of a crack can be obtained by evaluating the data point based on leak rate data as a function of throughwall crack length. Leak rate versus crack length can be expected to have a smaller uncertainty spread than the voltage correlation at a given throughwall crack length since this relation is physically based and more

analytically predictable. In this case, leak rates significantly higher than the regression line can be expected due to tearing of ligaments but leak rates for cracks with no ligaments that are much lower than the population have no known physical basis other than blockage of the crack or a measurement error. Thus high outliers can be expected for this correlation but very low outliers are unlikely without an additional influence such as deposits. An unusually high crack tortuosity can lead to a lower leak rate than the mean but would not realistically reduce the leak rate below the 99% confidence bound on the data. A conservative and quantifiable measure for much lower than the database is obtained by requiring that the leak rate lie below the lower 99% confidence level obtained from a regression analysis of leak rate versus crack length. If the leak rate is lower than the 99% confidence levels for both the voltage and crack length correlations, it can be reasonably assured that the leak rate was strongly influenced by blockage of the crack or the measurement was erroneous. Criterion 3a thus provides a well quantified criterion for excluding unacceptable leakage from the leak rate correlation and requires a very low leak rate on both the voltage and crack length correlations. Since it is known that the specimen leaks, the data point is included in the probability of leakage correlation as a leaker.

Criterion 3a applies only to specimens that leak and does not exclude specimens with throughwall cracks but zero measured leakage. A few specimens with short throughwall cracks, such as 3/4" specimen 595-2 (throughwall length of 0.17") and 7/8" specimen 509-3 (throughwall length of 0.16"), had no measured leakage. In this case, the specimens are included in the probability of leakage correlation as non-leakers and are not considered for the SLB leak rate correlation. This application of non-leakers with throughwall cracks is not inconsistent with data exclusion Criterion 3a. Abnormally low leakers (zero or slightly greater than zero) are excluded from the leak rate correlation but retained in the POL correlation based on whether or not any leakage was measured, independent of the leakage magnitude.

The specific effects causing lower than expected variation in leak rates are remaining ligaments in the crack face, tortuosity (oblique steps in the crack, surface irregularities) and presence of deposits. These effects tend to lower leakage for modest throughwall crack lengths. All three effects become smaller as crack length increases and crack opening increases. Longer throughwall cracks tend to have lost the ligaments by corrosion; the wider crack openings reduce the influence of surface irregularities and reduce the potential for deposits plugging the crack. From the database, "long" cracks appear to be about > 0.3" throughwall as above this length, the variability from predicted leak rates as a function of length appears to be smaller. For 0.3" throughwall cracks, the crack width is about 1 mil at 2560 psi and increases to about 10 mils for a 0.5" long crack. Thus, crack lengths < 0.3" are more susceptible to plugging from deposits. The presence of ligaments is a valid cause for low leakage and Criterion 3a (destructive exam data available) requires that the throughwall length have no remaining uncorroded ligaments.

9.4 Exclusion of the French Data from the ARC Database

In the initial evaluation of the French data in Addendum 1, it was recommended that the French data not be included in the ARC database due to significant differences in crack morphology and leakage behavior from the domestic data. The recommendation included a statistical evaluation that concluded that the French data had a low likelihood of being from the same population as the balance of the EPRI database. In Reference 9-13, the NRC staff commented that they did not concur that there was conclusive physical evidence to demonstrate that the French data should be

separated from domestic plant data, hence, the remaining statistical analyses alone did not provide a basis for excluding the French data. Addendum 4 proposed a new data exclusion Criterion 2c for atypical deep crack degradation morphology that also led to a recommendation to exclude the French data. Additional physical evidence and updated statistical evaluations supporting exclusion of the French data were provided to the NRC (References 9-14 and 9-15) in response to the requests for additional information. The NRC then approved exclusion of the French data from the ARC database in Reference 9-16 although exclusion Criterion 2c was not approved. The industry submittal of Reference 9-15 and the NRC approval of Reference 9-16 require that each ARC database addendum update provide confirmatory analyses to demonstrate that the French data remain statistically and physically different from the domestic data.

The specific industry commitments for updating the assessments of the French data are:

The statistical analysis for Comparison 2 of Table 9-3 (Table 1 of Reference 9-15) will be updated for each new addenda for the ARC database in NP-7480-L.

If the probability, Pr(F Statistic) in Table 9-3 that the null hypothesis for common regression lines (model 4) is true increases to 5% (the current value is 0.4%), the statistical analyses for Tables 9-3 and 9-4 (Table 5 of Reference 9-15) addressing both the burst and POL correlations will be updated.

If the burst correlation probability increases to 5% and the POL correlation test statistic (e.g., 0.54 in Table 9-4) decreases to less than or equal to the critical value at the 5% level of significance (e.g., 0.25 in Table 9-4), the EdF data would be included in the burst, POL and leak rate correlations issued for the new addenda. The EdF data would not be included in the correlations unless supported by the statistical analyses for both the burst pressure correlation and the POL correlation.

The required updates to the statistical analysis, including Tables 9-3 and 9-4, in the RAI response of Reference 9-15 are included in Section 6 of this addendum.

9.5 Revisions to Leak Rate Analysis Methods

One clarification of the GL 95-05 p-value requirements and one change to the leak rate analyses have been approved by the NRC.

In Reference 9-17, industry representatives recommended that the GL 95-05 requirement for a 95% confidence interval on the p-value for the slope parameter of the leak rate correlation be clarified to apply as a one-sided confidence level. At the Reference 9-17 meeting and by Reference 9-2, the NRC concurred that the one-sided p-test for the leak rate correlation is appropriate. This approval permits the leak rate correlation with voltage to be applied when the one side p-value for the correlation slope parameter is less than 5%.

By Reference 9-18, the NRC approved an updated method for accounting for the p-value in Monte Carlo leak rate calculations as submitted in Reference 9-19. This method determines whether a correlation should be applied during each Monte Carlo simulation of the generator. After simulating a potential value for the population slope, the value defines the leak rate

correlation to be applied. If the population slope is less than or equal to zero, then no correlation is assumed and the simulation of the leak rate is based on the mean and standard deviation of the leak rate data. If the population slope is greater than zero, the correlation is applicable and the leak rate is based on the regression line slope and intercept. This analysis method is required to be implemented in all ARC leak rate analyses after September 23, 2002.

9.6 References

9-1 Letter from R. Clive Callaway (NEI) to Mr. Edmund J. Sullivan (NRC), "Steam Generator Degradation Specific Management Tube Pull Database Addendum and Protocol (Project No. 689)", dated October 28, 1997.

9-2 Letter from Mr. Edmund J. Sullivan (NRC) to David J. Modeen (NEI), EPRI Report: Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates Database for Alternate Repair Limits, NP-7480-L, Addendum 1, November 1996", dated January 20, 1998.

9-3 Letter from David J. Modeen (NEI) to Gus C. Lainas (NRC), "Steam Generator Degradation Specific Management Tube (SGDSM) Database Protocol (Project No. 689)", dated January 15, 1997.

9-4 Letter from Brian W. Sheron (NRC) to D. Modeen (NEI), dated April 10, 1997.

9-5 Letter from Jack Strosnider (NRC) to D. Modeen (NEI), "Industry Recommended Steam Generator Tube Pull Program," dated January 31, 2000.

9-6 Letter from David J. Modeen to Document Control Desk, USNRC, Project Number 689, "Steam Generator Degradation Specific Management Database, Addendum 3", June 2, 2000.

9-7 Letter from David A. Steininger, EPRI, to Jack Strosnider, NRC, "Exclusion of Data from Alternate Repair Criteria (ARC) Databases Associated with 7/8 Inch Tubing Exhibiting ODSCC", April 22, 1994.

9-8 Letter from David J. Modeen (NEI) to Brian Sheron (NRC), June 9, 1994.

9-9 NPL-7480-L, Volume 2, Revision 1, *Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates - Database for Alternate Repair Limits, Volume 2: 3/4 Inch Diameter Tubing*, Prepared for EPRI by Westinghouse (August 1996).

9-10 NRC letter from Thomas H. Essig to David J. Modeen (NEI), "EPRI Report: Proposed Data Exclusion Criteria and Adjustments to Measure Leak Rate for Tube R28C41 (Plant S), February 26, 1996.

9-11 NRC letter from Gus C. Lainas to David J. Modeen (NEI), "Evaluation of Proposed Update to SGDSM Database and Modifications to the Methodology to Assess Steam Generator Tubing Outside Diameter Stress Corrosion Cracking", November 20, 1998.

9-12

9-12 NRC Letter, "Request for Additional Information Regarding NP 7480-L, Addendum 1, 'Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates, Database for Alternate Repair Limits,' 1996 Database Update, November 1996," S. L. Magruder (NRC) to D. Modeen (NEI), January 24, 1997.

9-13 NRC letter to David J. Modeen, NEI, "EPRI Report: Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates - Database for Alternate Repair Limits, NP-7480-L, Addendum 1, November 1996", January 20, 1998.

9-14 NEI letter from A. Marion to Brian W. Sheron, "Exclusion of French Data from the Steam Generator Degradation specific Management Database (Generic Letter 95-05), July 25, 2002.

9-15 NEI letter from A. Marion to Brian W. Sheron, "Exclusion of French Data from the Steam Generator Degradation specific Management Database (Generic Letter 95-05), October 4, 2002.

9-16 NRC letter from William H. Bateman to Alexander Marion, "Exclusion of French Data from the Steam Generator Degradation Specific Management Database", October 8, 2002.

9-17 Public meeting between industry and NRC staff representatives on the subject of statistical methods for the regression analysis of ARC data (December 3, 1997).

9-18 NRC letter from William H. Bateman to Alex Marion (NEI), "Refining the Leak Rate Sampling Methodology for Generic Letter 95-05 Voltage-Based Alternate Repair Criteria Application", March 27, 2002.

9-19 NEI letter from A. Marion to Brian W. Sheron (NRC), "Refining the Leak Rate Sampling Methodology for ODSCC ARC Applications (Generic Letter 95-05)", March 15, 2002.

Table 9-1
NRC/Industry SGDSM Database Protocol

1.	The pulled tube database will be updated each March to add additional data from the prior calendar year for steam generator tubes which have been burst, leak, and metallurgically tested, as necessary. This updated database will include updated correlations and a list of plants which provided pulled tube data (including the number of intersections).
2.	Utilities with spring outages commencing prior to June 1 will have the option of using the latest database and correlations submitted as an information copy to the NRC (by the end of March) or the prior version of the database and correlations, providing there is not a significant, non-conservative shift in the correlations submitted as an information copy to the NRC (by the end of March) or the prior version of the database and correlations, providing there is not a significant, non-conservative shift in the correlations as discussed in item 5 below. This approach is necessary to ensure sufficient time is available to finalize plant-specific procedures and conduct analyst training prior to the outage.
3.	Utilities may request NRC approval of modifications to the database and correlations in accordance with the guidance contained in Generic Letter (GL) 95-05. Examples which would require specific approval include questionable data, application of revised exclusion criteria, or use of a revised probability of detection. The annual update of the correlations discussed in item 1 above will occur regardless of specific requests for NRC approval of changes to the database or correlations. If specific approval of modifications to the database or correlations is requested from the NRC staff, the modifications will not be used until the NRC approves the correlations.
4.	Data may be excluded as appropriate under the approved exclusion criteria referenced in GL 95-05. Exclusion of data will be reported in the individual utility 90-day reports and in the pull tube database.
5.	If any domestic, pulled tube data fall outside the 95% prediction interval using the latest, approved correlations, the data will be identified to the NRC staff in accordance with Generic Letter (GL) 95-05 by the appropriate utility in the required 90 day report. If the inclusion of the new data results in a non-conservative and significant shift in the correlation predictions, industry representatives will discuss potential database changes with the NRC staff and/or issue a new database and associated correlations. If a revision to the correlations is required, the NRC will be notified, and it will be issued and effective within three (3) months of submittal of the 90 day report. A nonconservative shift in the correlations is one that results in a lowering of the structural limit, thereby increasing the probability of burst, or an increase in the probability of leak as a function of bobbin amplitude (voltage) associated with an ODSCC indication, or an increase in the predicted leak rate as a function of indication voltage. Significant is a term relative to the approved limits of operation and that involves the application of good engineering practice. For example, if the overall probability of burst increases from $1 \cdot 10^{-4}$ to $2 \cdot 10^{-4}$, , while the absolute change is 100% of the original value, the change relative to the GL 95-05 reporting threshold is inconsequential and would not be considered significant if it was suspected that an order of magnitude change in the value associated with indications at a plant previously determined to have an ed of cycle (EOC) probability on the order of $1 \cdot 10^{-3}$ could result in the calculated probability of burst exceeding the GL 95-05 limit. The term significant relative to leakage (i.e., probability of leak and leak rate correlations) should be viewed in a similar manner as discussed above for burst pressure. Because the requirements for EOC leakage are plant specific, consideration should be given to the relative margin between the plant specific calculated leak rate and the leak rate limit. Significant is also to be interpreted relative to the change histories of the correlations. If the change associated with the inclusion of a new data set is on the order of twice that of the largest change associated with a previous data set with a like number of indications, the inclusion of the additional data will be considered to be significant.

Table 9-2
Summary of Current (November 2007) Number and Target Number for Pulled Tube Intersections with Leakage – Excludes French Data

Voltage Range	Total No. of TSP Intersections		Current and Additional Target Number of Indications with Leakage				Comments
			3/4" Tubing		7/8" Tubing		
	3/4" Tubing	7/8" Tubing	Current No. Leakers	Additional Target No. Leakers	Current No. Leakers	Additional Target No. Leakers	
≤ 1.0	43	51	0	0	0	0	Negligible likelihood of leakage
> 1.0 – 2.0	17	26	1	0	0	0	Low (< 20%) likelihood of leakage for 7/8" tubing
> 2.0 – 3.0	6	7	3	0	1	0	
> 3.0 – 4.0	3	4	1	1	1	1	
> 4.0 – 5.0	5	2	3	0	2	1	(leakage rate not measured in tube discussed in Section 4)
> 5.0 – 6.0	1	3	1	1	3	0	
> 6.0 – 7.0	2	1	2	0	1	1	
> 7.0 – 8.0		1	0	2	1	1	
> 8.0 – 9.0	2		2	0	0	2	
> 9.0 – 10.0	3		3	0	0	2	
> 10.0 – 11.0	2		2	0	0	2	
> 11.0 – 12.0	3		3	0	0	2	
> 12.0 – 13.0			0	2	0	2	
> 13.0 – 14.0	1	1	1	1	1	1	
> 14.0 – 15.0			0	2	0	2	
> 15.0 – 16.0	2		2	0	0	2	
> 16.0 – 17.0	1		1	1	0	2	
> 17.0 – 18.0	1		1	1	0	2	
> 18.0 – 19.0			0	2	0	2	
> 19.0 – 20.0			0	2	0	2	
> 20.0 – 30.0	1	1	1	1	1	1	
> 30.0			0	2	0	2	
Total	**93**	**97**	**27**	**18**	**11**	**30**	

Table 9-3
Results of Comparisons of Burst Pressure Regression Analysis Models Copy of Table 1 of Reference 9-15

Comparison Parameter Description	Comparison 1		Comparison 2		Comparison 3	
	1996	2002	1996	2002	1996	2002
Null Hypothesis	Model 4		Model 4		Model 2	
Alternate Hypothesis	Model 1		Model 2		Model 1	
Null Hypothesis *SSE*	66.942	90.767	66.942	90.767	62.544	84.178
Null Hypothesis *DoF*	91	110	91	110	90	109
Alternate Hypothesis *SSE*	62.473	84.105	62.544	84.178	62.473	84.105
Alternate Hypothesis *DoF*	89	108	90	109	89	108
ΔSSE (Reduction of *SSE*)	4.469	6.662	4.397	6.589	0.0717	0.0730
Fraction of Model 4 to 1 ΔSSE	100.0%	100.0%	98.4%	98.9%	1.6%	1.1%
F Statistic	3.183	4.277	6.328	8.532	0.102	0.094
F Statistic Degrees of Freedom	2, 89	2, 108	1, 90	1, 109	1, 89	1, 108
Pr(*F* Statistic)	4.6%	1.6%	1.4%	0.4%	75.0%	76.0%
Comments	Large *F*		Large *F*		Small *F*	Small *F*
Indicated Action	Reject Model 4 Accept Model 1		Reject Model 4 Accept Model 2		Do Not Reject Models 2 or 1	

Description of the models:

Model 1 – Both the intercept and slope are from different populations.

Model 2 – The intercepts are different and the slopes are the same.

Model 3 – The intercepts are the same and the slopes are different.

Model 4 – The intercepts and the slopes are from the same parent population.

Table 9-4
Kolmogorov-Smirnov Test of Equality of EdF and US POL Data Distributions Copy of Table 5 of Reference 9-15

EdF Bobbin Amplitude (Volts)	Rank	Sample Cum. Dist. S(x)	US Calc Cum. Dist. F(x)	Absolute Value [S(x) - F(x)]	Test Statistic (D_n=Sup (x))	Critical D @ .05
2.040	1	0.04	0.06	0.02	0.54	0.25
3.710	2	0.07	0.29	0.21	Reject Null Hypothesis	
4.580	3	0.11	0.44	0.33		
5.050	4	0.14	0.52	0.37		
5.120	5	0.18	0.53	0.35		
5.390	6	0.21	0.57	0.35		
5.720	7	0.25	0.61	0.36		
6.050	8	0.29	0.66	0.37		
8.060	9	0.32	0.83	0.50		
9.730	10	0.36	0.90	0.54		
11.200	11	0.39	0.93	0.54		
11.700	12	0.43	0.94	0.51		
11.700	13	0.46	0.94	0.48		
12.100	14	0.50	0.95	0.45		
13.700	15	0.54	0.96	0.43		
17.000	16	0.57	0.98	0.41		
17.100	17	0.61	0.98	0.37		
17.200	18	0.64	0.98	0.34		
17.200	19	0.68	0.98	0.30		
17.800	20	0.71	0.98	0.27		
18.400	21	0.75	0.99	0.24		
20.400	22	0.79	0.99	0.20		
26.500	23	0.82	1.00	0.17		
27.100	24	0.86	1.00	0.14		
30.900	25	0.89	1.00	0.10		
33.100	26	0.93	1.00	0.07		
39.200	27	0.96	1.00	0.03		
39.400	28	1.00	1.00	0.00		

10
PRIOR INDUSTRY RECOMMENDED UPDATES TO ARC ANALYSIS METHODS AND DATA APPLICATIONS

This section provides industry recommended updates to ARC analysis methods and data applications. These recommendations provide details to analysis methods below the level requiring NRC approval. The methods updates include determination of bobbin voltages for indications detected only by RPC inspection, NDE techniques for cross calibration of ASME standards, voltage dependent growth rates, growth rates for deplugged tubes, Consideration of extreme growth values, noise analysis requirements, and preventative repair guidelines.

This Section combines the information from Section 10 and Section 8 of Addendum 6 (Reference 10-23). The methods discussed to divide the growth rate data into voltage bins based on statistical methods to define the break points between voltage bins are unchanged from Addendum 6 (Reference 10-23). Since GL 95-05 requires an assessment for voltage dependent growth, NRC approval is not required to apply voltage dependent growth analyses for the reference ARC analyses in operational assessments when voltage dependence is indicated by the growth rate data. The voltage dependent growth methods of Section 10.3 were submitted to the NRC for information by NEI on June 2, 2004. In most applications without preventative plugging, it is expected that the use of voltage dependent growth rates will lead to more conservative predictions of SLB burst probability and leakage.

The extreme growth values methods of Section 10.5 and the noise analysis requirements of Section 10.6 were submitted for NRC approval by NEI letters of July 9, 2004 and April 13, 2004, respectively. The preventive repair guidelines of Section 10.7 were submitted for information only to the NRC in the NEI letter of April 13, 2004. Based on subsequent NRC acceptance of POPCD for Diablo Canyon in October 2004, the April 13 guidelines have been slightly modified in Section 10.7 to increase the recommended RPC inspection to 100% of indications between 1.7 and 2.0 volts for plants with 7/8 inch tubing.

10.1 Determination of Bobbin Voltages for Indications Detected Only by RPC Inspection

10.1.1 Background

GL 95-05 requires repair of ODSCC indications found by RPC (or equivalent probe such as + Point) as a result of inspecting intersections for copper deposits, dents greater than 5 volts, axial ODSCC and PWSCC at the same TSP intersection and large mix residuals that could cause a 1.0 volt bobbin signal to be missed or misread. GL 95-05 does not require indications found in dents < 5 volts or mix residuals that do not mask a 1.0 volt bobbin flaw signal to be repaired. In

these cases, the indications have not been detected by the bobbin coil and a bobbin voltage is not directly available for the indications. In addition to the inspection cases identified in GL 95-05, ODSCC indications at TSP intersections may be found as a result of RPC inspections for dents less than 5 volts and as a result of inspecting the TSP intersections for other causes. The latter could include the use of the TSP intersection as a locating position for inspection of freespan indications. It is desirable to obtain bobbin voltages for these ODSCC RPC indications in order to include the indications in the SLB burst probability and leak rate analyses and to determine the potential need for tube repair. The need for tube repair could be a resulting bobbin voltage greater than the repair limit or greater than one volt at a mix residual.

One method for determining bobbin voltages for dents less than about 5 volts is based on identification of the flaw in a lower frequency channel (increased sensitivity to OD degradation) and reading the mix voltage for the identified flaw. A second means of inferring bobbin voltages from the RPC data is to develop a correlation between bobbin voltage and RPC voltage. A correlation can be reasonably expected since both voltages are primarily dependent upon the response to the deepest part of the indication.

10.1.2 Bobbin Voltages Obtained from Flaw Identification at Single Frequencies Such as 200kHz

The 200 kHz channel, or alternate single frequency such as 400 kHz, can sometimes be used to identify the flaw when the OD degradation found by RPC inspection cannot be identified in the prime/quarter frequency differential process channel (400/100 kHz for 7/8" tubing and 550/130kHz for 3/4" tubing). For many flaws at dents less than 5 volts, the flaw can be identified by evaluating the 200 kHz channel for a flaw-like response. A peak to peak voltage measurement is then made on the flaw-like response at 200 Khz (or alternate single frequency). The flaw segment ("dots" in Lisajous analysis) viewed without reevaluation in the prime/quarter frequency mix channel is recorded to obtain the reference bobbin voltage for the indication. The application of this technique for determining the mix voltage is limited to dents ≤ 5 volts. When the RPC flaw can be identified for bobbin sizing by this technique at non-dented intersections or mix residuals, the technique may also be applied for these cases. Indications found in dents > 5 volts, indications that have a resulting bobbin voltage greater than the repair limit and indications found in mix residuals that have a resulting bobbin voltage > 1.0 volt must be repaired.

10.1.3 Bobbin Voltages Inferred from Correlation of Bobbin Voltage to RPC Voltage

A general method for inferring bobbin coil voltages for indications found by RPC inspection but not identifiable in the bobbin data is based on application of a correlation between bobbin coil and RPC voltages. This method does not depend upon identification of a flaw-like response in the 200 kHz channel and can be applied for any RPC indication independent of dent size or mixed residual size. However, to maintain consistency with GL 95-05 requirements that indications found in dents > 5 volts are to be repaired, the applications of this technique are separated for dents ≤ 5 volts and for dents > 5 volts. GL 95-05 also requires repair of intersections having both ODSCC and PWSCC indications. A bobbin/RPC voltage correlation can be applied to obtain a voltage for the ODSCC indication. If an ARC is in place for axial

PWSCC, the correlation could be applied to obtain the bobbin voltage to assess the need for tube repair based on the repair limits for both degradation mechanisms, but this application would require NRC approval as an exception to the GL 95-05 requirements. This section describes a method for obtaining a correlation. A bobbin-to-RPC voltage correlation obtained using data for a plant with 7/8" tubes is included as an example, although not considered to be a generic correlation.

A database containing both bobbin voltage and RPC voltage for ODSCC indications is needed to develop the desired regression correlation between the bobbin and RPC voltages. Only data points with a RPC voltage between about 0.1 to 3 volts are of interest since voltages below about 0.1 volt are difficult to size, thus have a significant uncertainty, and indications above about 3 volts are beyond the range of interest (i.e., clearly require tube repair). Also, since the data outside the above voltage range are relatively sparse, variability in a few data points at the tail of the correlation could distort the correlation. Multiple axial indications with more than one deep flaw having significant RPC voltages should also be excluded since such indications could distort the correlation.

The ARC databases for 7/8" and 3/4" tubes were examined for developing generic bobbin-to-RPC voltage correlations for 7/8" and 3/4" plants. RPC voltages are available for only about 50% of the tube specimens in both these databases, and among those tube specimens, only 50% of the RPC voltages fall within the range of interest (0.1 to 3 volts). Hence, only about 25% of the data in the ARC database may be used to develop a correlation between bobbin coil and RPC voltages, and such a database is considered too small to yield a reliable correlation. Therefore, at present it is not feasible to develop generic bobbin-to-RPC voltage correlations for 7/8" and 3/4" tube plants. However, historical data from EOC steam generator inspections may be used to develop a plant-specific correlation. Development of a correlation between bobbin and RPC voltages based on plant operational data is described below.

10.1.3.1 Description of a Prior Plant-Specific Analysis

Historical data from a plant with 7/8" diameter tubes were used to develop a correlation between the bobbin and RPC voltages. The RPC voltage data considered were obtained from 80 mil pancake coil probes. It is expected that pancake coil voltage data would correlate better with bobbin voltage data than +Point voltage data, although adequate +Point data were not available at the time this evaluation was performed to confirm this expectation. The method of least squares was used to obtain a correlation between the bobbin voltage and RPC voltage amplitudes. Both linear and logarithmic forms of the variables were considered to determine the optimum combination of variables. The bobbin voltage versus RPC voltage data were plotted considering all four possible combinations of variable forms, and the data distributions were examined. A fifth case wherein the intercept for the linear bobbin to RPC correlation is forced to be zero was also considered. The data distribution did not suggest outright elimination of any of the variable combinations. Therefore, least squares regression analysis was performed for all five relationships. In addition, sensitivity analyses were performed for the range of RPC volts included in the correlation.

Table 10-1 provides a summary of the regression results. The square of the correlation coefficient (r^2, also called Index of Determination) and the p-values for the slope parameter in the regression are shown. The p-value for all five correlations considered are very small and they

meet the 5% criteria recommended in Generic Letter 95-05 for an acceptable correlation. The r^2 values in Table 10-1 suggest a linear relationship between RPC voltage and bobbin voltage as shown below.

$$V_b = b_0 + b_1 V_{r80}$$ **Equation 10-1**

where V_b represents the bobbin amplitude and V_r represents the RPC voltage amplitude.

Analyses were performed to assess the sensitivity of the correlation r^2 and the RPC volts at 2 bobbin volts to the RPC voltage range used in the correlation. The data of Figure 10-1 suggest that a range between 0.2 and 2.0 RPC volt might be more appropriate for the correlation than the 0.1 to 2.0 volts range used. Table 10-2 provides the results of the sensitivity study. It is seen in the table that r^2 does not significantly change for the 0.2 to 2 volt range but is notably reduced for the smaller RPC voltage intervals with a smaller database. The RPC voltage at 2 bobbin volts from the mean regression line does not change significantly between the correlations. Larger differences could be expected when confidence levels are added due to changes in the database size, but the mean correlation value at 2 bobbin volts appears to be well defined by the correlation. Since there is little difference in the correlation between 0.2 to 2 volts and 0.1 to 3 volts, the latter was used for the correlation to reduce the potential need to extrapolate beyond the range of the correlation in field applications. The regression relationship along with the data used in the regression analysis is shown in Figure 10-1.

An analysis of the regression residuals was also performed to check if the assumptions inherent in the least square analysis apply. A plot of the residuals of the bobbin voltage versus the bobbin voltage obtained using the regression correlation was prepared for each of the 5 relationships examined. The residuals plot should show random scatter without suggesting any type of correlation. The data for all relationships examined show random scatter indicating that a correlation does not exist between the residuals and the predicted values, and that the variance of the residuals is uniform. Figure 10-2 shows the residual scatter plot for the linear relationship shown in Equation 10-1.

Another implicit assumption in the least square analysis is that the regression residuals are normally distributed. To confirm the validity of this assumption for each correlation considered, the residuals were sorted in ascending order and then plotted against an ordinate representing cumulative percent value for a variable given by

$$100 \times \frac{(i - \frac{1}{2})}{n}$$

where n is the number of data points used in the regression and i is an index ranging from 1 to n. The data should fall approximately on a straight line if the residuals are normally distributed. The residuals for all 5 relationships considered approximate a straight line, thus indicating that the assumption of normal distribution for residuals is valid. Figure 10-3 shows the ordered residuals plot for the linear relationship shown in Equation 10-1.

10.1.3.2 Uncertainties in the Predicted Bobbin Voltage

The voltage predicted using the correlation described above provides a mean value for the bobbin voltage at a given RPC voltage. Since eddy current inspection and voltage-based repair limits are based upon the nominal voltage indicated by a bobbin probe, it is appropriate to use the mean value predicted with the regression correlation. To account for uncertainties in the predicted mean value, 95% confidence intervals for the mean were established and the upper 95% confidence bound on the mean was used to obtain a conservative bobbin voltage estimate at a given RPC voltage. A one-sided upper 95% confidence bound for the bobbin voltage is also shown in Figure 10-1. The difference between the upper, one-sided 95% confidence bound and the mean vary slightly with the RPC voltage (between 0.1 to 0.4 volt bobbin voltage in the RPC voltage range 0.2 to 3 volts). The use of the 95% confidence band reduces the RPC voltage that corresponds to 2 bobbin volts from 1.51 to 1.38 volts. The RPC voltage at 1 bobbin volt is reduced from 0.40 to 0.28 volts for the 95% confidence value.

10.1.3.3 Application of Regression Correlation

The RPC voltage corresponding to 2 volts bobbin voltage at the upper, one-sided 95% confidence bound on the mean can be used to define tube repair requirements as well as the threshold to determine the need for expansion of the augmented RPC inspection of dented intersections and mixed residual signals. The use of RPC voltage corresponding to 2 volts bobbin voltage is appropriate for mix residuals or dented intersections since it is used to assess the significance of the detected indication by comparison with the repair limit. The curve representing the one-sided 95% confidence bound in Figure 10-1 can be represented by the following equation.

$$V_b = 0.77 + 0.82 \times V_{rpc} + 0.06 \times V_{rpc}^2 \qquad \textbf{Equation 10-2}$$

where V_b represents the bobbin voltage and V_{rpc} represents the RPC voltage. The above correlation is valid for RPC voltages between 0.1 to 3 volts. It is noted that Equation 10-2 is presented as an example, and it is not recommended as a generic correlation.

The above equation may be used to obtain equivalent RPC voltage at the repair limit. For the example case presented, the RPC voltage from an 80 mil pancake probe corresponding to 2 volts mean bobbin voltage is 1.38 volts.

10.1.3.4 Recommendations

When a correlation between the bobbin and RPC voltages can be developed on a plant-specific basis, the correlation can be applied to determine the need for tube repair based on the estimated bobbin voltage (corresponding to a measured RPC voltage). The ODSCC indications detected at dented or mix residual intersections should be included in the tube integrity evaluations performed to support voltage-based repair criteria. A correlation similar to Equation 10-2 can be used to convert the RPC voltage measured for an ODSCC indication at dented intersections or intersections with large bobbin residual signals into an equivalent bobbin voltage for use in the

tube integrity analyses. However, it is necessary to separate the application of the correlation for consistency with the GL 95-05 requirements on dents as given below:

10.1.3.5 Application to Dents ≤ 5 Volts and Mixed Residuals

- Bobbin voltages are to be inferred from the bobbin to RPC voltage correlation at 95% confidence on the mean correlation.
- Bobbin voltages inferred from RPC volts by application of a correlation are to be included in the condition monitoring and operational assessments for burst probability and SLB leak rate calculations.
- Bobbin voltages greater than the ARC repair limit are to be repaired.
- Bobbin voltages greater than or equal to 1.0 volt found in a bobbin coil mix residual signal are to be repaired.

10.1.3.6 Application to Dents > 5 Volts

Several indications have been found to date in dents > 5 volts. Bobbin voltages for indications found in dents < 5 volts have been small and have negligible influence on the ARC leak and burst analysis results. When found by RPC in > 5 volt dents, the indications could potentially have larger bobbin voltages since bobbin coil detection of flaws in large dents would be expected to be significantly poorer than for small dents. Therefore, the application above 5 volts requires additional uncertainty considerations in the ARC leak and burst analyses as included in the following requirements for application of a correlation to > 5 volt dents:

- The bobbin to RPC voltage correlation must satisfy a p-value of < 5% for an acceptable correlation and bobbin voltages are to be inferred from the correlation at 95% confidence on the mean correlation.
- If a utility desires to leave ODSCC in service at > 5 volt dents, NRC approval for the application of a bobbin to RPC correlation is required since the application above 5 volt dents represents a deviation from GL 95-05.
- Bobbin voltages inferred from RPC volts by application of a correlation are to be included in the condition monitoring and operational assessments for burst probability and SLB leak rate calculations. The uncertainty in the bobbin to RPC voltage correlation must be compared with the bobbin voltage uncertainties to assess the need for including additional uncertainties in the leak and burst analyses.

The requirements for tube repair based on the inferred bobbin voltages would be the same as given above for dents < 5 volts although tube repair is currently required by GL 95-05 for indications in dents > 5 volts.

10.2 NDE Technique for Cross Calibration of ASME Standards to the Reference Standard

10.2.1 Background

Methodology for the normalization of EC standards to the reference standard in the ARC data base has not been uniquely defined. This led to multiple methods for normalization being applied. Experience obtained with many different standards has shown that the differences in the normalization technique can, in some cases, lead to larger than expected differences in the calibrated signal amplitudes. This, in turn, may lead to unexpectedly large changes in the growth rate information. This review of calibration methods was initiated based on finding unusually large negative growth rates at one plant.

There have been at least four separate methodologies used for the normalization of the calibration standards used in the field to the ARC reference standard. The normalization gets transferred from one standard to the next, frequently to two standards removed from the reference standard, but conceivably through four or more generations removed from the reference standard. Ideally any methodology used should be able to be set up on a standard from any generation and the measured amplitudes should correlate directly to the reference values. Based upon recent experience, this is not necessarily true of all methodologies used. The data have shown that there is, for some methodologies, a greater than expected dependence of the normalization of the mix channel upon both the tube and support plate material properties. This has led to the evaluation of the various techniques outlined in this report. The techniques evaluated in this report are:

1. Perform the mix on the new standard and set the prime frequency amplitude for the 20% flat-bottomed holes on the reference (or transfer) standard to the reference (or transfer) standard assigned value. This setting is saved and stored to all channels including the mix. The values for the new standard are then read for both the prime frequency and mix channels. (Method 1)
2. Perform the mix on the reference (or transfer) standard and independently set the prime frequency and mix amplitudes for the 20% flat-bottomed holes on the reference (or transfer) standard to their respective values. The values for the new standard are then read for both the prime frequency and mix channels. (Method 2)
3. Perform the mix on the new standard and independently set the prime frequency and mix amplitudes for the 20% flat-bottomed holes on the reference (or transfer) standard to their respective values. The values for the new standard are then read for both the prime frequency and mix channels. (Method 3)
4. Set the prime frequency amplitude for the 20% flat-bottomed holes on the reference (or transfer) standard to its assigned value. The values for the new standard are then read for the prime frequency. The ratio of the prime frequency amplitude for the new standard to that for the reference standard is multiplied by the ideal mix amplitude (2.75 Vpp) to get the mix amplitude for the new standard.

10.2.2 Theoretical Critique of the Four Methods

As stated previously, any methodology used should be able to be set up on a standard from any generation and the measured amplitudes should correlate directly to the reference values. This implies that the normalization technique is performed in a manner which tends to cancel out differences in the electrical and magnetic characteristics of both tube and support ring material used on a standard. In principle, the standard being correlated to the reference standard could have a different tube material (for example Inconel 690), or the support plate material could differ in origin (bar versus plate stock), but the correlation back to the reference standard should be successful. With this concept of normalization, the four methods described above can be assessed as follows:

Method 1: The idea of mixing on the new standard is good. This is where the mix will be performed in the field. However, the use of only the prime frequency for the normalization tends to ignore the effect of the variations in the support ring material on the scaling of the mix amplitudes. Because this does not relate the mix amplitudes measured to those for the reference standard, there may be variations in the relationship of the mix on the new standard to the reference standard.

Method 2: The idea of mixing on the reference standard ignores the possibility of differences in the support ring material leading to variations in the measured amplitudes. However, the direct relationship to the mix value on the reference standard should minimize the differences.

Method 3: The idea of mixing on the new standard is good. This, coupled with, the direct relationship to the mix value on the reference standard should lead to the smallest variations when comparing a new standard to the reference.

Method 4 This method assumes that the mix is unaffected by the materials (tube or support ring) involved, and that the relationship of the amplitude on the prime frequency on the new standard to that on the reference standard applies equally to the mix channel. It does, however, tie back to the mix amplitude for the reference standard. This method is unaffected by differences in mixes and is, therefore, also unaffected by chaining of transfer amplitudes through generations of standards.

Based upon this brief critique, an expected ranking of the ability of the methods to relate directly to the reference standard can be developed. It is expected that Method 3 and Method 2 should produce the best results. Methods 1 and 4 ignore certain variations in material parameters which can affect the result. It is expected, based upon a stronger relationship to an ideal mix amplitude, that Method 4 should prove to be better than Method 1.

10.2.3 Experimental Study

After reviewing the transfer values for a large number of standards, it was determined that the largest variations in data appeared in the population of 0.875" O.D. x 0.050" wall tube standards. Ten standards were selected for direct comparison with the master reference standard at the

Westinghouse Science and Technology Center. By collecting all of these standards together, a number of relationships could be developed in terms of the transfer of the amplitude values. If the reference standard is considered to be 'first generation', all of the standards could be evaluated as second generation. Then one of these could be used to transfer the voltages to the others to make them third generation. This was done until a fourth generation was developed for the two most promising methods.

The relative quality of the methods was evaluated by setting up on the transfer values for the nth generation, as would be done in the field, and then going back to the reference standard and measuring the amplitude on the mix channel. The evaluation was done by looking at the outcome as a percentage deviation from the true value (positive or negative relative to the ARC reference standard). A deviation of zero implies perfect correlation to the reference standard. In order to check the material insensitivity of the methods, the standards used include more than one heat of Inconel 600 tubing, Inconel 690 tubing, multiple heats of bar stock support plate material, and multiple heats and types of plate stock support plate material. The carbon steel bar and plate support material are in the same nominal range of compositions. The sample information can be found in Table 10-3.

10.2.4 Results

The results of the testing are summarized in Table 10-4. As expected, Method 3 and Method 2 produced the best results. Method 1 showed the greatest variability. The variability observed can be attributed to the variation in tube and support plate material properties. Methods 1 and 4 are the most sensitive to these differences. The average results are graphically illustrated in Figure 10-4. Figure 10-4 is a radial plot where the ten axes represent the ten standards. The solid ring denotes zero error relative to the relationship with the reference standard. The points plotted represent the average errors for all generations evaluated by any given method. Method 3 shows a small positive error while Method 2 shows a small negative error.

10.2.5 Recommendations

It is recommended that Method 3 be applied for ARC applications requiring cross calibration of ASME standards to the reference laboratory standard. Method 3 provides for direct cross calibration of the mix amplitudes from the reference or transfer standard to the new standard being calibrated. The mix is established on the new standard for this method. This method should be applied to obtain the cross calibrated standards for all ARC inspections beginning in the fall of 1998.

For existing standards to be used in future ARC inspections, it is further recommended that the values for standards normalized using Methods 1 and 4 be re-evaluated using Method 3. Standards normalized using Method 2 need not be re-evaluated since the difference from Method 3 is negligible and re-evaluation is not warranted.

The re-normalization of standards previously normalized using Methods 1 and 4 could affect growth rate information for ARC plants. It is recognized that there may be a change in the growth rates if the re-normalized standards/data are used. If a plant has been consistently using

standards normalized by a single method, the historical growth data would be reliable since the growth rate information would have all been gathered using a single type of normalization. If the voltage normalization method changed between inspections, growth rates could be influenced by the change in calibration methods. In this case, growth rates should be adjusted to obtain a consistent normalization method between the two inspections used to develop the growth rate unless it can be demonstrated that the growth data are conservatively high. Since the ARC analyses use only the last two cycles of growth data (including the current cycle to the next inspection), data for only the last two completed inspections would need to be reviewed. It is recommended that an evaluation be made as to whether or not the re-normalization needs to be performed for growth rates and that the conclusions be documented.

The effects of the different normalization methods on absolute voltages are within about one standard deviation (13%) or less of the NDE uncertainty. Consequently, there is no need to review non-growth rate related data for voltage indications. For example, pulled tube indications included in the ARC database do not have to be re-evaluated.

10.3 Voltage Dependent Growth Rate Methods

This section is a complete revision to Section 10.3 of Addendum 5 for voltage dependent growth rate methods. The revised methods are applied to divide the growth rate data into voltage bins based on statistical methods to define the break points between voltage bins. Since GL 95-05 requires an assessment for voltage dependent growth, NRC approval is not required to apply voltage dependent growth analyses for the reference ARC analyses in operational assessments when voltage dependence is indicated by the growth rate data. The voltage dependent growth methods of this section were submitted to the NRC for information by NEI on June 2, 2004. In most applications without preventative plugging, it is expected that the use of voltage dependent growth rates will lead to more conservative predictions of SLB burst probability and leakage. Significant voltage dependent growth has been identified in two plants with 7/8" tubing and a 2 volt repair criteria. It is recommended that the revised methodology described in this section be applied only after confirming voltage-dependent growth trends for a plant. Plants with two volt repair criteria should continue to monitor growth data for a BOC voltage dependence.

10.3.1 Introduction

The voltage dependent growth (VDG) methods in the previous ARC database addenda were developed from Braidwood and Byron experiences and were assumed to be necessary only with the application of a 3 volt ARC limit. The Diablo Canyon Unit 2 (DCPP2) experience in 2003 demonstrated that voltage dependent growth could become significant for repair limits of 2 volts. As a part of Pacific Gas and Electric's (PG&E) efforts in support of the DCPP2 Operational Assessment (OA), methods were developed for applying VDG based on a statistical analysis to define the number and voltage values for the break points between voltage growth bins. This report provides for incorporation of the methods developed for PG&E in the ARC database.

The information presented in this report was prepared to document the development of a methodology for the determination of break points to be used for the application of voltage dependent growth in performing ODSCC ARC evaluations of SG tube degradation. The results

from this effort were presented to the NRC staff on behalf of PG&E regarding the evaluation of indications in the SGs at DCPP2 in 2003. The results of the development are believed to be generically applicable when the use of VDG is appropriate, hence, the inclusion of the information in the EPRI database for ODSCC ARC applications. Although the analysis results can be useful in examining the data for changes that would be indicative of VDG, the development of criteria for making that determination was not within the work scope for the preparation of this report. An Excel™ workbook for performing the VDG analyses was provided to EPRI with this report. Although the workbook was checked for correctness, it was not subjected to the effort necessary to be considered verified and validated to the extent that it could be directly placed under configuration control, nor were built-in safeguards included to prevent its misuse.

The application of growth rates to predict end-of-cycle (EOC) voltage distributions from beginning-of-cycle (BOC) amplitude distributions for the evaluation of outside diameter stress corrosion cracking (ODSCC) of steam generator (SG) tubes is described in Reference 10-1. It is recognized therein that the growth rate of the degradation may depend on the current size of the indication, i.e., the growth of an indication during one cycle of operation can depend on the size or amplitude at the beginning of the cycle. Utilities employing alternate repair criteria (ARC) for the disposition of ODSCC indications at tube intersections with drilled tube support plate (TSP) holes in Westinghouse SGs are advised to be alert for the appearance of voltage dependent growth (VDG). It is further recommended that use of VDG techniques be considered in the Monte Carlo analyses performed to predict distributions of indications that may be present at the end of the next operating cycle. It can be formally demonstrated that all growth measured in terms of bobbin amplitude must be voltage dependent, however, the level of that dependence has usually been small and could be neglected without introducing meaningful errors in the prediction of end-of-cycle bobbin amplitudes.

The Monte Carlo simulation of the growth of tube degradation indications is accomplished by randomly sampling the empirical distribution function (EDF) of the observed growth rates from previous operating periods where guidelines for the analysis are provided in Reference 10-2. If VDG is suspected, the data may be separated to form an EDF for low voltage indications and one or more independent EDFs for higher voltage indications. The historical practice was for an engineer familiar with the ODSCC ARC analysis to make a judgment from an examination of the data as to where the demarcation or break points should be located to segregate the voltage growth regions. The following information describes a mathematical method that can be applied to determine where the break point locations should be determined based on an evaluation of the data being analyzed. This allows for the growth data to be segregated or separated into bins, "binned," according to a mathematical indicator of where the growth rates are exhibiting meaningful change.

The concept of establishing the break points is based on approximating a curve using linear segments. No break points are needed if the data do not exhibit significant curvature, meaning that VDG is not apparent. Once VDG is apparent in the population, the break points are determined to result in linear segments that best fit the curve. As the size of the population increases and ages, VDG is expected to occur and fitting of the data using a curve would be appropriate if the fitted curve was being simulated in the analysis. Since a curve is not being fitted, i.e., the empirical distribution function (EDF) of the growth data is being used in the SG analysis, it is appropriate to identify break points where separate EDFs would be developed to

accommodate changes that are implied by the data exhibiting significant curvature. Thus, the break points would be expected to move according to the strength of the VDG as indicated by the curvature of the instantaneous mean of the data as a function of voltage. The break points are found by minimizing the sum-of-squares of the errors of the data from the predictions from the piecewise linear function fitted to the data. The lowest break point would not be expected to shift significantly since the population curvature in the lower volts range would likely be consistent from one outage to the next. The upper break point or points could be expected to be relatively insensitive with time if the overall shape of the growth data remains constant. A change in the break point values and the number of break points could be expected with an increase in the amplitude of indications being retained in service.

Analyses were performed of tube ODSCC growth data for SG 2-4 at DCPP2 to identify appropriate break points for the performance of the operational assessment for the SG tubes, Reference 10-3. The analyses resulted in the identification of appropriate break points for the performance of EOC predictions for Cycle 12. The rationale for the method is to minimize the sum-of-squares of prediction errors (SSE) from multiple linear regression relations of the growth data by adjusting the locations where one regression line would terminate and another regression line would begin. It is emphasized that the method is not for the purpose of developing voltage growth regression relations for use in operational assessments (that is done by sampling the EDFs), but only to identify those voltage locations where the results from an analysis of the data indicate a change in the relation, i.e., a change in the intercept and slope of the regression lines. The relationship is characterized as being bilinear if two linear relations are used to describe the data. The concept can be extended to consider descriptions of data which would be characterized as trilinear and quadrilinear for two and three break points respectively. An Excel™ workbook used for the analysis will analyze data for up to three break points.

10.3.2 Piecewise Linear Regression Analysis

The concept of piecewise linear regression analysis follows from the concept of the use of "dummy" variables in multiple regression analysis, Reference 10-4 for example. The purpose of the analysis is to depict relations where the dependent variable (EOC amplitude) follows a particular linear relation up to some specific value of the independent variable (BOC amplitude) and a different linear relation beyond that value. An example of a bilinear dependence relation is illustrated on Figure 10-5. To the left of the break point, i.e., the discontinuity between line slopes, the linear relation follows one intercept and slope combination and to the right of the break point it follows a different combination of intercept and slope, where both relations intersect at that particular point. A trilinear regression relation is illustrated on Figure 10-6 and a quadrilinear regression relation is illustrated on Figure 10-7. Each of these are discussed in the following sections relative to the analysis of the DCPP 2 data as an example, but the methodology is equally applicable to the data from any plant.

10.3.3 Discussion of Growth Plotting

The bobbin amplitude growth data are usually plotted on the ordinate axis of a scatter chart so as to indicate a dependence, or lack thereof, on the BOC voltage which is plotted on the abscissa. Thus, a linear 1st order correlating relationship would be represented as,

$$\Delta V = V_2 - V_1 = b_0 + b_1 V_1,$$

Linear Growth
Equation 10-3

where b_0 and b_1 are coefficients to be obtained from a regression analysis of the data. A correlation of the growth relative to the initial voltage must exist because the initial voltage, V1, appears on both sides of the equation. Rearranging, it is seen that the relation being examined by Equation 10-3 is,

$$V_2 = b_0 + (b_1 + 1) V_1$$

Equation 10-4

The measured value of the initial and final voltages are V1 and V2, where both are subject to measurement error, so,

$$V_1 = V_{a1} + \varepsilon, \text{ where } \varepsilon \sim N(0, \zeta V_{a1})$$

Measured Voltage
Equation 10-5

That is, the error of measurement is a constant fraction of the magnitude being measured. The measurement error consists of two parts, the error associated with the eddy current probe wear and the error associated with the eddy current analyst recording of the amplitude of the indication.

A rearrangement of the equations is provided in the following to provide a visualization of the fact that there is the potential for negative slopes to be observed from the analysis of the data. If V2 were plotted on the ordinate axis the regression relation would be of the form,

$$V_2 = g_0 + g_1 V_1$$

Equation 10-6

where the regression coefficients are represented by g0 and g1 to avoid confusion. Then the relation for the growth becomes,

$$\Delta V = V_2 - V_1 = g_0 + (g_1 - 1) V_1$$

Equation 10-7

Thus, it is readily apparent that the slope term in Equation 10-3 could become negative. The appearance of slightly negative slope terms for the first line segment from the regression analysis should not be interpreted as indicative that an error has occurred.

10.3.4 Analysis

For the example data considered, the analysis of the growth data to determine break points is somewhat insensitive to the locations determined for the break points, i.e., the optimized variable, the sum of squares of the regression errors, does not change much with small changes in the location of the break point. This means that the past practice of using engineering judgment did not likely result in significant contributions to the overall uncertainty of the analysis results. The following sections describe considerations made to process the growth data and the types of analyses that can be performed. Three levels of piecewise linear regression were

considered for the DCPP data sets, bilinear, trilinear, and quadrilinear. The results for the quadrilinear fits did not aid in understanding the data and are not recommended for the initial analyses of VDG. Conclusions are provided at the end of this section.

10.3.4.1 Upper Range Number of Data

One of the considerations that has been made regarding growth rates since the inception of VDG concepts has been with regard to the number of indications binned into the upper range of the data. The determination of the break point can be significantly skewed by one or two indications if the number of indications is too few. For example, there was one extremely high growth value associated with the data of DCPP SG 2-4. A break point at the extreme indication will be calculated if the analysis algorithm does not restrict the number of indications in the upper range to some minimum value. This is because the square of the error of prediction for that indication is much larger than for the other indications, causing it to exert undue *leverage* on the establishment of the break point. The minimum number of data for the upper range was established to be fifteen based on engineering judgment. If the number is chosen too small, the influence of a single large indication could bias the results of the analysis to always converge to the minimum allowable. The experience with using the number fifteen has been that the analysis generally converges to leaving a larger number, than fifteen, of indications in the upper bin. This is evident by the results illustrated on the figures accompanying the following discussions for piecewise linear regression analysis. It is also noted that the single largest growth value, which was much larger than the remaining growth data, was omitted from consideration for these analyses. Inclusion would have the effect of always making the solution converge to the bin limitation instead of a true or more intuitively correct solution.

10.3.4.2 Bilinear Regression

Table 10-5 illustrates a data set used in a bilinear regression analysis of the DCPP SG 2-4 growth data. A snapshot of the screen from the Excel™ worksheet analysis of the data is shown on Figure 10-8 and the discussion of the analysis is keyed to the cell coordinates of that figure. The original independent variable data are listed in column B with the initial dependent data in column D. The dummy independent variable data, one set, are listed in column C. Each cell in column C contains a formula that returns the maximum of the difference between the independent variable, V1, at that row and the break point value, VBP, which is listed in cell F5. Thus, the regression line is of the form,

$$V_G = b_0 + b_1 V_1 + b_2 \langle V_1 - V_{BP} \rangle \qquad \textbf{Equation 10-8}$$

where the coefficients, b_0 through b_2, are found by a standard least squares procedure. The angle brackets, $\langle$ and $\rangle$, indicate a singularity notation that is zero if the operation in the brackets is negative or zero and the value of the operation otherwise. Here it is understood that the exponent on the brackets is unity. Examination of the equation shows that the intercept and slope when V_1 is less than V_{BP} are b_0 and b_1 respectively. When the converse is true the intercept is b_0 minus $b_2 \cdot V_{BP}$ and the slope becomes b_1 plus b_2. The principle extends readily to multiple break points.

In many instances the value of the break point is known *a priori* and the regression proceeds in the usual fashion. The approach to the analysis of the growth data is to perform the analysis in a manner in which the value of the break point is also determined. A nonlinear regression analysis could be performed to effect a solution. An equally valid approach, the method employed herein, is to use the Excel solver routine to calculate the value of the break point that results in a minimum value for the sum of squares of the errors of regression. The solver interface window for the analysis of this document is illustrated on Figure 10-9 and the information depicted is keyed to the cell coordinates shown on Figure 10-8. The target cell, J9, is the sum of squares of the prediction errors from the regression analysis. The break point value is entered in cell F5; the solver routine changes the value in that cell to minimize the value calculated for the target cell. There are two constraints identified in the interface window, the solution value has to be less than or equal to the number in cell G8, identified as "Bound 2," and greater than or equal to the value in cell F8, "Bound 1." The value of the first bound was picked, i.e., the value of 0.5 was selected based on engineering judgment, as a standard for the width of the first data region. The value in cell F8 can be set to less than 0.5 to give the solver more latitude in calculating a break point, which could then be less than 0.5. This approach was used by DCPP for the evaluation of the Unit 1 Cycle 12 data, with the results being illustrated of Figures 3-1 and 3-4 of the Reference 10-5. The value in cell G8 is obtained from the data in column B, referring again to Figure 10-8, using the value in cell G9 to count from the bottom of the data. This then determines the upper bound value allowed for the solution. Cell G6 of Figure 10-8 contains the actual number of data in the upper range and serves as a check that the solution for the break point is actually less than the bounding value. One other feature of the regression analysis is noted. The intercept term for the regression equation was not restricted to zero, see cell K5 on Figure 10-8. This is not a necessary feature and the determination of the break points is likely insensitive to this specification. The solution value for this case was 0.59, comfortably greater than the lower bound of 0.5 and significantly less than the specified upper bound of 1.67. The results of the regression analysis for a sample set of data are illustrated separately on Figure 10-10.

10.3.4.3 Trilinear Regression

The worksheet for the performance of a trilinear analysis is shown on Figure 10-11. The solver interface is shown on Figure 10-12. A point to note is that there are two cells to be changed to effect the desired solution, F5 and G5. In addition, the lower bound constraint is only on the value in cell F5 and the upper bound constraint is on the value in cell G5. The other point is that the cell to minimize the value has been specified as J7, which is the standard error of prediction. This is really the same specification as J9 since the standard error of prediction is the square root of the sum of squares of the errors of prediction after dividing by the degrees of freedom. The equation for a trilinear regression analysis is,

$$V_G = b_0 + b_1 V_1 + b_2 \langle V_1 - V_{B1} \rangle + b_3 \langle V_1 - V_{B2} \rangle \qquad \textbf{Equation 10-9}$$

where V_{B1} and V_{B2} are the two break points needed in the analysis. The solution is independently illustrated on Figure 10-13. The trilinear regression analysis illustrated is for a different data set than used for the bilinear regression, since upper range values from the growth during Cycle 10 were included to increase the probability of experiencing some of the larger growth values. The sum of squares of the errors is greater for the trilinear regression than for the bilinear because

different data sets were analyzed for the two examples. However, the improvement as measured by decreasing the SSE for the latter set of data which was obtained by increasing the complexity of the model was marginal at best. Although the SSE was only marginally improved, the use of the trilinear regression was and is recommended where practical. Recall that the purpose of the analysis is not to fit useable regression functions to the data, but only to find locations where there is evidence that the growth may be changing. The results for the break points are readily apparent from an examination of the information presented on Figure 10-13. An additional break point is found at location 1.66 Volts which results in greater predicted growth for the larger values. This is a desirable feature to include in the operational assessment. There are nineteen (19) data pairs included in the solution for the upper bin, indicating that the solution was not converging to the remaining single highest growth value. Had the single extreme growth value been included in these analyses, the solution would have converged to whatever limit was in place for the upper bin, e.g., fifteen (15) in this case.

10.3.4.4 Quadrilinear Regression

The expansion of the model from three to four line segments follows in the same manner as increasing the number of segments from two to three. A worksheet for performing a quadrilinear regression analysis of the data is illustrated on Figure 10-14, where provisions have been made to include three break points and three bounds for the break points (a lower bound for the first break point, and upper bounds for the second and third). The solver screen for performing the analysis is shown on Figure 10-15. One constraint has been added to account for the additional break point. The equation for a quadrilinear regression analysis is,

$$V_G = b_0 + b_1 V_1 + b_2 \langle V_1 - V_{B1} \rangle + b_3 \langle V_1 - V_{B2} \rangle + b_4 \langle V_1 - V_{B3} \rangle \qquad \textbf{Equation 10-10}$$

where V_{B1}, V_{B2} and V_{B3} are the three break points to be calculated. The results of extending the model to consider four regression lines are illustrated on Figure 10-16. An undesirable consequence, the third line has a lower slope than the second line, is immediately apparent. This is counter to expectation and is a flag that the added complexity should not be included in the model.

By comparing the numerical information on Figure 10-14 with that on Figure 10-8, it is apparent that the improvement in the SSE is minimal 85.9 versus 86.1. A similar result is obtained if the trilinear fit is compared to the bilinear fit.

10.3.5 Example Application to Plant DCPP Data

10.3.5.1 SG 2-4 Cycle 11 Growth Data

As previously noted, data were obtained from the examination of the SG tubes at DCPP Unit 2 during refueling outage 11, referred to as 2R11, Reference 10-3, and analyzed to estimate locations for the break points for the analysis considering voltage dependent growth. The data were used to develop the information presented in this report for an operational assessment of the

DCPP 2 SG tubes. The steam generator with the most significant degradation and growth was DCPP SG 2-4.

The Cycle 11 growth data for the 975 indications found in the SG were analyzed using a piecewise linear regression analysis and break points of 0.61 and 1.66 Volts were obtained. A second analysis was performed by adding the 30 largest indications in the SG from the inspection at the end of Cycle 10 of operation to the Cycle 11 data. The number of indications corresponded to a growth break point value of 1.17 Volts which was obtained from the analysis of the growth data for that cycle. The analysis is discussed in the following section. The results of the analysis indicate that the break points for the Cycle 11 growth rates should be at 0.59 and 1.66 Volts for a three region simulation. It is noteworthy that the break points obtained from both analyses are similar and the upper break point is unaffected by the presence of the Cycle 10 indications. This is likely due to the fact that most of the indications had BOC amplitudes that were less than the upper break point value.

10.3.5.2 SG 2-4 Cycle 10 Growth Data

The growth data from Cycle 10 for SG 2-4, a total of 488 indications, were analyzed using the same techniques to find break points in the growth that would minimize the corrected sum of squares of deviations from the piecewise regression predictions. The Excel screen for the analysis is shown of Figure 10-17. The results of the analysis indicate that break points of 0.69 and 1.17 Volts should be used for analyses employing the Cycle 10 growth data. The dependence of growth on BOC amplitude is significant above the second break point where it is apparent that the change in slope is somewhat dramatic. The results are illustrated in larger scale on Figure 10-18.

The Cycle 10 data also provide an illustration for a potential drawback in using quadrilinear regression without a restriction on the minimum number of data that may be used for the third segment or piece of the curve. A near step function results as illustrated on Figure 10-19 from the influence of the large growth value at about 1.25 volts, i.e., minimization of the standard error of the regression is achieved by having a step at that value, with a smaller slope for the fourth segment of the curve. The noted point, and two others, are also influential in the determination of the slope of the third segment for the trilinear regression. A comparison of the two curves shows that the growth in the range of less than 1.2 Volts is less than if the trilinear curve is used, in the range of 1.2 to 1.5 Volts the growth is greater if the quadrilinear curve is used, and growth for indications greater than 1.5 Volts is greater if the trilinear curve is used. Figure 10-20 illustrates the Excel input screen for setting a data limitation on the number of data in the third and fourth bins respectively and Figure 10-21 illustrates the solution for the same data if the limitation on the number of data for the third segment is used. In this case, the growth rate in the range below about 1.2 Volts is greater for the trilinear curve and slightly lower thereafter to about 1.5 Volts. It should be noted that for the trilinear fit, the number of data in the upper bin is 30 even though the specified minimum was 15. For the quadrilinear fit the number of data in the third and fourth bins exactly matches the specified minimum. Thus, the analysis is converging to the specified limits instead of seeking out the natural break point. As for the analysis of the Cycle 11 data, there is no advantage to using a quadrilinear fit to determine the break points.

10.3.6 Discussion

The following discussion was developed to provide clarification based on the tenor of requests for additional information (RAIs) transmitted by the NRC staff to PGE following submittal of DCPP 2R11 inspection report. A question was asked regarding the accuracy of pinpointing the break points with the following response being developed to that request. The pinpointing of the break points is achieved by the fitting of the prior cycle growth data once VDG has been established. The implementation protocol for the determination of the break points prevents the number of data in the upper bin from becoming too small (i.e., <15), thus arbitrary shifting of the upper point is not possible. The establishment of the break points is not subject to meaningful variation once the growth data have been obtained. The break points will always be accurately calculated to achieve the best locations for the simulation of the current growth curve if it were intended to be approximated by piecewise linear segments. The statistically based methods for calculating the break points eliminate any arbitrary choice of the break points. A study with arbitrary shifts in the break points would not provide meaningful information relative to the establishment of the break points.

In the case of the DCPP U2 Cycle 12 analyses, it is anticipated that moving of the lower break point would not be expected to have a significant effect on the probability of burst simply because of the range of indications in the lower bin near the break point with the middle bin and because of the relatively small growth rates for this bin. It is noted that there are two results that ensue from arbitrarily moving the upper break point in the positive direction, something that is not permitted under the VDG methods guidelines. The first is the number of growth points in the upper bin would decrease, leading to an attendant increase in the frequency at which the largest growth value(s) would be sampled during the simulation for indications in the upper bin. The second effect is that the number of indications that would be in the BOC voltage range for which the upper growth values would be sampled would also decrease. For most analyses without preventive plugging, the number of indications returned to service in the upper bin would usually exceed the number of indications in the upper bin growth distribution, which ultimately leads to conservative frequencies for the large growth values. Preventive plugging at 1.2 volts, as applied at DCPP-2 for Cycle 12, reduces the number of BOC indications in the upper voltage bin, thus reducing the potential for indications to have large growth rates. The two effects of large growth frequency and number of indications returned to service in the bin may or may not offset each other in the calculation of the probability of burst or potential total leak rate depending on the population being simulated. However, the voltages for the population being simulated will always well represent the voltages for the population from which the bin growth rates were derived.

An addition query was made regarding whether the method could be reasonably expected to be applicable from plant-to-plant or would the evaluation be plant specific. Since the break points represent locations where a least-squares piecewise linear approximation to the growth of the data is being estimated, it can be assumed that the results would be plant-specific but the methodology can be applied from plant-to-plant. A related question requested that consideration be given as to whether or not the break points could be assumed to be defined by a mature population and used on a generic basis. This question is of a similar nature and using a generic set of break points is not recommended unless an analysis is performed demonstrating that a significant shift in their locations has not occurred. However, performing such an analysis results in the calculation of the break points so no advantage would be gained by trying to establish a

generic set. In addition, the ARC populations continue to mature as more indications left in service approach the repair limit such that the best estimate of a mature population increases with operating time or with increases in the repair limit.

Finally, the staff requested that DCPP address the potential for shifts in the VDG break points to occur under increases in the ARC repair criterion, e.g., 4V. It was noted that implementation of an ARC on the order of 4V could be expected to lead to the need to utilize three break points, a quadrilinear regression analysis, in order to achieve a reasonable level of agreement between the piecewise linear function and the curvature exhibited by the data. This is based on anticipating an increase in the range of the growth data and the need for a more complex model, achieved by increasing the number of break points, to approximate the curvature of the growth data as a function of initial amplitude.

10.3.7 Summary

The purpose in performing the analysis is to "let the data determine" where the break points should be. Recall the caution that the analysis is not being performed to obtain growth relationships to be used in the analysis of the ODSCC indications. Care must be taken to avoid making judgments about the analysis results stemming from an unintentional anticipation of using the relationships for analysis simulations or predictions. Moreover, the purpose of the analysis is to identify break points when it is suspected that VDG is taking place, not to determine if VDG is taking place. This is because criteria for use with the curve fitting worksheets were not developed for this effort. However, the analyst could perform the evaluation of the break points independently and conclude that a change in slope at a break point appeared to be meaningful, thus indicating that additional consideration of the potential for VDG should be made.

The following are observations based on the analysis of data from a plant where VDG was quite evident. It is to be expected that the observations are generic in nature and constitute a set of applicable directions for other plants.

1. The trilinear regression performed as well as or better than a quadrilinear regression. The standard error of the regression and, hence, the correlation coefficients were the same for the analysis of the Plant Y data. Increasing the complexity of the model is not indicated since it is not likely to improve the fit. There may be instances where the quadrilinear model simply converges to the specified limits instead of a pseudo natural break point. If the BOC voltages include significant numbers of indications above about 2 volts, it might be expected that a quadrilinear model may become appropriate due to the exponential dependence of voltage on crack depth and throughwall length.
2. The analyst should reject adding additional break points to the model if the analysis results in any succeeding line slope being less than its predecessor. This applies to intermediate and final line segments. For example, a bilinear dependence would be indicated if the center segment of a trilinear fit has a slope less than that of the first segment. This caution does not apply to the insertion of the first break point, see item 3 below.

   However, suppose a trilinear fit is attempted and it is apparent that the slope of the final segment is significant while the slope of the second segment is less than that of the first

segment. One would expect the bilinear fit to result in a break point near that of the second break point of the trilinear fit. This should result from the process of minimizing the error sum-of-squares. If it is found that this is not the case, then additional analysis must be performed.

3. It is expected that there will be cases where the slope of the data in the first segment will be negative. This region of the growth curve is expected to have the a slope approaching zero even if VDG is evident in the data. VDG is controlled by the growth of the largest indications and the smallest indications would be expected to exhibit no VDG. If there were not VDG for the data, i.e., a true slope of zero, obtaining a negative slope from the data would be as likely as obtaining a positive slope due to uncertainties in the voltage measurements.
4. Although the trilinear fit is recommended because of its potential flexibility in handling growth variations, there may be occasions when the bilinear fit is acceptable. For example, a bilinear fit would be judged to be appropriate when the change between the 2nd and 3rd slopes of a trilinear fit are small.
5. Improvements in the fit in going from a bilinear to a trilinear model are not large, e.g., the reduction in the SSE can be absolutely and relatively small. This would normally indicate that the increase in complexity is not balanced by the improvement in the model. However, the use of a trilinear curve permits more sensitivity to the voltage dependent growth and therefore has an engineering advantage.
6. There may not be statistically best locations where the break points are strongly indicated, simply meaning that several choices may offer similar results. However, the analysis results do indicate where changes in the growth rate as a function of initial amplitude are likely to be occurring.

The analysis methodology for location of the break points is a recommended ARC analysis methodology.

10.4 Growth Rate in Deplugged Tubes Returned to Service

10.4.1 Introduction

In several plants with 7/8" diameter steam generator tubing, deplugged tubes returned to service have experienced a significantly larger in-service growth rate than tubes active during the prior cycle. For one of these plants, SLB leak rate and tube burst probability calculated using the actual measured voltages after one cycle of operation following deplugged tubes returned to service were found to be higher than the projections performed at the beginning of the cycle. The higher growth rates of the deplugged tubes are the primary causative factor leading to underestimates of the projections.

For ARC leak and tube burst projections following the return of deplugged tubes to service, it is necessary to account for potential growth rate increases in order to maintain margins in the projected SLB leak rate and burst analyses. To accomplish this objective, a method of combining the growth data for active tubes with those for deplugged tubes should be established. If plant-specific, historical growth data for deplugged tubes are available from prior cycles, these data can be used. If there are no plant specific prior deplugged tube growth rates, it is suggested

that a conservative growth distribution based on deplugged tube growth data available from other similarly designed and operated plants be used to provide an increased growth allowance for indications in deplugged tubes. Details of a bounding growth distribution recommended for first cycle of operation for deplugged tubes returned to service and a method for combining the growth data for previously active tubes with the deplugged tube growth data are discussed below.

10.4.2 Selection of a Bounding Growth Distribution for Deplugged Tubes

In the absence of a plant-specific deplugged tube growth database, a conservative growth distribution should be selected based on data from similarly designed and operated plants. This approach is consistent with the guidance given in Generic Letter 95-05 for selecting growth data for leak and burst analysis for plants where adequate plant-specific growth data are not available. It is recommended that a growth rate distribution that bounds all available deplugged tube data from similar plants be used. Only the growth data for the cycle in which deplugged tubes are returned to service are of interest. Deplugged tube growth rates during the second and subsequent cycles after return to service are not included since no adjustment is necessary for those cycles (i.e., measured growth rates already reflect any increase in growth rate for deplugged tubes).

At present, growth data during the first cycle of operation after returning deplugged tubes to service are available from 4 inspections, all in 7/8" tube steam generators. The cumulative probability distributions for the available growth data are plotted in Figure 10-22. The data shown for each plant represent the composite data from all SGs in the plant, and they were converted to growth rates per EFPY to account for different plant operating periods. It is evident that growth rates observed for deplugged tubes vary significantly between plants and between cycles for one plant.

Clearly, deplugged growth data for Plant A-2 envelopes the data from the other three inspections; thus, it provides an upper bound growth distribution for deplugged tubes returned to service in plants with 7/8 inch diameter tubes. It is recommended that the deplugged tube growth distribution for Plant A-2 (composite data from all SGs) be used as a conservative approximation when plant-specific data are not available for deplugged tubes. Table 10-7 provides the recommended distribution in a tabular format.

10.4.3 Method of Combining Active and Deplugged Tube Growth Data

It would be convenient to perform leak and burst calculations for the combined indication population in active and deplugged tubes. The growth distribution applied in such an analysis for the combined indication population must be representative of growth rates for indications in both active and deplugged tubes. The growth rates for active and deplugged tubes should be combined in such a manner as to reflect the fraction of the total population that each type of indication represents. It is therefore recommended that each growth distribution be weighted by the number of each type of indication returned to service. As the growth data applied to leak and burst calculations are binned in small voltage intervals (usually 0.1 volt intervals), the number of

indications in bins defining the composite growth distribution should be established per the equation below.

$$n_{i,comb} = \left(\frac{n_{i,ag}}{n_{t,ag}}\right) \times N_a + \left(\frac{n_{i,dg}}{n_{t,dg}}\right) \times N_{dp}$$ **Equation 10-11**

where,

$n_{i,comb}$ = number of indications in the ith bin of composite growth distribution,

$n_{i,ag}$ = number of indications in the ith bin of active tube growth distribution,

$n_{i,dg}$ = number of indications in the ith bin of deplugged tube growth distribution,

N_a = total number indications in active tubes returned to service,

N_{dp} = total number indications in deplugged tubes returned to service,

$n_{t,ag}$ = total number indications in the active tube growth distribution,

$n_{t,dg}$ = total number indications in the deplugged tube growth distribution.

The active and deplugged tube growth data used to define the composite distribution must be normalized to the same cycle duration, say one year, prior to combining them. The above equation results in normalizing the active and deplugged tube growth distributions to the corresponding number of indications returned to service. The $n_{i,comb}$ values define the cumulative probability growth distribution for the combined active and deplugged indications.

Table 10-8 shows an example of composite growth data established by combining growth data for active tubes (obtained from prior cycles) and the limiting growth data for deplugged tubes recommended above. The three growth distributions are also illustrated in Figure 10-23.

10.4.4 Comparison of Leak and Burst Projections Considering Increased Deplugged Tube Growth with those Based on Actual Voltages

Benchmarking analyses were performed to support the proposed method of obtaining a composite growth distribution considering both active and deplugged tube growth data for use in SLB leak and burst projections. Results projected with the composite growth distribution were compared with those based on the actual measured voltages. Two of the three plants for which deplugged tube growth data are available were chosen for benchmarking: Plants A-2 and P. The limiting growth distribution recommended above for the deplugged tube indications actually occurred in the cycle selected for Plant A-2. The actual growth observed for deplugged tubes was used to project EOC conditions for Plant A-2. With Plant P, tubes were deplugged and returned to service in two consecutive cycles. Therefore, deplugged tube growth rates for the first cycle having deplugged tubes returned to service were used to project EOC conditions for the next cycle.

Table 10-8 shows the growth distributions for indications in active and deplugged tubes for Plant A-2 as well as the composite growth distribution obtained using the method described above. Growth rate data for the active tube indications were taken to be the higher of growth data for the prior two inspections. The active tube indication growth distribution shown is based on data from 81 indications, and the deplugged tube indication growth distribution is based on data from 111 indications. For the cycle simulated, there were 97 indications in active tubes and 89 indications in deplugged tubes returned to service. The composite growth distribution obtained by weighting the two growth distributions by the number of each type of indication returned to service is shown in Table 10-8.

Results from leak and burst projections as well as those based on the actual EOC measured voltage distribution for Plant A-2 are summarized in Table 10-9. Leak and burst analyses were carried out for the following four cases:

1. Considering only indications in tubes active in the previous cycle.
2. Considering only indications in deplugged tubes returned to service.
3. Based on combined EOC voltage distribution for Cases 1 and 2 (more rigorous application of upper 95% leak rate than adding Cases 1 and 2).
4. Calculations for the combined active and deplugged tube population using the composite growth distribution shown in Table 10-8.

For the actual distribution, SLB leak rate and tube burst probability calculated using a NDE analyst uncertainty consistent with GL 95-05 (standard deviation of 10.3%) are 2.8 gpm and 8.2×10^{-4}, respectively, (Case 1 in Table 10-9). The actual voltage distribution includes 41 indications over 2 volts, and over 65% of the leak rate and 75% of the tube burst probability resulted from those indications. The NDE uncertainty of 10.3% was developed from analyses of indications dominantly less than about 2 volts. Comparisons of independent NDE analyses for indications above 2 to 3 volts have shown excellent agreement, and the NDE uncertainty would be bounded by about 5% or less. Therefore, the actual EOC calculations were repeated using a NDE uncertainty of 5%, and the leak and tube burst probability decreased to 2.6 gpm and 5.8×10^{-4}, respectively (Case 2 in Table 10-9). Results based on 5% NDE uncertainty are judged to be more accurate estimates for comparison with projected values.

Table 10-9 also shows the leak and burst projections performed for the same cycle considered in the analysis with actual volts. Results obtained using a constant POD of 0.6 as well as a voltage-dependent POD distribution (POPCD) presented in Reference 10-6. The application of POPCD provides results which are not artificially made conservative using a POD value too conservative for indications over about 1 volt. The analyses utilize leak rate not correlated with voltage (applicable ARC method at the time of the Plant A-2 inspection).

Case 3 in Table 10-9 shows leak and burst results obtained using the standard methodology without distinguishing indications in active tubes from those in deplugged tubes. It is evident that the predicted maximum EOC volts, SLB leak rate and tube burst probability are significantly below the corresponding values based on the actual EOC distribution. Cases 4 through 8 in Table 10-9 utilize the POPCD distribution for POD adjustment. Case 4 shows leak and burst results obtained considering only indications present in tubes active during the last cycle, and Case 5 shows the results for only indications in deplugged tubes calculated using the limiting

growth distribution recommended for deplugged tubes. Straight addition of leak rates and tube burst probabilities calculated separately for the active and deplugged tubes would not necessarily represent results for the combined population at the 95%/95% limit. To obtain leak and burst values at the 95%/95% limit for the combined indication population, EOC voltage distributions calculated separately for the active and deplugged tube indications were combined, and an additional leak and burst calculation was performed for the combined EOC distribution. No NDE uncertainties or POD correction were applied to the combined EOC voltage distribution since these factors are already included in the individual voltage projections. Case 6 in Table 10-9 shows the results for the combined EOC voltage distribution, and the results compare well with those based on the actual measured voltages and NDE uncertainty of 5%.

Case 7 in Table 10-9 shows results obtained by applying a composite growth distribution calculated as described in Section 10.4.3 to the combined active and deplugged tube population. The peak EOC voltage, leak rate and burst probability values are essentially the same as those obtained by combining the EOC voltage distributions calculated separately for the active and deplugged tubes. This demonstrates acceptability of a single analysis for the combined active and deplugged tube indication population by applying a composite growth distribution calculated as described in Section 10.4.3. Thus, instead of calculating EOC voltage distributions separately for the active and deplugged tubes and then performing leak and burst calculations for the combined EOC voltage distribution, a single analysis can be performed for the combined active and deplugged tube indication population by applying a composite growth distribution calculated as described in Section 10.4.3.

The recommended growth distribution for deplugged tubes (shown in Table 10-7) is based on combined data from all SGs in the inspection chosen for the benchmarking calculations. The specific SG for which calculations were performed had a slightly larger growth rate than the all SG composite growth. Therefore, calculations for Case 7 in Table 10-9 were repeated using the SG-specific growth for deplugged tubes and the results are shown under Case 8. The use of SG-specific growth for the deplugged tubes improved the agreement between the projected results and those based on the actual measured voltages, but the absolute magnitude of the impact is small. Since the all SG composite distribution is based on a larger number of data points (111 vs. 89 for the largest SG-specific distribution), it is recommended for leak and burst projections.

Case 9 in Table 10-9 shows the results when a constant POD=0.6 is utilized along with the composite growth distribution. The predicted leak rate exceeds that calculated based on actual measured and NDE uncertainty of 5%. The corresponding burst probability values are within about 10^{-4} which is considered as good agreement.

For ARC analyses applying a POD of 0.6, the indication population in deplugged tubes returned to service was not adjusted with a POD factor because all indications in such tubes are adequately detected compared to a detection probability of 60%. However, the POD factor also accounts for new indications formed during the cycle analyzed. Available data for the first year of operation of deplugged tubes returned to service were examined to ascertain if a significant number of new indications are detected, and the results are summarized in Table 10-10. It is evident that new indications found in the first inspection after return to service vary from 0% to 11.7% of the total indication detected, with an average of about 8.3%. Thus, the number of new indications appearing in deplugged tubes is much smaller than the 67% implied for the NRC mandated POD=0.6. It is recommended that while performing leak and burst projections using

voltage-dependent POPCD, the POD factor should be applied to BOC indications in deplugged tubes also. This was done for Cases 3 through 8 in Table 10-9. Results shown in Table 10-9 for a constant POD of 0.6 (Case 9) were obtained without applying a POD correction for deplugged tube indications. Good agreement between these results and those based on the actual measured voltages indicate that additional conservatism introduced by applying the conservative POD=0.6 to deplugged tube indications is unnecessary. Therefore, a POD adjustment for deplugged tube indications is not recommended when a constant POD of 0.6 is applied.

It is evident from leak and burst projected results for Cases 6 and 7 that projections based on POPCD slightly under predict those based on the actual voltages. To find a means for further improving the agreement between projected and actual results, the growth data for active and deplugged tubes were examined more closely. Figure 10-24 shows growth data for the deplugged tubes plotted against the beginning of cycle (BOC) voltage (composite data for all SGs). Examination of data in Figure 10-24 suggests that beyond about 1 volt at BOC the proportion of indications in a selected voltage range experiencing larger growths (say, above 0.5 volt) appears to increase with the BOC voltage, which suggests that the growth rate for deplugged tubes increases with the BOC voltage. Therefore, a second set of calculations was performed considering deplugged tube growth rates to be dependent on BOC voltage. The guidelines for binning growth data to account for dependency on BOC voltage used for this analysis were based on judgment for the break points as these analyses preceded that given in Section 10.3. There are about 50 indications in the BOC voltage range above 1.2 volts. Therefore, the deplugged tube growth data were represented by two separate growth distributions, one representing BOC voltages up to 1.2 volts and the other above 1.2 volts, and they were used in the analyses to project EOC conditions. These two distributions are shown in tabular form in Table 10-11 and in graphical form in Figure 10-25. It is evident that indications with a BOC voltage above 1.2 volts show a higher probability of experiencing larger growth. In the analysis for the combined active and deplugged tube population, the combined growth data were also split into two groups and the active and deplugged data for each group were combined to obtain a composite distribution for each BOC voltage range using the methodology discussed in Section 10.4.3.

Results for projection analysis using voltage-dependent growth are also shown in Table 10-9 (Cases 10 to 12). It is evident that the use of voltage-dependent growth simulation slightly increased the peak voltage and burst probability values, but the leak rate values did not change significantly from Cases 5 to 7. The impact of voltage-dependent growth varies with the BOC voltage distribution, and the effect could be significant in other cases. It is recommended that voltage dependency of growth rate for deplugged tubes be considered only when the active tube growth data also show dependency on BOC voltage. Table 10-12 shows the actual growth (per EFPY) vs. BOC voltage data for the recommended limiting growth distribution. This data should be used if it is necessary to split the growth distribution at a BOC voltage other than 1.2 volts.

Results from projection analyses performed for Plant P are shown in Table 10-13. As noted earlier, plant-specific deplugged tube growth rates obtained from one cycle can be used to project EOC conditions for a subsequent cycle in which additional deplugged tubes were returned to service. Cases 2 and 5 in Table 10-13 show leak rate and tube burst probability values calculated by applying the same growth rate distribution for active and deplugged tubes that was determined using the standard methodology (Reference 10-6). These cases utilize a

conservative POD value of 0.6; therefore, the results are higher than those based on the actual voltages. The analysis utilizing a composite growth based on active and deplugged tube growth rates use more realistic POD values given by the POPCD distribution (Cases 3 and 6 in Table 10-13), and those results are also conservative relative to those for the actual conditions. The reason for both projection results based on POD=0.6 and EPRI POPCD over predicting those based on the actual measured voltages is that the actual growth during the cycle simulated was less than that assumed in the projections. Also, growth rates in deplugged tubes returned to service were comparable to those in the active tubes, and they were less than the deplugged tube growth rates assumed in the projection.

10.4.5 Conclusions

Data available from several plants indicate that indications in tubes deplugged and returned to service may experience a significantly higher growth rate in the first cycle of operation than those in tubes active in the prior cycles. Therefore, analysis to project EOC leak rate and tube burst probability for a cycle in which deplugged tubes are returned to service should account for potentially larger growth rates for deplugged tube indications. The following guidelines are provided regarding the method of calculating leak rate and tube burst probability for the combined indication population in active and deplugged tubes, and selection of growth data for deplugged tubes.

A single analysis is recommended for the combined active and deplugged tube indication population. The growth distribution applied to the combined indication population should be representative of both active and deplugged growth distributions.

If plant-specific data is not available for growth in deplugged tubes, the limiting growth distribution in Table 10-7, which was obtained considering data from several plants, should be used.

An acceptable method of combining growth distributions for indications in active and deplugged tubes is shown by Equation 10-11. The two growth distributions are weighted by the number of indications in active and deplugged tubes returned to service.

For the limiting growth distribution suggested for deplugged tubes, growth dependency on BOC voltage needs to be considered only when the growth data for active tubes also show a similar dependency. A method for considering voltage-dependency of growth is described in Section 10.3 of this report.

When the voltage-dependent POPCD distribution is used, the POD correction should also be applied for indications in deplugged tubes returned to service. However, if a constant POD of 0.6 is applied, POD adjustment for deplugged tubes is not recommended since there is significant conservatism already present when POD=0.6 is applied.

10.5 Extreme Values of ODSCC ARC Indications or Growth

This section describes a methodology for incorporating allowances for extreme growth values in the ARC operational assessments. These methods were submitted for NRC approval in July 2004 for inclusion in ARC analyses upon NRC approval to apply POPCD (see Section 7 of this report) rather than a POD of 0.6 for the analyses and are not intended for analyses applying the GL 95-05 POD of 0.6.

There have been infrequent occurrences of large voltage growth rates in ARC inspections. In most cases, particularly for 7/8 inch tubing, the occurrences of large growth rates appear to be random events. The rapid exponential increase in voltages near and at throughwall crack penetration and the additional approximately exponential increase in voltage with throughwall length appears to be a principal contributor to the large growth rates. The extreme values for voltage growth can occur without correspondingly large average depth growth rates.

The extreme value methodology of this section is based on the probability of occurrence of a large growth rate based on historical data. Separate probabilities would be applied for 3/4 and 7/8 inch tubing based on differences in the historical probabilities of large growth values. Table 10-14 provides the historical values for extreme growth rates for both tubing sizes. As of Addendum 7, NRC approval has not been received. Upon NRC approval of the extreme value methods, Table 10-14 together with the number of historical ODSCC indications in each tubing size are to be updated in future ARC addenda.

10.5.1 Introduction

Alternate repair criteria (ARC) have been in use for outside diameter stress corrosion cracking (ODSCC) indications in steam generator (SG) tubes since the early 1990's[1]. The criteria apply to tubes in Westinghouse SGs with drilled hole tube support plates (TSPs) when the cracking is confined to the crevice between the tube and the TSP. A detailed description of the criteria and the conditions for their application is provided in Generic Letter (GL) 95-05, Reference 10.7, issued by the United States Nuclear Regulatory Commission (NRC). The ARC replace the 40% depth criterion generally used for SG tube degradation with a repair limit based of the eddy current test (ECT) bobbin coil amplitude. The ARC plugging limit for plants with 3/4 inch nominal diameter tubes is 1 volt and the limit for plants with 7/8 inch diameter tubes is 2 volts.[2] Typical maximum or extreme indication amplitudes are usually expected to be on the order of 5V. The largest value found in an inspection of a SG is an extreme, although extremes may also be defined as any indication exceeding a specified threshold. The values meeting the latter definition are usually referred to as exceedances. Five methods were evaluated in Addendum 6 (Reference 10-23) for potentially including the influence of extreme growth values in the ARC analyses. The recommended method is described in Section 10.5.6 and is based on sampling the frequency and distribution of large extreme growth values, which are dependent upon tube size based on historical data. This extreme growth methodology is to be applied in conjunction with

[1] The first applications were referred to as interim plugging criteria or IPC.

[2] Specific exceptions to these standard limits have been approved for use by the NRC staff on a case basis.

the use of POPCD as the licensed POD since the use of a POD of 0.6 already includes large numbers of high voltage indications in the BOC distribution.

An indication with a bobbin coil inspection amplitude of 21.5 Volts (V) was found during the 2003 inspection of the SG tubes at Diablo Canyon 2, References 10-8, 10-9 and 10-10. The large end-of-cycle (EOC) amplitude resulted from a growth rate of 11.9V per effective full power year (EFPY or EY) during the previous plant operating cycle with a hot leg temperature of 603°F. Both the end-of-cycle amplitude and the growth of the indication would be considered to be unusually large extreme values and are very rare. A destructive examination of the indication showed that it had a large throughwall length and extended through the thickness of the tube, a combination that is expected given the amplitude of the indication, but is not normally anticipated to be associated with the application of the ARC. The probability of leak (POL) for TSP ODSCC indications in 7/8 inch diameter tubes is illustrated on Figure 10-26. The probability of leak under steam line break (SLB) conditions, roughly equivalent to being throughwall during operation, is about 5% for a 2 volt indication and 99% for a 20 volt indication. The occurrence of such an indication is not restricted to tubes where the ARC have been implemented. The random occurrence of extremely large indications would be less likely when the standard 40% depth plugging criterion is being applied because the corresponding size of the indications at the beginning of the operating cycle would be expected to be smaller. Regardless, it is desired that actions be taken to better understand the potential for significant extremes to occur along with their attendant consequences relative to plant performance during a postulated SLB situation.

One of the ARC requirements is that the total or joint probability of burst (POB) of all of the TSP ODSCC indications in a single SG should not exceed $1 \cdot 10^{-2}$ during accident event conditions when the ARC are being applied. The POB of the Diablo Canyon indication was calculated to be relatively significant. While the results from the destructive testing of the pulled tube section demonstrated that all performance criteria were met, the calculation result based only on the nondestructive examination (NDE) measurements indicated that the POB criterion of the ARC was exceeded, i.e., a 95% one-sided upper confidence value for the POB was calculated to be $2.4 \cdot 10^{-2}$ per Enclosure 4 of Reference 10-9. The calculation leads to a statistical prediction of what might happen. Although all indications are constrained from burst by the presence of the TSP during normal and most other operating conditions, the elevation of the TSPs has been assumed to shift relative to the tubes during the usual limiting accident condition of a postulated steam line break (SLB) event. The primary-to-secondary pressure can reach a peak value on the order of 2405 to 2560 psi, corresponding to pressure relief valve set points of 2335 and 2500 psi respectively, at a temperature on the order of 600°F near the terminus of such an event.

The magnitude of the maximum observed growth is relatively rare and the next largest voltage growth was found to be 3.0V per EFPY at Diablo Canyon. However, none of the methodologies employed for predicting the growth of indications remaining in service would lead to the expectation of a value on the order of that observed, including methods that consider the potential for growth to depend on the magnitude of the indication at the start of the cycle. Singularly large growth values have been observed at several plants during the 10-year application history of the ODSCC ARC. Thus, while the observation at Diablo Canyon 2 is relatively rare, it is not unique. In greater than eighty (80) applications of the ODSCC ARC there have been few extremes, or outliers as they have been referred to. There have been three (3) indications in 7/8 inch diameter tubes that have exhibited a growth in excess of 5V/EY when

adjusted to an operating temperature of 603°F, including the most recent Diablo Canyon 2 indications. Moreover, the frequency of occurrence of indications greater than 5V/EY does not appear to be increasing.

The concern to be addressed from this observation is the development of a model aimed at predicting singularly large values of amplitude growth. The largest indication that is found in any single inspection is the extreme value for that inspection, thus it is the appearance of very large extremes of growth that is to be accounted for. However, it must be recognized that individual occurrences of the largest extreme cannot be predicted. The historical approach to compensating for the lack of a direct prediction model for large growth rates was employed in the GL in the form of using a uniform probability of detection (POD) of ODSCC indications of 0.6. Simply put, for every three indications detected during an inspection of the SG tubes, two indications of the same magnitude are assumed to go undetected. The number of indications present at the beginning of a operating cycle is calculated as,

$$N = \frac{N_D}{POD} - N_P + N_R \qquad \textbf{Equation 10-12}$$

where N_D is the number of indications detected during the inspection, N_P is the number of indications plugged, and N_R is the number of previously plugged indications returned to service. The application of a uniform POD means that a large number of significant indications are assumed to be initially present when the plant starts up following an inspection for the purpose of predicting the level of degradation at the end of the next period of operation. However, the largest indications are typically in the range of 5 to 6V with maximum observed growth rates on the order of 3V, thus the maximum end-of-cycle (EOC) predicted amplitudes would not exceed the 9V structural limit. Hence, the rationale for the use of 5V/EY is based on the consideration of adding 5V growth to a 2 to 4V indication effectively remaining below the 7/8 inch diameter tubes structural limit as defined in Reference 10-7.

The use of a uniform value for the POD of 0.6 was originally conceived by the NRC staff to account for both the probability of detection and the initiation of new indications. It has been demonstrated through experience to frequently provide conservative predictions of the number of indications present at the next inspection, however it does not result in a good prediction of the distribution of the indications nor does it, or can it, result in the prediction of the largest extreme values.

In order to address the problem of predicting the value of the extremes, or exceedances, a good predictor of the number of indications is needed. The industry has developed a methodology for predicting the number of indications and their severity based on using information available at the current inspection to update the probability of detection as a function of indication amplitude observed at the previous inspection. The POD thus calculated is then used predict the number and distribution of amplitudes expected to be found in the following inspection. The method has been designated as the probability of prior cycle detection (POPCD) and has been demonstrated to agree fairly well with inspection data, see Reference 10-11 (four more addenda provide additional data to support the application of the methodology).

10.5.2 Regulatory Topics of Interest

Information gleaned from the several discussions with the NRC staff on the subject of the Diablo Canyon ODSCC degradation indicates that their interests parallel that of the industry, e.g., Reference 10-12. There are several items of interest regarding the performance of the ODSCC ARC process and the results of subsequent evaluations. Of course, one must identify what is to be classified as an extreme, for example, an indication is an extreme if its magnitude of degradation is outside of the expected bounds, i.e., an exceedance. The concept of a trigger voltage based on the probability of burst could also be considered based on the number of indications that could be permitted to occur. For example, if the ARC POB is limited to $1 \cdot 10^{-2}$, any indication with a POB of $2 \cdot 10^{-3}$ might be considered to be an extreme. it also appears from the discussions that it is technically desirable to keep track of normal and extreme values for the POB and growth rate, however, this is somewhat impractical because there are no criteria that could be applied based on the results of the calculations.

10.5.2.1 Function of the Analysis

The primary function of the analysis is to demonstrate whether or not the requirements of GL 95-05 were complied with, e.g., to demonstrate that the results of the inspection of the tubes are consistent with meeting the 5% criterion for the probability of burst. Recall that the total probability of burst limit is $5 \cdot 10^{-2}$, but that one-fifth of that or $1 \cdot 10^{-2}$ is allotted for the ODSCC ARC. In keeping with the spirit of that requirement, if the probability of burst of the extreme indication is the only thing that results in exceeding the limit then the probability of an extreme should be low. If an extreme is going to cause leakage in excess of the limit, you have to quantify the frequency of occurrence. The assumption of an extreme value may increase the probability of not meeting the performance criteria.

The second primary function of the analysis is to determine if the process of implementing the ARC is maintaining an understanding of the initiation and progress of the degradation under technical control, i.e., it must be verified that the methodology is not degrading in its ability to reliably estimate the consequences associated with a postulated SLB event.

Consideration must also be given with regard to the potential for multiple phenomena to be active, e.g., causative as at Diablo Canyon or potentially random as for an indication in one of the Braidwood 1 SGs prior to their replacement (the prior inspection amplitude was small). This is based on the supposition that extremes for cause, if such can be identified, are potentially different than those from random occurrence and implies the need to understand the source for those extremes or exceedances. With regard to dealing with root cause, consideration has been given to implementing ameliorative measures, e.g., the increased use of lower RPC information. Enclosure 1 to Reference 10-2 provides guidelines for supplemental RPC inspection of indications with bobbin amplitudes below the ARC repair limit to increase the likelihood of identifying those ODSCC indications with large +Point amplitudes for 7/8 inch diameter tubes. The expressed rationale is that large +Point voltages are indicative of an increased potential for large growth during the next cycle of operation. Moreover, quantitative guidelines are provided for preventive tube repair at less than the licensed voltage based repair limit to reduce the potential for large voltage growth rates for indications left in service.

10.5.2.2 The "Fractional Flaw Paradox"

In References 10-13 and 10-14 the NRC staff discussed the use of a variable POD, i.e., a POD that is a function of the indication size; the application of the probability of prior cycle detection, POPCD, is such an approach. The NRC staff discussed what they first termed the "paradox" of the use of a fractional flaw approach associated with the use of a variable POD in Reference 10-13 with regard to analysis information presented in Reference 10-15. The fractional flaw referred to is the mathematical construct that results from the application of Equation 10-12 to the number of indications found. The fraction term in the Equation 10-12 leads to the need to consider a fraction of an indication for each indication found. For example, a POD of 0.6 results in the consideration that 1.7 flaws were actually present when one indication was detected. If the detected indication is removed from service, 0.7 of an indication must be considered to remain in the SG. When the POD is a function of the size of the indication, say area or depth, the fraction remaining will vary by the size of the detected indication population; the detection and plugging of an indication with a POD of 0.8 results in 0.3 of a like indication being considered to remain undetected. The method used for the treatment of the fractional indications per Reference 10-15 was to accumulate the fractional indications into groups summing to one indication. "Profiles with fractional indications from the POD corrected are grouped from highest to lowest depth until the sum of the fractional indications totals unity to define a POD group number for burst pressure distribution calculations. In the Monte Carlo sampling for a POD group, the profiles comprising the group are sampled at the frequency of their contribution to unity for the group." The POD group represents a single indication in each Monte Carlo simulation analysis but the initial morphology of the indication changes from simulation to simulation. The POD group concept is used to assess whether each POD group satisfies the burst pressure margin requirement, but does not influence the burst probability calculation compared to the ODSCC ARC methods for evaluating fractional indications.

The paradoxical concern as described by the NRC staff in Reference 10-13 was as follows:

> "In certain situations, the fractional flaw approach appears to lead to a paradox when used in conjunction with a variable POD. As an illustration, plant A experiences a tube rupture near the end of its operating cycle after a flaw grows to 90% through wall. A look back analysis of the failed tube indicates that a 70% through wall flaw was present during the previous inspection but was missed. No other indications are found. Because the POD of a 90% through wall flaw is essentially 1, no corresponding fractional flaw needs to be considered in the operational assessment." On the other hand, plant B shuts down for its planned inspection outage. The inspection reveals one flaw, 60% through wall. A look back analysis indicates that a 40% through wall flaw was present during the previous inspection but was missed. The POD for a 60% flaw is less than 1, so a corresponding fractional flaw must be assumed in the operational assessment. Plant B's operational assessment will predict a larger flaw to be present at the end of the next operating cycle than plant A's."

Evidently the staff considered the paradox of this example to be the fact that Plant B has to assume that a flaw will be present at the end of its next operating cycle while Plant A does not, even though it was Plant A that had the forced outage due to a tube rupture event. There is no paradox associated with this discussion, simply the stating of one of the random events that could occur in an extreme situation without consideration of its probability of occurrence. This line of reasoning would lead the staff to a similar conclusion in any situation where an one severe event

was postulated to occur more frequently than a more likely event. Moreover, the example doesn't have anything to do with the application of the fractional flaw methodology. The appropriate operational assessment (OA) methodology to address the "paradox" is that the Plant A POD used for the OA should be sufficiently degraded such that there is a much higher probability of not detecting a 70% or deeper flaw than the POD applied for Plant B.

The NRC staff's conclusion from the example was that an alternative to the "fractional flaw" approach would be needed to provide for a realistic analysis when using a variable POD assumption. The NRC staff reiterated the above concern in Reference 10-14 as:

> Issue 9: Use of a "fractional flaw" method or other similar methods for determining a beginning-of-cycle flaw distribution may lead to nonconservative results when used in conjunction with a POD parameter that varies as a function of flaw size or voltage.

The NRC staff noted that the issue derived from their review of the Indian Point 2 (IP-2) licensee's operational assessment, i.e., Reference 10-15support restart after the SG tube failure event on February 15, 2000. The staff went on to state that

> "...the fractional flaw method is based on the assumption that for each flaw found by inspection, there are flaws of the same size which were not detected by the inspection. For each detected flaw of a given size, the number of undetected flaws of that size is assumed equal to 1/POD - 1. This methodology has been approved by the staff for implementing voltage-based alternate repair criteria in accordance with NRC Generic Letter 95-05 and for implementing an alternate repair criterion for PWSCC at dented tube support plates. For these applications, licensees are currently assuming a constant POD of 0.6.
>
> The fractional flaw method was recently used in an operational assessment of small radius U-bend PWSCC at IP-2. However, the operational assessment used a POD parameter that varied with crack size. The effect of the variable POD function in conjunction with the fractional flaw method made the results of the analysis insensitive to the size of the indications found by [the] inspection. The staff considered this finding unrealistic."

The industry's response, Reference 10-16, was as follows, in summary, the use of a variable POD (dependent upon depth, area, or volts) that results in fractional indications for the undetected population is technically correct and appropriate for operational assessments. The appropriateness of this POD technique is not dependent upon specific Monte Carlo applications, wherein the undetected indications can be evaluated as fractional indications for each SG sample or as whole indications occurring in SG samples at the fractional frequency. The application of variable PODs correctly simulates the inspection process and does not arbitrarily introduce conservatism or non-conservatism in an operational assessment. Interpretation of the IP-2 example as a non-conservative basis for requiring a constant POD introduces arbitrary conservatism that inhibits benchmarking and the causal assessment of finding larger indications in an inspection such as larger growth rates or a poor prior cycle POD.

10.5.2.3 Extreme Growth of Indications at V. C. Summer

Five atypical voltage indications were found in SG B at the V. C. Summer plant in 1993, Reference 10-17. A summary of the indications is provided in Table 10-15, note that all of the indications were at the elevation of the flow distribution baffle (FDB). Sections of the tubes in locations R28C41, R33C20, and R42C43 were removed for examination to ascertain the strength and the root cause of the tube indications. Each of the indications was found to have regions that were 100% of the tube wall thickness deep over lengths ranging from 0.33 to 0.50 inch. The presence of the FDB would have prevented the burst pressure of the tubes falling below the $3\Delta P$ structural performance criterion. An analysis of the FDB displacement during postulated SLB conditions resulted in the conclusion that the $1.4\Delta P_{SLB}$ structural performance criterion would have also been met.

The examination of the pulled tube sections demonstrated that the cause of the high growth rates of the indications was the presence of high cation-to-anion ratios in a copper oxidizing environment. It was also concluded that there was a synergistic relationship between three causative factors, dissolved copper species, a localized caustic environment, and a partially packed hot leg flow distribution baffle (FDB) location. The copper plays a direct role in accelerating the crack growth; the presence of the copper resulted from an incomplete copper removal step in chemical cleaning the SGs during a prior outage. The analysis of the SG blowdown sodium and chloride data indicated that an alkaline environment was likely which led to strong caustic environments in regions of high superheat, provided by the partially packed crevice locations. The partially packed FDB crevices were identified as being more susceptible to rapid growth over short periods of chemistry imbalance due to the greater surface area of the crevice deposits and higher superheat which facilitated the accumulation of impurities. The potential for a reoccurrence of the V. C. Summer incident is unlikely and modification of the ODSCC ARC analysis methodology to account for such a possibility is unrealistic and impractical.

10.5.3 Objective of the Analyses

The overall objective of the ODSCC ARC analyses is to demonstrate compliance with the requirements of Reference 10-7 with regard to the probability of burst of tubes with ODSCC at TSP intersections and the total leak rate that could result from those same tubes during a postulated SLB event. Two such demonstrations are required, one for the as-found condition of the SG tubes at the time of the inspection and one for the projected condition of the SG tubes at the end of the next operating cycle. These evaluations are referred to as Condition Monitoring (CM) and Operational Assessment (OA) respectively. Monte Carlo simulations of the size of the ODSCC indications, the material of construction of the SG tubes, and the error associated with predicting the burst pressure as a function of the bobbin amplitude are performed to demonstrate compliance with the structural requirement of Reference 10-7 that the probability of burst of one or more tubes with ODSCC indications is less than $1 \cdot 10^{-2}$. The second portion of the tube integrity evaluation results in the prediction of the total primary-to-secondary leak rate that could be expected to occur during a postulated SLB event and a comparison of that result against an allowable value that is within the licensing basis for the plant. The size of the indications, the growth rate, and the probability of leak and the leak rate from indications that leak as a function of the size of the indications is simulated for the leak rate analysis. The details of the

methodology are described in Reference 10-2. A projection of the distribution of the size of indications that might be present at the end of the next operating cycle based on the probability of detection of the current indications and their potential growth during the next operating cycle is required for the performance of the Operational Assessment.

There are two approaches that were considered as exemplifying the objective of the analysis. The first is based on modifying the simulation process so as to increase the total growth rate reported for all analyses of SG indications. The second is based on changing the reporting philosophy so that two values of the total growth rate are reported, the expected 95th percentile and an unexpected 95th percentile. There are merits to both approaches, however, it is the statistics that are important to demonstrating safe operation of the plant that are important while maintaining compliance with current regulatory requirements. The first approach is considered to be such that it can be implemented within the current guidance of the ODSCC ARC generic letter, Reference 10-7, because additional conservatism is introduced and the reporting requirements for the results are unchanged.

One potential methodology that adds conservatism to the analysis consists of simulating a large extreme of the growth rate with a representative frequency and include it in the growth rate analysis. The net effect will be that the 95th percentile total growth rate will increase slightly because the extreme growth rate will always be the maximum value in the sorted list of growth rates.

As an example, suppose the number of simulations performed was 1000. The 95th percentile growth rate at 95% confidence is the 961st value in the list of results once the simulations have been completed and the results sorted in ascending order. Suppose now, that the simulation process has been modified to include the potential for extreme values to occur in the Monte Carlo analysis. Extremes would not be expected to occur during all of the simulations, but for those simulation where extremes were predicted to occur, they would become the 1000th value in the sorted list. If one simulation included an extreme value, the list element that would have formerly been number 962 would be shifted into the 961st position and would be reported as the 95th percentile at 95% confidence. The net effect being that the reported value from the condition monitoring and operational assessment simulations would be increased slightly, or significantly depending upon the frequency assigned to the large extreme values and the slope of the leak rate curve near the 95th percentile. While this approach adds conservatism to the reported results of every analysis, there would still be situations where an extreme growth value would occur and not be bounded by the operational assessment from the previous cycle. However, the nature of extremes is that the timing of the occurrence of the largest extreme cannot be predicted only the probability that the extreme in any given analysis will be bounded by some calculated value.

The second approach considered was to address the issue of extremes of the growth rate directly by reporting the expected 95th percentile of the probability of burst and the growth rate without extremes being present and the POB and the growth rate with extremes being present along with the probability of the extreme occurring. This information would be expected to be of the most use to anyone performing risk-based integrity calculations with regard to the SG. However, such reporting is not within the current framework associated with GL 95-05, Reference 10-7, and the acceptance criteria associated with such a change to the methodology would likely require regulatory approval. Since the probability of a large extreme would be based on historical data

and is not like to change dramatically with future inspections, acceptability can only be based on the results of risk-based integrity calculations.

In summary, the modification of the analysis to account for the potential for large extreme values to occur for each analysis of the SGs is recommended on the basis that it can be incorporated within the current regulatory requirements of Reference 10-7 without changing the reporting requirements.

10.5.4 Distribution of ODSCC ARC Growth Rates

Experience has shown that large extremes of the growth rate appear infrequently, as expected. Extremes of growth affect both the probability of burst and the 95th percentile predicted total leak rate. The appearance of large extremes is expected to be random in nature, although there is a significant example where the extremes occurred for cause, i.e., the previously discussed incident at the V. C. Summer plant was such a case and would not be expected to be applicable to the prediction of the appearance of large extremes at other plants. Singularly large growth rates are observed infrequently, that this occurs is simply due to the fact that the maximum values from repeated sample observations from a population of data follow a different distribution than the parent distribution of the data. The appearance of large extremes has historically been more frequent in SGs with 3/4 inch diameter tubes than in SGs with 7/8 in diameter tubes. Several were in the SGs at a single plant, ostensibly due to the operating conditions, e.g., high temperature, in those SGs.

10.5.4.1 Analysis of SG Data

An analysis of data from SG 2-4 at Plant Y illustrates the growth rate model; the distribution is illustrated on Figure 10-27 for indications exhibiting positive growth. The fit of the lognormal distribution to the histogram data is quite strong and further illustrated on Figure 10-28 the ordered raw data. A normal distribution plot of the logarithmic data is shown on Figure 10-29. The replication of results in the lower tail of the distribution, first shown on Figure 10-27 is a result of the lack of resolution of when the bobbin amplitude is small.

10.5.4.2 Generic Letter Requirements

The requirements of the GL allow for the distribution of the growth rate to be considered as an empirical distribution function (EDF) or by fitting a functional cumulative distribution function (CDF) equation to the data. It is noted in the GL that it is intended that the analysis conservatively model the tail of the distribution of the growth rate of the ODSCC indications. It is also stipulated that the growth rate can be modeled in units of Volts, viz. ΔVolts, or as a percent of the previous voltage amplitude, viz. percent ΔVolts. There is guidance provided in Reference 10-7 relative to the use of a functional growth rate instead of an empirical distribution function, to wit,

> "It is acceptable to use a statistical model fit of the observed growth rate distribution as part of the tube integrity analysis provided that the statistical model conservatively accounts for the tail of the distribution. It is also acceptable that the voltage growth

distribution be in terms of Δ volts rather than percent Δ volts, provided the conservatism of this approach continues to be supported by operating experience. For the purposes of assessing the conditional probability of burst and conditional growth rate, negative growth rates should be included as zero growth rates in the assumed growth rate distribution. However, for the purposes of determining the upper voltage repair limit in accordance with Sections 2.a.2 and 2.a.3, it is appropriate to consider negative growth rates as part of the estimate for average growth rate."

The following are some examples of modeling the growth that would be acceptable within the framework of the generic letter:

1. Model the probability of an indication exhibiting positive growth binomially, for example, the probability of an indication exhibiting positive growth is 90%. This simply accounts for the occurrence of large extremes directly.
2. Model the distribution of growth using a lognormal distribution for example. This type of approach to modeling empirical was specifically mentioned in Reference 10-7 regarding the leak rate data.
3. Model the distribution of extremes of the growth using an appropriate distribution for the expected maximum value in any given sample. The extremes of the lognormal distribution follow a Gumbel distribution.[3]

In this manner the probability of occurrence of a large extreme value would be expected to be predicted as described by the first approach described in this report.

10.5.4.3 Root Cause of Extreme Growth

The appearance of extreme growth of an indication is with respect to the bobbin amplitude. For example, the indication in the Plant Y tube increased to an amplitude level of 21.5V. This does not mean that there was an extreme level of growth in either the depth or the length of the indication. Historical information was presented in References 10-8 and 10-18 demonstrating a linear dependence of the logarithm of the bobbin amplitude on the destructive examination maximum depth as a fraction of the tube thickness. Moreover, a linear dependence of the logarithm of the bobbin amplitude on the destructive examination throughwall length was also demonstrated. Indications that are near throughwall can be expected to exhibit a bobbin amplitude on the order of 2 or 3V. Thus, a joint dependence of the form

$$V = \exp\left(g_0 + g_1 h + g_2 L + g_3 hL\right) \qquad \textbf{Equation 10-13}$$

could be expected. Thus, it is possible for an indication to be on the verge of becoming throughwall and have its bobbin amplitude increase significantly with a small amount of depth growth.

[3] The consideration that this is within the framework is based on the fact that it is essentially a simulation of the extremes of the tail of the lognormal distribution.

10.5.4.4 Growth Rate Predictions

Note that one of the implications of the exponential form of Equation 10-13 is that all growth in terms of bobbin amplitude depends on the beginning voltage, i.e., it is voltage dependent. In practice, it is assumed that the cross-term between depth and length can be ignored, i.e., g_3 is taken to be zero. Thus, for a constant or relatively constant length, if the growth rate in depth is relatively constant, then,

$$\frac{dV}{dt} = g_1 e^{g_0 + g_1 h} \frac{dh}{dt} = V g_1 \frac{dh}{dt}$$ **Equation 10-14**

Thus, the growth in bobbin amplitude is a function of the current bobbin amplitude, i.e., voltage dependent growth. Moreover, the growth of cracks in A600MA SG tubes has been described as following an Arrhenius relation, i.e.,

$$r = \frac{dx}{dt} = b\frac{dh}{dt} = A\sigma^n e^{-\frac{Q}{RT}}$$ **Equation 10-15**

where r is the rate of crack growth in units of length per time, e.g., mils per month or meters per second, b is the tube thickness, h is the relative crack depth, t is time, A is a constant of proportionality, σ is applied stress, n is a constant in the range of 2 to 4, Q is the activation energy for the growth of cracks in the material, typically 30 kcal/mole for A600MA, R is the universal gas constant, and T is the absolute temperature measured in units matching R, that is, °K or °R. Combining the two equations and taking the derivative of the logarithm of V yields,

$$\frac{dV}{dt} = V\frac{g_1}{b} A\sigma^n e^{-\frac{Q}{RT}}$$ **Equation 10-16**

Thus, the rate of growth of the bobbin amplitude depends on its current value and on the absolute temperature at the location of the crack. This observation has been noted in discussions of voltage dependent growth (VDG), Reference 10-19 (provided as Attachment 2 to Enclosure 4 of Reference 10-9). This result is in concert with the previously discussed observation that the growth can be well described as following a lognormal distribution, a factor affecting growth increases with the size of the indication. This does not mean that VDG must always be modeled. It is apparent from the discussion and figures in Reference 10-19 that the relation is usually so weak that the dependence can be ignored up to an amplitude of about 1.5 Volts. The implication is that the dependence on stress, which appears directly in Equation 10-16, is weak relative to other effects, such as environmental factors, and approximations that consider the growth to be a linear function of time can be used. The VDG approach is a refinement that results in parsing the empirical distribution function (EDF) growth curve into two or more segments to identify where a series of piecewise EDFs should be developed and applied as a function of increasing voltage. In summary, although the growth rate depends on the current amplitude of the indication signal, the dependence can be effectively modeled by piecewise empirical distribution functions. In addition, adjustments for temperature can be accounted for by the use of ratios of the Arrhenius model values. Note that the constants in the relation that are not in the exponential cancel.

10.5.5 Potential Approaches

There are several potential approaches discussed in Reference 10-23 to dealing with the extremes, but the following method is recommended:

> Insert randomly chosen samples from the observed extremes in the applications of the ARC since it inception, or shortly thereafter, to model the observed frequency of large extremes of growth.

10.5.6 Insertion of Random Extreme Values

During the course of application of the ODSCC ARC a number of large indications have been found at the end of an operating cycle. A summary of the maximum voltage growth values is provided in Table 10-16. It has been noted that the frequency of occurrence of singularly large growth rates, while small, is not insignificant. It is possible in such cases for a single large indication to be responsible for the total probability of burst or predicted leak rate being near or in excess of the condition monitoring criteria. That this occurs is simply due to the fact that if observations from a distribution of data are repeated, it will be found that the largest observed values follow a different distribution than the parent distribution of the data. This approach is appealing because it directly addresses the issue of the potential for large extremes of growth to occur and distributes those large extremes in proportion to the frequency of occurrence observed during application of the ARC. There are several factors that affect growth that may need to be accounted for because the database used for developing the statistics was obtained from a variety of plants with different size tubes, normal operation temperatures, and operating cycle lengths. The potential effects are considered in the following sections.

10.5.6.1 Factors Affecting Growth

Potential factors affecting the appearance of a large indication are maturity of the population of indications in the SG, the number of indications in the SG, the chemistry of the secondary side of the SG, the temperature of operation, and the length of the operating cycle. The tube size is not a factor in the stress analysis because the radius-to-thickness ratios for the sizes under consideration are effectively the same, 8.22 and 8.25 respectively for nominal 3/4 and 7/8 inch diameter tubes. This means that the hoop stress as a function of pressure is the same for each plant. However, experience has shown that the frequency of designated large extremes is greater in SGs with 3/4 inch diameter tubes relative to 7/8 inch diameter tubes, e.g., see the list of larger extremes in Table 10-14.

The ODSCC ARC regression curves relate the burst pressure, the probability of leak and the logarithm of the leak rate for indications that leak to the logarithm of the amplitude of signal from the bobbin inspection probe. The growth of the indications is measured in terms of the change in volts from one outage to the next as opposed to the change in the depth of the indications or the change in their length.

10.5.6.1.1 Maturity of the Population of Indications

The issue here is whether or not the maturity of population of the indications has a bearing on the probability of a plant experiencing and extreme growth indication. The maturity does not appear to be a significant factor other than indirectly through the number of indications and the number of indications in service at or near throughwall in depth. There have been instances where an anomalous growth of a single indication has occurred when the remainder of the indications experienced no such abnormalities.

10.5.6.1.2 Number of Indications in the SG

The appearance of extremes of growth would be expected to be a function of the number of indications in a SG if the combination of contributing factors leading to the development of an extreme growth is random. In other words, if the probability of a tube experiencing a growth extreme is constant, then the probability of a growth extreme occurring in a SG bundle increases with the number of indications in the bundle. In other cases extremes can appear for cause, see Section 10.5.2.3 for example.

10.5.6.1.3 Chemistry of the Secondary Side

The chemistry of the crevice must have an affect on the average growth rate of the indications. However, it is likely of secondary importance regarding the probability of a plant experiencing an extreme growth indication.

10.5.6.1.4 Temperature of Operation

The rate of growth of the indications, r, is considered to be a direct function of the applied stress, σ, raised to some power, n, on the order of 2 to 4.4 depending on the environment, and an Arrhenius relation function of the absolute temperature, T, of operation, i.e.,

$$r = A\sigma^n e^{-\frac{Q}{RT}}$$

Equation 10-17

where Q is the activation energy of the material, 30 kcal/mole for A600MA, and R is the universal gas constant 1.986 cal/mol/°K or 1.103 cal/mol/°R (absolute zero is -459.67°F). As the temperature increases, the value of the exponent decreases and the inverse of the exponential and the rate of growth increases. Using the above expression the time at temperature, t, taken as effective full power days or years, EFPD or EFPY, can be converted from one operating temperature to another, i.e.,

$$t_2 = t_1 e^{\frac{Q}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)}$$

Equation 10-18

where t_2 is the adjusted time of operation corresponding to temperature T_2, and t_1 is the time of operation at temperature T_1. For example, if T_2 is greater than T_1, the term in parentheses in Equation 10-18 is negative and the time that Plant 2 could operate for the same expected indication growth is shorter than for Plant 1. The approach considered herein is to normalize all of the data from the operating plant conditions to a standard temperature, 610°F, using Equation 10-18 for the bobbin probe amplitude growth instead of the depth of penetration.

10.5.6.1.5 Normal Operation Differential Pressure

Equation 10-17 relates the rate of indication growth, usually crack size, to the applied stress raised to a numerical power, about 4. The stress is directly proportional to the differential pressure. Thus, unrestrained indications in a plant with a normal ΔP of 1450 psi would be expected to experience growth on the order of 1.6 times that of indications in a plant operating with a ΔP of 1300 psi. The example pressures roughly correspond to plants with 7/8 and 3/4 inch nominal diameter tubes respectively. The reason unrestrained indications were specified in the example is that the stress field associated with tube indications at tube support plate elevations is not likely to be similar to that at freespan locations. The reason for the cracking is associated with the concentration of a corrosive environment within the tube-to-TSP crevice that also leads to corrosion of the TSP material to the extent that the crevice may become closed, especially true for SGs with carbon steel TSPs. Thus, the difference in operating ΔP would be expected to not be meaningful. The second consideration for this variable is that stress is usually considered to be secondary relative to environmental effects. This is supported by the observation that tubes with large indications show no apparent geometric differences or other stress risers from tubes with low growth. In conclusion, there is no apparent reason to believe that the differential pressure stress has a significant effect on growth for ODSCC.

10.5.6.1.6 Adjustment of Voltage Growth

The growth of the indications is taken to be a linear function of the length of the operating cycle per the ODSCC ARC references, e.g., Reference 10-7.

$$\Delta V_2 = \Delta V_1 \frac{\Delta t_2}{\Delta t_1} e^{-\frac{Q}{R}\left(\frac{1}{T_2}-\frac{1}{T_1}\right)}$$

Equation 10-19

where ΔV2 is the growth during the cycle to be simulated and ΔV1 is the growth during the cycle taken as a reference. The same identification is made for the EFPD of operation of the cycle being simulated, Δt2, versus the EFPD for the reference cycle, Δt1. The terms in the exponential follow those of Equation 10-19, i.e., activation energy, universal gas constant, and absolute temperatures of operation.

10.5.6.2 Simulation Approach Based on SG ARC Applications

There are two approaches that can be taken using the available data from the applications of the ODSCC ARC. The first is to consider the frequency of occurrence of large extreme values as a

function of the number of SGs for which the ARC have been applied and the other is to consider the frequency of occurrence of large extreme values, i.e., exceedances, as a function of the total number of indications that have been observed, discussed in Section 10.5.6.3.

The general approach to a simulation using the frequency of occurrence of large extreme values on a per SG inspection basis is to:

1. Adjust the growth to a reference temperature of 620°F.
2. Adjust the growth to be in units of Volts/EFPY.
3. Identify all of the indications with growth exceeding 5 Volts/EFPY when normalized to 620°F, see Table 10-14.
4. Adjust the frequency of simulating large extremes for the number of indications in the SG population for the simulation of the tube degradation.

The first three steps are common to both approaches to the simulation process, SG or indication basis. The last step is necessary because the frequency of occurrence of a large extreme should also depend on the number of indications in the SG. Step 4 is also common to both approaches, but is easier to apply if the simulation is based on the total number of exceedances on an indication basis as described in Section 10.5.6.3, which is also the recommended approach. The following describes the steps that could be taken based on the frequency of exceedances on a SG basis:

1. Given the database of extreme values of voltage growth, ΔV_E, at a reference temperature, T_R and for one EFPY. The total number of applications of the ARC is N_A and the total number of SGs for which the ARC has been applied is N_G.
2. Simulating a SG with NJ indications. The probability of a SG having an extreme is given by,

$$P_E = \frac{N_E}{N_G} \qquad \textbf{Equation 10-20}$$

   Draw random numbers until one is drawn that is greater than PE to determine the total number of extremes in the SG during that simulation of the SG, i.e., the number of extremes is the number of draws minus one. For example, there is no extreme during that simulation of the SG if the first number drawn is greater than PE. However, there is at least one extreme during that simulation of the SG if the first number is less than PE. There will be the potential for at least two extremes if the second number is also less than PE, et cetera.

3. Pick the voltages of the potential extremes from the population of extremes without replacement. If there are to be N_{GE} extremes for that simulation of the SG, pick N_{GE} voltage values from the list of extremes. Keep track of the number of indications in the SGs that go with those extremes.
4. For each of the potential extreme values, calculate the ratio of the number of indications in the SG being simulated to the number that go with the growth extreme value. Pick a uniform random number, U_3, the indication is retained in that simulation of the SG if U_3 is less than the ratio. If the ratio number is greater than one, that value will appear in the simulation and the value of U_3 will be used to determine if a second extreme is to be included in that

simulation of the SG. This is to be repeated for each extreme growth value that is determined in Step (3).

5. Pick an indication at random from the population of indications that are expected to be present at the end of the operating cycle and add that value of growth to the BOC amplitude to obtain the EOC amplitude for that indication.

In summary, the number of times that large extremes have occurred is counted, that value is then weighted by the number of indications in the SG; the number of extremes that occur is correlated to the number of indications in the SG and there is a joint probability of occurrence that is simulated by following the previous steps. Say that there have been 25 extremes of growth in the greater than eighty (80) applications of the ARC. Further note that there have been 250 SGs involved in those applications. Some of the SGs in which extremes occurred had almost 2000 indications. The Diablo Canyon extreme had almost 1000 indications in it. This increases the likelihood of an extreme value of growth taking place, i.e., the fraction of large extreme growth values per indication that is found at the end of the operating cycle is effectively constant.

10.5.6.3 Simulations Based on the Total Number of Indications

For the large number of indications observed in both 3/4 and 7/8 inch diameter tubes and the small number of large extremes of growth it is acceptable to use statistics based on the binomial distribution. Before proceeding with the discussion, some background on the statistical equations is appropriate. The individual probability, p, of any one indication exhibiting a large extreme of growth when K is the number of large extremes in the population and M is the number of indications in the population is calculated as,

$$p = \frac{K}{M}$$

Probability of Large Extreme

Equation 10-21

The probability of zero large extremes occurring, $P(0)$, in a sample of n indications in the SG is given by,

$$P(0) = (1-p)^n = q^n$$

Probability of Zero

Equation 10-22

where q is the probability of a single indication not being a large extreme, i.e., 1-p. The probability of one large extreme occurring in the same sample of indications is given by,

$$P(1) = n\frac{p}{q}P(0)$$

Probability of One

Equation 10-23

The following recurrence formula can be applied to obtain the probability of exactly z large extremes occurring,

$$P(z) = \frac{n+1-z}{z}\frac{p}{1-p}P(z-1) = \frac{n!}{(n-z)!z!}p^z q^{n-z}$$ **Equation 10-24**

the latter term being the standard notation for the binomial distribution density function. Hence, the probability of three large extremes occurring is found as,

$$P(3) = \frac{n-2}{3}\frac{p}{q}P(2)$$ **Equation 10-25**

For example, if the total number of indications of one or both tube sizes was 100,000 and 20 large extremes had been observed, the probability, p, of any one indications being a large extreme is 0.0002, and the probability that an indication is not a large extreme, q, is 0.9998. The probability of no extremes being observed in the simulation of 500 indications is 0.905 and the probability of at least one large extreme being observed is 0.095. The probability of exactly one large extreme being observed in the sample is 0.0905, 0.0045 for two, $1.5 \cdot 10^{-4}$ for three, $3.7 \cdot 10^{-6}$ for four and so forth. A summary of the calculations of this example is provided in Table 10-17. It is apparent that a practical limit for the number of large extremes in SG indication populations of less than about 1,000 is four for 100,000 simulations, depending on the values of K and n. A practical approach would be to find the value of z for which $P(z)$ is less than about $5 \cdot 10^{-5}$, an engineering judgment, to obtain a reasonable upper bound for the number of large extremes to be considered. Even at the potential for four, the effect on the results of the calculation of the total leak rate and the probability of burst would be expected to be negligible. The probability of the largest of the K largest extremes being present in any simulation where a large extreme is predicted to occur is $1/K$.

There have been greater than eighty (80) applications of the ODSCC ARC to over 250 SG inspections using data from historical records of inspection campaigns at seventeen (17) plants starting with information available in 1988, which was prior to the technical development of the ARC. More than 115,000 indications, for both 3/4 and 7/8 inch diameter tubes, have been found with only twenty-one (21) detected large extremes, ≥ 5V, occurring corresponding to an operating temperature of 603°F as listed in Table 10-14. Thus, the probability of an extreme is about 19 in 100,000 on a per tube basis. These values are similar to those used in the above example. Thus, the probability of at least one or more of those large extremes occurring in 500 detected indications is on the order of 9.5%. The 3/4 inch diameter tube values dominate the determination of the total number of extremes, i.e., dictate a higher number, but the 7/8 inch diameter tube data contains the two largest extremes values. Thus, simulating the 7/8 inch diameter tubes only results in less large extremes being simulated, but the ones that are simulated are larger. This proportion is not expected to change significantly. The data of Table 10-14 were complete through the ARC inspections conducted in the Spring of 2004 and subject to change as more data are collected from future SG tube inspections. Plants that apply the ODSCC ARC are required to report their findings and growth data in 90-Day ARC reports. Thus, the plants that apply the extreme growth methods for their 90-Day Operational Assessments are required to review the recently published ARC data and update the Table 10-14 growth data and factor the results into their growth calculations.

It is recommended that ODSCC ARC simulations of large extremes of growth be tube size specific. Consideration of SG tubes in United States plants with 7/8 inch diameter tubing need only consider the 3 defined large extremes of growth for the 56,874 found indications of Table 10-18. The probability listed in Table 10-18 of no extremes occurring in a SG with 500 predicted found indications is 0.9740. The simulation process does not effectively change with POD considerations. The probability of one extreme indication being present is 0.0257 and the probability of two extremes being present is 0.00034. Thus, one of the large extremes of growth would be expected to appear in 2,568 of 100,000 simulations of the indications in the SG. The following steps would be taken in order to incorporate the simulation of the extremes of growth into the Monte Carlo analysis, where the example probabilities correspond to the operation at 603°F with 500 BOC indications after application of the probability of detection process:

1. Generate a uniform random number, U, for each simulation of the indications in the SG.
2. Determine the number of large extremes to be considered for that simulation of the SG using the following logic where Pr(z) is the cumulative probability of occurrence of at least z specified indications,

   if $U \leq \Pr(z = 0)$ there will be 0 large extreme indications, otherwise,

   if $U \leq \Pr(z \leq 1)$ there will be 1 large extreme indications,..., otherwise,

   if $U > \Pr(z \leq m-1)$ there will be m large extreme indications to consider for that SG simulation, where m is the maximum number of large extremes to be considered.

   For the 7/8 inch diameter tubes for example, m is 2 for a SG with 500 indications per Table 10-18, that is the maximum credible number of large extremes is 2 in one SG at the same time. So, if U is ≤ 0.97397 there will be no large extremes for that simulation. If U is > 0.97397 and ≤ 0.99966 there will be one large extreme in the SG for that simulation. Finally, if U is > 0.99966 there will be two large extremes in the SG for that simulation.
3. Following the example of the previous step, pick one of the extremes associated with the 7/8 inch diameter tubes at random, i.e., generate a random integer from 1 to 3 to determine which of the three extreme values will be present for that simulation. Multiple integer values need to be selected if there is more than one extreme to be considered, noting that sampling can be performed with replacement.
4. Generate an integer random number between 1 and the total number of indications to remain in service in the SG and assign the large extreme value of growth to that indication. If there is more than one large extreme value to be simulated, the number of indications to be assigned a large extreme value must be selected. If voltage dependent growth (VDG) has been confirmed to be evident in the SG the selection of the indication to be assigned the large growth value should be selected from the upper bin if there is only one break point or from the upper two bins if there are two break points, etc.
5. Simulate the remaining indications in the SG using the growth curve determined to be applicable for the SG. Alternatively the analyst may consider the number of indications to be increased by one, the indication from Step 4, and simulate all of the indications in the SG. Although acceptable, it is only identified as a means of reducing the complexity of the simulation, the appearance of large extreme values do not change the number of indications in service.

6. Accumulate the total leak rate and probability of burst for all of the simulations of the SG and report the results according to the methodology described in References 10-2 and 10-20, the latter was approved for use by Reference 10-21.

It is recommended that the above method be applied to the separate frequencies for 7/8 and 3/4 inch diameter tubes, according to the temperature dependent frequency of large extremes specified in Table 10-14. This frequency should be applied to the number of indications returned to service prior to application of the POD for consistency in the method of defining the frequencies. Since this methodology is to be applied in conjunction with POPCD applications, the number of indications in the database after POD application cannot practically be defined. The distribution of large extreme growths should be obtained from Table 10-14 for the plant specific tube size and operating temperature closest to, but greater than one of those listed in Table 10-14, alternatively linear interpolation of the growth values as a function of the temperature can be used. For example, for an operating temperature of 608°F the growth rates for 610°F could be used, or alternatively, interpolated rates can be found by interpolating between 603 and 610°F or between 600 and 620°F for that matter. For a temperature of 608°F the linearly interpolated largest extreme growth rate is 13.73V while the Arrhenius equation calculation yields 13.38V, thus the linear interpolation is conservative.

It is noted that one easy implementation of the methodology for the total leak rate would be to assume that all of the simulation of the extremes result in a total leak rate that is greater than the largest value simulated without the extremes. Then, add the number of extremes that could occur to the simulation value representing the 95% confidence value for the 95th percentile of the population. For example, the 95,114th ordered leak rate represents the 95th percentile at 95% confidence of 100,000 simulations. Since 2,568 extremes could occur, a bounding value of the leak rate with the extremes considered would be obtained by considering the 97,432nd ordered value. Likewise, a hybrid approach could be taken where the 95th percentile rank is increased by the expected number of two extremes, and the probability of one extreme is simulated. It is expected that this approach would lead to a significantly conservative estimate for the total leak rate and would be undesirable in practice. A similar approach for the probability of burst would also be expected to lead to undesirably large values unless an accounting of the probability of burst of each of the potential large extremes was made. The modeling would have to be included in the Monte Carlo simulation coding, thus negating any potential benefit.

10.5.7 Summary/Recommendation

A number of potential approaches were explored relative to the simulation of large extreme values of growth for ODSCC indications at TSP intersections in Addendum 6 (Reference 10-23). The recommended approach from this evaluation is to simply insert random extreme values into the growth distribution in proportion to their occurrence in operating SGs, i.e., the latter of the two recommendations considered in the preceding paragraph. The rationale for the selection is based on the potential ease of application, since both approaches would be expected to result in similar predictions of total leak rate and probability of burst. The simulation based on numbers of indications is consistent with the historical experience in that all the extreme growths occurred in plants with large numbers of ARC indications in service and none have occurred with a small number of indications, e.g., SGs with < 200 indications, even in 4-loop plants. A distribution of large extreme values for growths greater than 5V at temperatures of 600, 603, 610, and 620°F is

included in Table 10-14 as a reference. When it has been determined that an extreme value should be included in the simulation, one of the extremes from the table is selected at random and added to the population of indications being simulated. This is the basic process as described herein in Section 10.5.6.3 for the total number of simulations. The database of large extremes will be updated for plants that apply the large extreme growth methods in their 90-Day ODSCC ARC reports. Periodic updates will also appear in Addenda to the ODSCC ARC database, Reference 10-11 of this report for example. This extreme growth methodology is to be applied in conjunction with the use of POPCD as the licensed POD because the use of a POD of 0.6 already includes large numbers of high voltage indications in the BOC distribution.

10.6 Noise Requirements for Voltage Based ARC

10.6.1 Introduction

This section provides recommendations on noise inspection, analysis and repair for application to the ARC for ODSCC at TSP intersections. These recommendations differ from the noise guidelines for mix residuals given in GL 95-05. The noise analysis methods may be applied without NRC approval to select indications for RPC inspection but the increased repair limits of this section beyond that permitted by GL 95-05 cannot be applied without NRC approval. The methods of this section were submitted to the NRC by NEI letter on April 13, 2004.

Tube noise considerations for indications at TSP intersections for the voltage based ARC are currently based on measurements of the mix residual signal. The mix residual was applied in the early development of the ARC as a measure of noise prior to more recent efforts in the industry to assess the effects of noise on detection. The mix residual is a measure of the noise across the entire TSP length and is not an appropriate quantity for assessing the effects of noise on detection since most TSP indications develop at the TSP center where noise influence is minimal. The noise at TSP intersections develops over the first and second cycle of operation and is not significantly sensitive to the NDE setup for the frequency mix at TSP intersections or significantly variable from cycle to cycle. To update the ARC noise inspection and repair requirements to current noise assessment methodology, revised requirements for inspection and repair at noisy TSP intersections are developed in this report.

NRC Generic Letter 95-05 (Reference 10-7) requires RPC inspection of intersections with large mix residuals that could cause a 1.0 volt bobbin signal to be masked or misread. The GL states that "Any indications found at such intersections with RPC should cause the tube to be repaired." The latter GL requirement has had two interpretations. The industry interpretation, as given in Section 10.1.1 of this report is that repair "at such intersections" refers to repair at intersections having mix residuals that mask a 1.0 volt indication so that repair is only required when the bobbin voltage is estimated to be •1.0 volt. The statement has alternately been interpreted by the NRC to imply that all indications found by RPC during mix residual inspections are to be repaired independent of the estimated bobbin voltage. As discussed in Section 10.6.2, all TSP intersections have mix residual signals and the influence of the mix residual signals (better defined as a measure of TSP noise) on voltage measurements is built into the ARC burst and leak rate correlations. The concept of misreading a voltage due to TSP noise should not be applied for the ARC since the effects of noise on voltage measurements are already included in the ARC

database and contribute to the voltage variability in the ARC burst and leakage correlations. The repair criteria for ODSCC indications found at noisy TSP intersections are redefined in this note to more closely tie the noise intersection repair limits to the plant specific voltage based repair limits. As shown in this report, bobbin voltages can be adequately assigned to indications found by RPC inspections so that the indications can be included in condition monitoring and operational assessments, thus eliminating any need for lower repair limits based on potential influence on burst and leakage.

GL 95-05 also requires 100% inspection of all dents > 5 volts and repair of any indications found in dents > 5 volts. Since these indications can be adequately sized using correlations of bobbin to RPC volts such that the indications can be included in condition monitoring and operational assessments, this report also recommends that repair for these indications be tied to the plant specific voltage based repair limits.

Section 10.6.2 discusses noise considerations at TSP intersections to demonstrate the importance of applying noise measurements specific to the center of the TSP rather than the mix residual signal, which measures noise across the entire TSP resulting in an overestimate of noise at the location of the cracks near the center of the TSP. In Section 10.6.3, the adequacy of the References 10-1 and 10-22 methods for assigning bobbin voltages to RPC indications is demonstrated by field data and recommendations for repair of the RPC indications are provided. Section 10.6.4 defines the recommended requirements for selecting samples for RPC inspection of noisy TSP intersections and for expanding the inspections if indications exceeding the GL 95-05 ARC repair limits are found in the sample inspection. Section 10.6.5 summarizes the conclusions of this report.

10.6.2 Considerations for Noise at TSP Intersections

With regard to the presence of mix residuals and their influence on sizing of indications, it must be emphasized that all TSP intersections have mix residuals after the first one or two cycles of operation. The mix residuals may be more easily understood as a measure of TSP noise. After about two cycles, the mix residuals generally do not change significantly with operating time. The dominant voltage for the mix residual signals is not strongly affected by the mixing used to analyze the bobbin data so the mix residual signal amplitude does not vary significantly with operating time or NDE analyst. Frequently, a significant part of the mix residual signal is present in bobbin data obtained without a TSP for pulled tubes examined in the laboratory. Some of the model boiler specimens show mix residuals although generally smaller than field data due to the shorter time at temperature. The bobbin response apparently includes an effect of the time at temperature at a TSP on the electrical and/or magnetic properties of the tube. Metallography was performed on a pulled tube to attempt to identify the cause for the signal, but was not successful in identifying any physical change to the tube or grain structure.

Many of the pulled tubes in the ARC database (and the prior cycle probability of detection or POPCD database) have mix residual signals larger than typically found in currently operating SGs. Figure 10-30 shows the 1.87 flaw voltage and the 3.23 mix residual voltage for pulled tube R27C54 from plant A-1 in the ARC database. This is only one example of the pulled tube data. The flaw signal is easily detectable which would imply easy detection at signal to noise (S/N) of about 0.58 for the associated flaw and mix residual peak-to-peak voltages. As shown in Section

8.2.3, a S/N of 0.58 would be expected to have a probability of detection of about 0.25. This indicates that the use of the mix residual as a measure of noise is not appropriate for assessing detection.

The mix residual voltage is not being used, nor should it be used, in current assessments of the influence of noise on detection or sizing. For signal to noise evaluations, the noise is being evaluated as the maximum voltage response over approximately one third sections of the TSP to distinguish the relatively low noise at the center of the TSP from the larger noise near the edges of the TSP. Figure 10-31 shows the lower and upper TSP noise amplitudes for R27C54-1H. Noise at the middle section cannot be evaluated due to the presence of the flaw. Figure 10-32 shows the mix residual voltage and noise levels at the center, upper and lower one-third sections of the R27C54-2H TSP, where the mix residual is the same as at 1H. The noise level affecting detection and sizing at the center of the TSP, where most of the TSP ODSCC indications are found, is 0.70 volts peak-to-peak while the edge noise amplitudes are 1.70 and 1.52 volts. These noise levels are in the upper 20% of noise amplitudes expected at TSP intersections. The noise differences between the center and edge affect detectability of short, low voltage indications located at the edges of the TSP. The short indications at the TSP edges must grow to the center of the TSP to become structurally significant and the lower noise levels at the TSP center provide for detection of even low voltage indications. The noise levels in these figures are peak-to-peak amplitudes although the vertical amplitudes are more appropriate for assessing signal to noise for flaw detection. However, the applications of this report are related to amplitude sizing for which peak-to-peak flaw and noise amplitudes are the recommended quantities. Applying the peak-to-peak amplitudes of 1.87 volts for the flaw from Figure 10-30 and 0.70 volt for the noise at the TSP center from Figure 10-32, the S/N for the flaw would be about 2.7 (expected POD about 0.96 from Section 10.6.3), which supports the ease of detection found for the flaw. This result is consistent with the recommended use of the flaw and noise evaluated at the TSP center.

The above noise and mix residual discussion demonstrates that it is neither feasible nor necessary to attempt to define bobbin flaw voltages that are not affected by the TSP noise or mix residuals. All indications have negligibly small to a range of noise influence on voltage sizing, and the ARC database includes many indications with larger noise levels than most currently active SGs. Whatever influence the mix residuals may have on voltage sizing for TSP indications is built into the ARC database by the pulled tubes and the concept of misreading voltages is irrelevant to the ARC.

Since nearly all TSP indications are located near the center of the TSP or span the center of the TSP, the appropriate quantity for assessing the influence of noise is the amplitude over approximately the center 1/3 of the TSP between the peaks associated with TSP edge effects. Short indications at the edges of the TSP would not have a significant influence on tube integrity. Amplitude measurements at the area of interest are being applied for tube integrity applications under the EPRI Tools for Tube Integrity Program. These measurements are being utilized to develop ETSSs and PODs based on performance testing of multiple analyst teams. The use of amplitude noise measurements are recommended for ARC noise assessments for consistency with the EPRI methodology for tube integrity applications. The following sections apply the amplitude noise measurements at the center of the TSP to develop RPC repair and inspection requirements for ARC applications.

10.6.3 Tube Repair Requirements for Indications Found by RPC at Noisy TSP Intersections

10.6.3.1 Bobbin Voltage Sizing for Indications Found by RPC

Axial ODSCC indications found only by RPC inspection can be sized for bobbin voltages by the methods described in Section 10.1 of this report. Methods are described based on obtaining voltages from detection at the half-prime frequency and from correlations of bobbin to RPC voltages, which may be pancake or +Point coils. When detection can be adequately obtained at the half-prime frequency, this method is preferred over the bobbin/RPC voltage correlation since the method is closely related to the normal inspection process for detecting and sizing indications. However, it is shown below that both methods yield essentially the same bobbin voltages and that the inferred bobbin voltages are consistent with voltages obtained from the normal primary/secondary/resolution detection and sizing process.

The most extensive inspection of TSP intersections with significant mix residual noise signals was performed at Plant P-1 in 2003. The results of these inspections can be used to demonstrate the adequacy of the bobbin voltage sizing methods. Figure 10-33 compares the ratio of bobbin voltages in the 400/100 kHz mix to the 200 kHz volts for indications reported in the normal primary/secondary/resolution analysis process to the ratios obtained from detecting the flaw (identified by the RPC) on the 200 kHz channel and using the inferred mix signal measurement with no additional adjustments. It is seen that the distributions obtained from both sizing methods are equivalent, which supports the adequacy of sizing by identifying the flaw in the half-prime frequency signal and obtaining voltages from the mix signal. Figure 10-34 compares the regression correlations of bobbin to +Point volts obtained using the normal inspection process with that obtained from the half-prime frequency analyses. The bobbin to RPC voltage correlations are essentially the same for both analysis methods. Since Figure 10-33 shows the adequacy of sizing from detection in the half-prime frequency and Figure 10-34 shows that correlations of bobbin to RPC volts are the same between the normal ODSCC sizing and half-prime frequency analyses, it can be concluded that both of the methods for bobbin voltage sizing of RPC indications yield essentially the same bobbin voltages and both methods are acceptable for ARC applications.

10.6.3.2 Tube Repair Requirements for Indications Found by RPC at Noisy TSP Intersections

As noted in Section 10.6.1, the industry interpretation of GL 95-05 is that indications associated with large mix residuals and found only by RPC should be repaired if the inferred bobbin voltage is ≥1.0 volt. This repair limit is inconsistent with the differences in repair limits between 3/4" and 7/8" tubing. Since a bobbin voltage is assigned to the indications found only by RPC and the indications are included in the condition monitoring and operational assessments, there is no need to apply repair limits more conservative than the licensed repair limits.

For consistency in ARC repair limits, it is recommended that the following tube repair limits be applied for indications found only by RPC:

- Based on bobbin voltages determined by the methods of Section 10.1.1 of this report from indications found only by RPC inspection, indications with inferred bobbin voltages exceeding the licensed plant specific bobbin voltage repair limit are to be repaired. The GL 95-05 repair limits are > 1.0 volt for 3/4" tubing and > 2.0 volts for 7/8" tubing. Some plants may have larger repair limits such as obtained from locked TSP intersections.
- This repair limit applies for RPC indications found at noisy TSP intersections and at dented TSP intersections for dents of any voltage. For indications found at TSP intersections with both ODSCC and PWSCC indications for plants having a licensed PWSCC ARC, the above repair limit can be applied only if consistent with the licensed requirements.
- The bobbin voltages obtained by the Section 10.1.1 methods from RPC testing of noisy TSP and dented TSP intersections are to be included in the ARC condition monitoring and operational assessments.

10.6.4 RPC Inspection Requirements for Noise at TSP Intersections

The selection of noisy TSP intersections for potential RPC inspection is to be based on POD versus signal/noise (S/N) correlations for axial ODSCC at TSP intersections. When available, the POD vs. S/N correlations for noise levels at the center of the TSP as obtained from ETSSs based on multiple analyst testing should be applied. Until these ETSS POD correlations are available, the POD vs. S/N correlation from SSPD testing of multiple analysts described in Reference 10-24, as shown in Figure 10-36, is to be applied. Figure 10-36 is based on flaw and noise peak-to-peak amplitudes to permit application of peak-to-peak voltage repair limits in defining S/N. For more general applications of S/N for detection, the vertical max voltages would be used as this quantity is more closely tied to NDE detection methods.

The GL 95-05 repair limits are the appropriate limits for detection of indications found at noisy TSP intersections based on burst and leakage considerations. The lowest voltages found for leaking indications in the ARC database (Section 5 of this report) is 1.13 volts for 3/4" tubing and 2.81 volts for 7/8" tubing. The leak rates for these two indications were very small at 0.000088 and 0.00035 gpm, respectively. Thus, indications below the GL 95-05 repair limits would not be expected to leak and, if they do leak, would have a negligible leak rate. The probability of burst for indications at the GL 95-05 repair limits are less than about 5×10^{-6} (Section 6 of this report) for both 3/4" and 7/8" tubing, and thus undetected indications below the repair limits would have a negligible contribution to the burst probability. The GL 95-05 repair limits are to be applied to develop the inspection requirements of this section even for plants with higher licensed repair limits in order to assure that indications with potential significant leakage are included in the ARC analyses.

A S/N value for a nominal POD of 0.9 is to be obtained from the POD versus S/N correlation for axial ODSCC peak-to-peak amplitudes at the center of the TSP. For plants licensed to apply the Probability of Prior Cycle Detection (POPCD) for operational assessments, the POD value to be applied to obtain S/N values is the nominal POPCD POD at the appropriate GL 95-05 repair limit. The use of POPCD distributions (Section 7 of this report) at 1.0 and 2.0 volt repair limits would likely lead to POD values within about ± 0.05 of 0.9. The use of a POD on the order of 0.9 to define a S/N value at the ARC repair limit assures that the detection for ODSCC at noisy intersections is consistent with or conservative relative to the POD used in ARC operational

assessments. From Figure 10-35, the associated S/N value for a POD of 0.9 is 1.9. To obtain a noise threshold for potential RPC inspections, detection at a POD of 0.9 (or that from POPCD at the repair limit when POPCD is licensed) is applied to obtain the S/N value and the signal, S, is applied at the ARC repair limit. The noise threshold value for the mix at the center of the TSP is then 0.53 volt for a repair limit of 1.0 volt and 1.05 volt for a repair limit of 2.0 volt. As noted, these values are to be updated when the EPRI ETSS POD versus S/N correlations from multiple analyst testing are available.

Noise evaluations should be performed for a minimum of 100 hot leg TSP intersections per SG to identify noisy TSP intersections. Since the TSP noise levels do not change significantly from cycle to cycle, the noise analyses may be performed on the bobbin data from the last inspection or the current inspection. RPC inspection shall be performed for a minimum of 25 intersections (total summed over all SGs) exceeding the noise threshold values. The noise measurements shall be made at the TSP intersections where most of the ODSCC indications are found, which are typically the lower three hot leg TSPs. If this sample does not identify at least 25 intersections with noise levels exceeding the noise threshold values, the noise evaluation sample size shall be increased to include an additional 100 TSP intersections per SG to obtain a total noise sample population of 200 TSP intersections per SG to identify intersections for RPC inspection. The RPC inspection shall then be performed at the 25 TSP intersections with the highest noise levels in the noise analysis population evaluated.

If axial ODSCC indications are found in the sample RPC inspection, the following guidelines are to be applied to determine whether an expansion of the inspection is required:

- If the inferred bobbin voltage of any indication found in the RPC inspection of noisy TSP intersections (sample with noise exceeding threshold values) is found to exceed the GL 95-05 repair limits of 1.0 and 2.0 volts for 3/4" and 7/8" tubing respectively, the noisy TSP intersection RPC inspection shall be expanded to include an additional 100 TSP intersections with the next highest noise levels in the noise sample population. If this inspection expansion identifies a flaw with a bobbin voltage exceeding the GL 95-05 repair limit, the inspection should be expanded in 100 sample increments until one of the samples is found with no indications exceeding the GL repair limit.
- The fraction of TSP intersections inspected that are found to have axial ODSCC indications defines an average undetected fraction, or 1-POD, for the base inspection since the RPC inspection is a supplemental sample inspection applied to assess the adequacy of the base inspection. If the operational assessment applies the GL 95-05 POD of 0.6, the associated undetected fraction is 0.4. If POPCD is applied for the operational assessment, the average bobbin voltage for the ODSCC indications should be used to determine an average or expected POD for the indications by application of the latest licensed nominal industry or plant specific POPCD distribution (Figure 7-4 in Section 7 of this provides an industry POPCD distribution for combined 3/4 and 7/8 inch tubing). The expected POD is defined as the POPCD value at the average bobbin voltage for the ODSCC indications found by RPC inspection. If the sample fraction of intersections with detected flaws in the RPC inspection (undetected in base inspection) is greater than the expected 1-POD (0.4 if POPCD is not licensed) by more than a 0.1 difference, the inspection should be expanded in 50 sample increments (applying next highest noise levels in the noise sample population) until one of the samples is found with an average POD equal to or greater than the expected POD. This requirement is applied to provide reasonable confidence that the detection capability in noisy

tubes is comparable to that used in the operational assessments for the overall population of indications.

The required expansion sample size of 50 samples for the POD comparison is smaller than the 100 samples required if an indication is found to exceed the repair limits. This difference is applied to reflect the significance on the operational assessment between the two conditions. Undetected indications left in service below the GL 95-05 repair limits are expected to have a negligible impact on leakage or burst as described above.

Examples of peak-to-peak amplitude noise distributions are shown in Figure 10-36 for a plant with 3/4" tubing and for a TSP dataset used for performance testing to development ETSSs under the EPRI Tools for Tube Integrity Program. The planned ETSS and plant noise distributions are very similar. For a plant with 3/4" inch tubing and a 0.53 volt noise threshold for potential RPC inspection, about 40% of the intersections exceed this level. The sample inspection would start at the highest noise levels in the distribution. Due to the low 1.0 volt repair criterion, the noise threshold for RPC inspection is very conservative. The noise distributions for plants with 7/8" tubing are expected to be similar to those in Figure 10-36. For the associated 1.05 volt noise threshold with 7/8" tubing, less than 5% of the TSP intersections would be expected to exceed this threshold. The sample size applied to develop the noise distribution for 7/8" tubing may have to be expanded to 200 TSP intersections per SG in order to identify the 25 intersections with the highest noise levels for RPC inspection. It can be noted that the POD versus S/N curves, such as Figure 10-35, are used to assess differences in noise levels and a plant specific noise distribution does not have to be bounded by the noise distribution used in developing the POD correlation.

10.6.5 Conclusions

The use of mix residuals to characterize noise at TSP intersections was initiated in the early 1990s and is shown in this report to be a poor measure of the influence of noise on detection. The noise at TSP intersections for bobbin probes varies significantly between the center and edges of the TSP whereas the mix residual is a single measure of noise across the entire TSP. Since nearly all ODSCC indications at TSP intersections extend through the center of the TSP, the noise levels at the TSP center provide the best measure of noise for the influence on detection and amplitude sizing. The few indications found only at the edges of the TSP that could be masked by the higher noise levels are very short and would have negligible impact on burst and leakage. Therefore, it is recommended that the ARC noise methods be based on evaluations of the noise amplitude at the center of the TSP.

The EPRI Tools for Tube Integrity Program is developing ETSSs based on performance testing of multiple analysts. Noise analyses are an integral part of this program with noise analyses for tube integrity applications based on measurements of the noise amplitudes at the regions of interest. As part of this program, PODs as a function of S/N are being developed. These correlations permit identification of the noise level that supports a specified POD level at the ARC voltage based repair limits. The recommended threshold noise value for RPC sampling of noisy intersections is based on obtaining a POD of 0.9 at the ARC repair limits of 1.0 and 2.0 for 3/4" and 7/8" tubing, respectively. Plant noise analyses for a minimum of 100 TSP intersections per SG are recommended to characterize the plant specific noise levels. If this sample does not

identify at least 25 intersections with noise levels exceeding the noise threshold values, the noise evaluation sample size shall be increased to include an additional 100 TSP intersections per SG to obtain a total noise sample population of 200 intersections per SG to identify intersections for RPC inspection. The 25 TSP intersections with the largest noise levels are recommended for RPC inspection. If an axial ODSCC indication exceeding the ARC repair limit of GL 95-05 is found in the noise sample inspection, the inspection would be expanded by steps of 100 TSP intersections until no ODSCC indication exceeding the repair limits is found in the 100 intersection sample. The inspection would also be expanded in steps of 50 TSP intersections if the fraction of indications found in the RPC inspection, which represents the fraction undetected in the base inspection, exceeds the undetected fraction expected from the POD used for operational assessment by more than 0.1. Bobbin flaw amplitudes for the RPC indications can be obtained either by identification of the flaw in the half-prime frequency response or by correlations of bobbin to RPC voltage. It is shown by plant data that these two methods yield very similar bobbin voltages and voltages consistent with the normal primary/secondary/resolution analysis.

It is recommended that indications found by the RPC inspection be repaired if they exceed the licensed plant specific repair limit based on bobbin voltages assigned to the RPC indications. This provides a consistent ARC repair limit independent of how the indication was found in the inspection. Based on the bobbin voltages assigned to the indications, all indications found in the RPC inspection are to be included in the ARC condition monitoring and operational assessments. The bobbin voltages for the RPC indications are adequately defined to obtain tube integrity margins consistent with all bobbin indications, and there is no need to define different repair limits for the indications found by RPC. Since indications found by RPC inspection in dents > 5 volts can be adequately sized using correlations of bobbin to RPC volts, it is also recommended that repair for these indications be based on the plant specific voltage based repair limits. Since GL 95-05 requires 100% inspection of all dents > 5 volts, no additional inspection or expansion requirements are necessary for the dented TSP intersections.

If the guidelines of this section are to be implemented for selecting TSP intersections for inspection prior to NRC approval, the repair limit must be applied at one volt for consistency with GL 95-05 as discussed in Section 10.6.1, and the RPC inspection requirements of Section 10.6.4 should be applied based on a one volt repair limit.

10.7 ARC Guidelines for Preventive Repair of Large +Point Indications

10.7.1 Introduction

This note provides guidelines for preventive tube repair (i.e., repair at less than the licensed voltage based repair limits) to reduce the potential for finding large voltage growth rates for indications left in service under the ARC for axial ODSCC at TSP intersections. Since the guidelines apply to preventive repair, implementation of these guidelines is optional on a plant specific basis.

ARC inspections periodically find large voltage indications (such as > 8 volts) that are not predicted to occur and generally do not occur in successive inspections. These indications with

unusually large voltage growth have been shown, where successive RPC inspection data are available, to occur with normal growth in depth. Voltage increases exponentially with depth and again approximately exponentially with increasing throughwall length. Consequently, an indication that is near throughwall over a significant length at the BOC can grow with normal depth growth to a significant throughwall length over one operating cycle with an associated large voltage growth rate. Most of the large voltage growth indications found in ARC inspections have been pulled and found to satisfy burst margins at the EOC conditions. However, the ARC burst versus voltage correlation will predict burst probabilities near the ARC reporting threshold of 0.01 due to the large uncertainties in the correlation.

The likelihood of finding a large voltage indication can be reduced by preventive plugging at less than the ARC repair limit. The best currently available methods for depth sizing of axial ODSCC are based on correlations of depth with +Point voltage when developed to provide a good estimate of the voltage at initial throughwall penetration. The latter is a principal factor in the development of sizing correlations under the EPRI Tools for Tube Integrity Program and associated correlations are applied in this report to provide a recommended +Point voltage for preventive tube repair for axial ODSCC at TSP intersections.

Section 10.7.2 provides additional background information and Section 10.7.3 provides guidelines for preventive repair. Section 10.7.4 provides guidelines for supplemental inspections to further inspect for indications potentially desirable for preventive repair. Section 10.7.5 summarizes the conclusions of this report.

10.7.2 Background Information

The largest voltage indication found during ARC inspections was a 21.5 volt bobbin indication (12.2 volt by +Point) at Plant Y-2. Fortunately, for providing a good database for evaluation, this indication had been +Point inspected at the prior outage. At the prior inspection, this indication was found to measure 2.0 volt by bobbin and 2.97 volt by +Point (maximum volts from profile analysis). The occurrence of +Point amplitudes greater than the bobbin voltage is infrequent for ODSCC partially due to the bobbin coil integrating degradation around the circumference of the tube while RPC measures a single crack location. The two voltages tend to be closer in magnitude when there is a single dominant crack at the TSP intersection.

The range of +Point amplitudes for a short throughwall axial ODSCC indication is about 2.0 to 3.0 volts. The lowest throughwall +Point amplitude in the ARC database is 1.89 volts. This indication had two interacting axial cracks, which tends to result in a +Point voltage reduction due to cancellation between the two coils. It can be expected that the Plant Y-2 indication was near or just throughwall at the BOC condition. The growth rate in average depth for this indication was about 12% per EFPY which is in the range of the upper 90% to 95% probability for normal growth rates and considerably smaller than ODSCC indications found to have large growth rates. The Plant Y-2 indication grew from imminent throughwall at BOC to the throughwall length of 0.42 inch found by destructive examination. The large voltage growth resulted from throughwall penetration and growth in throughwall length.

Plants P-1, Y-1 and Y-2 have performed significant +Point inspections below the 2.0 volt repair level that include some indications with data from two or three +Point inspections over the last

three cycles. These data permit an assessment of the larger +Point voltage and +Point to bobbin voltage ratio indications retained in service. The last three cycles of data were reviewed to identify the largest +Point volts left in service, the largest ratio of +Point to bobbin voltage and the largest bobbin indications. The resulting data for Plant P-1 cycles 1R13 to 1R15 are given in Table 10-19 and for Plants Y-1 and Y-2 cycles 9 to 11 are given in Tables 10-20 and 10-21. For Plant P-1, the largest +Point volts returned to service that can be assessed at the subsequent cycle are 1.65 volts at 1R13 and 1.71 volts at 1R14. None of the indications with +Point volts up to 1.71 had a large bobbin or +Point voltage growth in the subsequent cycle. The largest bobbin indication of 4.57 volts, which would not be considered an outlier indication, for tube R11C77 had a prior cycle +Point 0.61 volt indication. Similarly, indications with +Point to bobbin voltage ratios up to 2.0 showed no significant bobbin voltage growth in the subsequent cycle. The Plant Y-1 data of Table 10-20 show that there have been no high +Point volts or +Point to bobbin voltage ratios for data with successive +Point inspections. Thus, these data do not provide any additional insight on potentially limiting +Point voltages. The Plant Y-2 data of Table 10-21 show the 2.97 +Point volt indication left in service that led to the 21.5 bobbin volt outlier indication. Indications with +Point volts as high as 1.6 volts and +Point to bobbin voltage ratios up to 2.07 did not show any significant bobbin voltage growth in the subsequent cycle. The higher ratios of +Point to bobbin voltage, such as > 1.4, are generally associated with dominant single indications with relatively small bobbin voltages (i.e., < 0.7 volt) such that the effect of increasing bobbin voltage with increasing cracking around the tube circumference is not present. There is no technical reason to expect that single indications have a higher potential for large voltage growth in the next cycle since voltage growth rates are highest for crack depths near 100% and for increases in throughwall length rather than multiple indication effects. The Tables 1 to 3 results indicate that the +Point to bobbin voltage ratio is not a meaningful predictor for large bobbin voltage growth and is, therefore, not recommended for considerations of preventive plugging.

The Table 10-19 results also indicate that +Point voltages up to about 1.71 do not appear to be a meaningful predictor of large bobbin voltage growth. As discussed in Section 10.7.3 below, the crack depth for a 1.71 +Point voltage indication would be expected to be too shallow to grow to a significant throughwall length with normal growth rates over one cycle of operation. The threshold for considering preventive plugging should be greater than about 1.71 volts.

10.7.3 Guidelines for Preventive Repair

Based on the discussion of Section 10.7.2, only +Point indications greater than about 1.71 volt appear to be candidates for preventive repair considerations and the use of +Point to bobbin voltage ratios for preventive repair considerations is not recommended. The objective for preventive repair considerations is to prevent significantly large throughwall lengths, but to not exclude the potential for any throughwall cracks which would be too conservative for a repair guideline. Growth in average depth is applied to estimate a reasonable depth for preventive repair as growth over a significant length rather than local crack penetration is of interest. A growth rate of about 10% in average depth per EFPY is a reasonable estimate for normal growth at about the 90% confidence level. Thus, for preventive repair based on +Point amplitude sizing considerations, the amplitude should be based on average crack depths in the range of 85% over the deepest segment of about 0.1 to 0.2 inch. Since the amplitude sizing correlations are based on maximum crack depth, the 85% segment average depth must be adjusted upward to define a

preventive repair guideline. Since the ratio of maximum depth to average depth over the burst effective crack length for a crack is typically about 1.25, it is reasonable to assume that the maximum depth for a deep crack segment would be at least 10% greater than the average depth. Thus, the maximum depth for preventive repair should be about 95% with a lower bound of about 90%. The +Point amplitude for these depths can be estimated from a correlation of maximum depth to +Point amplitude as described below.

Sizing correlations based on +Point amplitudes are being developed under the EPRI Tools for Tube Integrity Program but these correlations have not been finalized at this time. The sizing developments show that the expected exponential dependence of voltage with depth is consistent with pulled tube data and should be the basis for amplitude based sizing correlations. Given the exponential behavior, only two data points are needed to define a sizing correlation, one of which should be tied to providing good estimates of throughwall crack lengths. The development efforts show that +Point amplitudes in the range of 2.25 to 2.75 volt provide good estimates of initial throughwall penetration and throughwall lengths for ODSCC at TSP intersections. The second point for a sizing correlation can be tied to an amplitude at a given depth such as about 40%. A mean estimate for depths near 35% to 40% for ODSCC at TSP intersections is about 0.1 +Point volt. To avoid being overly conservative for preventive plugging, an estimate for depths near 95% can be based on amplitude sizing fit to 2.5 volts for throughwall and 0.1 volt at 35% depth. Since depth is being inferred from volts, depth has a logarithmic dependence on volts.

Figure 10-37 shows a sizing correlation fit to 0.1 volt at 35% depth and 2.5 volts at 100% depth. For a 95% maximum depth repair guideline, the +Point indication would be about 1.9 volts. At a maximum depth of about 90%, the +Point indication would be about 1.55 volts, which is too conservative for a preventive repair guideline based on the plant experience described in Section 10.7.3. It is suggested that consideration be given to preventive repair of ODSCC indications found to have a +Point maximum voltage of 1.9 volts.

Although the data of Tables 10-19 to 10-21 were obtained for plants with 7/8 inch tubing, +Point amplitudes for deep indications are not significantly different for 3/4 inch tubing since voltages are calibrated for all tube sizes to 20 volts for a throughwall notch. For +Point amplitude sizing of axial ODSCC, the same correlation is applied to both 3/4 and 7/8 inch tubing. Consequently, the suggested preventive repair limit of 1.9 volts would be applicable to both 3/4 and 7/8 inch tubing. Since the GL 95-05 repair limit for 3/4 inch tubing is >1.0 bobbin volts and +Point volts are less than bobbin volts for the dominant population of indications, the suggested preventive repair limit of 1.9 +Point volts is not likely to impact plants with 3/4 inch tubing. Figure 10-38 shows the trend of +Point volts versus bobbin volts for an inspection in a plant with 3/4 inch tubing. For this inspection, essentially all +Point volts are less than the bobbin volts and no preventive repair would need to be considered.

The preventive repair guideline is developed based on considerations of normal growth in depth. Most plants found with large growth rates as a function of depth have had outlier bobbin voltage indications that initiated from bobbin voltages less than one volt. These plants generally had high operating temperatures which may have contributed to larger growth rates in depth. It would be excessively conservative for currently operating SGs to consider preventive repair limits low enough to encompass large growth in depth considerations.

10.7.4 Guidelines for Supplemental RPC Inspection

Figures 10-39 and 10-40 show +Point versus bobbin voltage trends for two plants with 7/8 inch tubing. Some tubes are found to have +Point volts comparable to or slightly exceeding the bobbin voltages. Thus, +Point voltages of about 1.9 volts may be found below the GL 95-05 repair limit for 7/8 inch tubing. A +Point to bobbin voltage ratio of about 1.1 envelopes nearly all bobbin indications. Thus, there is a high probability that bobbin indications less than 1.7 bobbin volts would have less than 1.9 +Point volts.

To increase the likelihood of identifying ODSCC indications with >1.9 +Point volts for plants with 7/8 inch tubing, a 100% RPC inspection of bobbin indications between 1.7 volts and the GL 95-05 repair limit of > 2.0 volts should be considered for preventive repair applications. Indications greater than the GL 95-05 repair limit of >2.0 volts are required to be inspected and are repaired so that preventive repair considerations are not applicable. If a plant applies locked TSPs to prevent burst and has a repair limit greater than the GL 95-05 limits, there is no need to apply preventive repair unless leakage from a single large voltage indication would potentially cause leakage limits to be exceeded. There is no identified basis to suggest expansion of +Point inspections for plants with 3/4 inch tubing.

10.7.5 Conclusions

ARC inspections periodically find large voltage indications (such as > 8 volts) that are not predicted to occur and generally do not occur in successive inspections. Since voltage increases exponentially with depth and again approximately exponentially with increasing throughwall length, an indication that is near throughwall over a significant length at the BOC can grow with normal depth growth to a significant throughwall length over one operating cycle with an associated large voltage growth rate. The likelihood of finding a large voltage indication can be reduced by preventive plugging at less than the ARC repair limit. Plant experience indicates that +Point volts up to about 1.71 volts and +Point to bobbin volt ratios as high as 2.07 have not resulted in large +Point indications in subsequent cycles. Since a +Point to bobbin ratio of about 2.0 bounds essentially all bobbin indications, this ratio does not provide a meaningful indicator for considerations of preventive tube repair. The data indicate that +Point amplitudes should exceed 1.7 volts for preventive repair considerations. The most appropriate measure for preventive repair considerations would be near throughwall depths that can grow to large throughwall lengths for which 95% maximum depth is shown to be a reasonable depth for preventive repair considerations. The best current methods for depth sizing of axial ODSCC are based on correlations of depth with +Point volts.

Based on applying a typical amplitude sizing correlation, a preventive tube repair at 1.9 +Point volts is suggested corresponding to about 95% maximum ODSCC depth. Since a +Point to bobbin voltage ratio of about 1.1 bounds most ODSCC indications, it is suggested that a 100% RPC inspection be performed for indications >1.7 bobbin volts. Since the GL 95-05 repair limit for 3/4 inch tubing is 1.0 bobbin volt and +Point volts are less than bobbin volts for the dominant population of indications, the suggested preventive repair limit of 1.9 +Point volts is not likely to impact plants with 3/4 inch tubing. Given the lower repair limit, no supplemental inspection for preventive repair considerations is recommended for plants with 3/4 inch tubing.

10.8 References

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Table 10-1
Summary of Alternate Bobbin to RPC Voltage Correlations 80 mil Pancake Coil RPC Data

Functional Form	Index of Determination, r^2	p-value for Slope Parameter	RPC Voltage[1] Corresponding to Bobbin 2 volt Repair Limit
Bobbin Voltage vs RPC voltage	47.3%	1.7×10^{-32}	1.51
Bobbin Voltage vs RPC Voltage (zero intercept)	21.4%	3.5×10^{-19}	Not Considered
Log_{10}(Bobbin) vs RPC Voltage	36.1%	4.8×10^{-26}	Not Considered
Log_{10}(Bobbin Voltage) vs Log_{10}(RPC Voltage)	38.4%	4.8×10^{-28}	Not Considered
Bobbin Voltage vs Log_{10}(RPC Voltage)	42.4%	1.2×10^{-31}	1.74

Notes:

(1) Mean Correlation Values

Table 10-2
Bobbin to RPC Voltage Correlation Sensitivity Analysis on Data Range

RPC Voltage Range	Correlation Coefficient (r^2) Linear-Linear Regression	RPC Volts[1] at 2 Bobbin Volts
0.1 to 3 volts[2]	43.3 %	1.51
0.2 to 2 volts	42.3 %	1.50
0.5 to 2 volts	30.8 %	1.46
0.5 to 1.5 volts	25.5 %	1.55
1.0 to 1.5 volts	7.0 %	1.46
1.0 to 2 volts	9.5 %	1.58

Notes:

(1) Mean correlation values

(2) There is only one data point between 2 to 3 volts

Table 10-3
Sample Information

Standard ID	Tube Material	Tubing Heat	Support Material	Support Heat
AD-014-89 (APC Reference)	I600	1017 (Westro)	A285C Plate	55477
AS-019-91	I600	0197 (Westro)	A285C Plate	432S8361
AD-009-94	I690	765151 (Sandvik)	A285C Plate	411B8653
IH-AD-001-96	I600	NX7368 (Plymouth)	A108 Bar	516K062
AS-004-96	I600	NX9815 (Dubose)	A108 Bar	950090
ADVB-010-97	I690	753290 (Sandvik)	SA240 Plate	60332
ADVB-012-97	I690	753290 (Sandvik)	SA240 Plate	60332
ADVB-046-97	I600	NX9815 (Dubose)	A285C Plate	H406
ADVB-047-97	I600	NX9815 (Dubose)	A285C Plate	H406
ADVB-003-98	I600	NX9815 (Dubose)	A285C Plate	421C0381
ADVB-004-98	I600	NX9815 (Dubose)	A285C Plate	421C0381

Table 10-4
Percentage Variation in Mix Measurements Relative to the APC Reference Standard

Standard	Method	Generation 2	Generation 3	Generation 4
AS-019-91	1	12.1%	12.1%	N/A
AD-009-94	1	-7.7%	-4.8%	N/A
IH-AD-001-96	1	21.0%	21.3%	N/A
AS-004-96	1	5.5%	6.3%	N/A
ADVB-010-97	1	-2.2%	-2.2%	N/A
ADVB-012-97	1	-1.8%	-1.8%	N/A
ADVB-046-97	1	12.9%	13.2%	N/A
ADVB-047-97	1	5.5%	5.9%	N/A
ADVB-003-98	1	10.3%	10.7%	N/A
ADVB-004-98	1	9.6%	10.3%	N/A
AS-019-91	2	-2.2%	-2.2%	-3.7%
AD-009-94	2	-4.4%	-1.8%	-1.1%
IH-AD-001-96	2	-3.3%	-3.7%	-6.6%
AS-004-96	2	-0.4%	-0.4%	-1.5%
ADVB-010-97	2	-4.0%	-1.5%	-2.9%
ADVB-012-97	2	-3.7%	-0.7%	-1.1%
ADVB-046-97	2	-1.8%	-1.1%	-2.6%
ADVB-047-97	2	-0.7%	-0.4%	-1.5%
ADVB-003-98	2	-1.8%	-1.1%	-3.3%
ADVB-004-98	2	-2.6%	-1.8%	-1.1%
AS-019-91	3	-0.4%	2.6%	1.8%
AD-009-94	3	2.9%	-1.1%	0.0%
IH-AD-001-96	3	-0.7%	3.3%	2.2%
AS-004-96	3	0.7%	1.5%	0.7%
ADVB-010-97	3	1.1%	0.7%	0.0%
ADVB-012-97	3	0.7%	1.1%	0.4%
ADVB-046-97	3	-0.4%	2.6%	1.8%
ADVB-047-97	3	2.6%	1.1%	1.1%
ADVB-003-98	3	0.0%	2.9%	1.5%
ADVB-004-98	3	-0.7%	1.8%	0.4%
AS-019-91	4	7.0%	N/A	N/A
AD-009-94	4	-4.0%	N/A	N/A
IH-AD-001-96	4	8.5%	N/A	N/A
AS-004-96	4	8.5%	N/A	N/A
ADVB-010-97	4	-4.8%	N/A	N/A
ADVB-012-97	4	-5.1%	N/A	N/A
ADVB-046-97	4	5.9%	N/A	N/A
ADVB-047-97	4	5.5%	N/A	N/A
ADVB-003-98	4	6.3%	N/A	N/A
ADVB-004-98	4	6.6%	N/A	N/A

Table 10-5
Bilinear Regression Sample Data

Index Number	Previous Voltage	Dummy Variable 1	Volts / EFPY
1	0.09	0.00	0.06
2	0.09	0.00	0.10
3	0.10	0.00	0.10
4	0.10	0.00	0.11
5	0.11	0.00	0.03
6	0.11	0.00	0.05
7	0.11	0.00	0.07
8	0.12	0.00	0.05
9	0.12	0.00	0.08
...	...	...	...
967	1.77	1.15	0.04
968	1.82	1.20	1.35
969	1.87	1.25	1.44
970	1.90	1.28	2.62
971	1.91	1.29	0.04
972	1.92	1.30	2.15
973	1.96	1.34	1.46
974	1.97	1.35	0.24
975	2.00	1.38	1.83

Table 10-6
Cycle 10 Data Added to Cycle 11

Index Value	BOC Amplitude (Volts)	Growth (Volts/EFPY)
1	1.18	0.13
2	1.18	0.38
3	1.19	0.21
4	1.20	0.08
5	1.20	0.50
6	1.21	0.46
7	1.22	0.37
8	1.22	0.54
9	1.23	0.00
10	1.25	0.29
11	1.25	0.66
12	1.26	0.19
13	1.26	2.89
14	1.28	0.18
15	1.28	1.01
16	1.30	0.08
17	1.30	0.13
18	1.31	1.10
19	1.34	1.38
20	1.35	0.01
21	1.35	1.88
22	1.39	2.55
23	1.47	0.00
24	1.47	0.53
25	1.58	2.53
26	1.62	0.10
27	1.64	1.25
28	1.76	1.65
29	1.89	1.74
30	1.93	0.80

Table 10-7
Recommended Limiting Growth Distribution for Indications in Deplugged Tubes During First Cycle of Operation

Growth Volts/EFPY	Number of Indications ($n_{i,dg}$)	Cumulative Probability
0	2	0.018
0.1	20	0.198
0.2	24	0.414
0.3	17	0.568
0.4	9	0.649
0.5	9	0.730
0.6	4	0.766
0.7	5	0.811
0.8	5	0.856
0.9	5	0.901
1	1	0.910
1.2	2	0.928
1.3	1	0.937
1.7	3	0.964
1.8	1	0.973
1.9	2	0.991
3.8	1	1

Table 10-8
Combining Growth Data for Active and Deplugged Tubes Indications Using Recommended Method

Number of Indications in Tubes Active Prior Cycle = 97

Number of Indications in Deplugged Tubes Returned to Service = 89

Growth	Active Tubes Growth (from Prior Cycles)		Recommended Deplugged Tubes Growth		Composite Growth#	
Volts/EFPY	No. of Indications	CPDF	No. of Indications	CPDF	No. of Indications	CPDF
0	26	0.321	2	0.018	32.7	0.176
0.1	26	0.642	20	0.198	47.2	0.430
0.2	10	0.765	24	0.414	31.2	0.597
0.3	11	0.901	17	0.568	26.8	0.742
0.4	2	0.926	9	0.649	9.6	0.793
0.5	3	0.963	9	0.730	10.8	0.851
0.6	0	0.963	4	0.766	3.2	0.869
0.7	0	0.963	5	0.811	4.0	0.890
0.8	0	0.963	5	0.856	4.0	0.912
0.9	0	0.963	5	0.901	4.0	0.933
1	0	0.963	1	0.910	0.8	0.938
1.1	1	0.975	0	0.910	1.2	0.944
1.2	1	0.988	2	0.928	2.8	0.959
1.3	0	0.988	1	0.937	0.8	0.963
1.5	1	1	0	0.937	1.2	0.970
1.7	0		3	0.964	2.4	0.983
1.8	0		1	0.973	0.8	0.987
1.9	0		2	0.991	1.6	0.996
3.8	0		1	1	0.8	1
Total	81		111		186	

Composite growth calculated using Equation (1). For example, number of indications in the 0.1 volt growth bin is given by [(26/89)*97 + (20/111)*89] = 47.2.

Table 10-9
Comparison of Leak and Burst Results for a Cycle in which Deplugged Tubes are Returned to Service – Plant A-2

Case	Analysis Type		POD	No. of Indications[1]	Max. Volts[2]	Burst Probability		SLB Leak Rate (gpm)
						1 Tube	1 or more Tubes	
Based on Actual Measured Voltages [2]								
1	Analyst variability σ = 10.3%		1	232	6.8[3]	8.2×10^{-4}	8.4×10^{-4}	2.8
2	Analyst variability σ = 5%					5.8×10^{-4}	5.8×10^{-4}	2.6
Projections Based on Prior Cycle data (No distinction made between indications in active and deplugged tubes)								
3	Same growth for all indications		0.6	252	3.9	1.2×10^{-4}	1.2×10^{-4}	1.8
Projections Using Larger Growth Rates for Deplugged Tubes (Composite growth based on all SG data applied for deplugged tubes)								
4	No voltage dependency for growth	Tubes in service prior cycle[4]	POPCD	132.2	3.5	5.2×10^{-5}	5.2×10^{-5}	0.7
5		Indications in deplugged tubes only[5]		106.4	6.4	4.1×10^{-4}	4.1×10^{-4}	1.8
6		All Indications Combined EOC Volts[6]		238.6	6.5	4.8×10^{-4}	4.8×10^{-4}	2.6
7		All Indications Composite growth[7]		238.6	6.3	4.2×10^{-4}	4.2×10^{-4}	2.5
8[8]					6.4[8]	4.9×10^{-4}[8]	4.9×10^{-4}[8]	2.7[8]
9		All Indications Composite growth[7]	0.6	252[9]	6.3	4.2×10^{-4}	4.2×10^{-4}	2.7
10	Voltage dependent growth 50 indications in the top bin	Indications in deplugged tubes only[5]	POPCD	106.4	6.7	5.3×10^{-4}	5.3×10^{-4}	1.8
11		All Indications Combined EOC Volts[6]		238.6	6.7	4.8×10^{-4}	4.8×10^{-4}	2.5
12		All Indications Composite growth[7]		238.6	6.7	5.3×10^{-4}	5.3×10^{-4}	2.5

Notes:
1) Number of indications adjusted for POD.
2) Voltages include NDE uncertainties from Monte Carlo analyses.
3) Largest actual voltage assigned in the inspection.
4) Based on growth rate data for indications in tubes active during the prior cycle.
5) Bounding growth rate distribution recommended for deplugged tubes applied.
6) To obtain 95%/95% leak rate and burst probability, EOC voltage distributions obtained separately for active and deplugged tube indications were combined and leak and burst calculation were repeated.
7) A composite growth distribution obtained by combining growth data for active and deplugged tubes applied.
8) Largest SG-specific growth applied for deplugged tube indications.
9) No POD adjustment for deplugged tube indications.

Table 10-10
New Indications during First Year of Operation in Deplugged Tubes Returned to Service

Indications	SG-A	SG-B	SG-C	Total
Plant A-2 - Deplugged Tubes Returned to Service in 1995				
Indications detected in 1995	21	1	86	108
Indications detected in 1996	21	1	89	111
New Indication in 1996	0	0	3	3
Percent of 1996 indications new	0.0%	0.0%	3.4%	2.7%
Plant P - Deplugged Tubes Returned to Service in 1995				
Indications detected in 1995	113	110	0	223
Indications detected in 1996	128	124	0	252
New Indication in 1996	15	14	0	29
Percent of 1996 indications new	11.7%	11.3%	0.0%	11.5%
Plant P - Deplugged Tubes Returned to Service in 1996				
Indications detected in 1996	133	123	252	508
Indications detected in 1997	138	137	261	536
New Indication in 1997	9	14	20	43
1996 Ind. not found in 1997	4	0	11	15
Percent of 1997 indications new	6.5%	10.2%	7.7%	8.0%

Table 10-11
Recommended Limiting Growth Distribution during First Cycle of Operation for Indications in Deplugged Tubes Growth Dependent on BOC Voltage

BOC Voltages < or = 1.2 volts		BOC Voltages > 1.2 volts	
Growth Volts/EFPY	Cumulative Probability	Growth Volts/EFPY	Cumulative Probability
0	0.016	0.000	0.020
0.1	0.279	0.100	0.100
0.2	0.574	0.200	0.220
0.3	0.754	0.300	0.340
0.4	0.820	0.400	0.440
0.5	0.902	0.500	0.520
0.7	0.934	0.600	0.600
0.9	0.967	0.700	0.660
1.8	0.984	0.800	0.760
1.9	1.000	0.900	0.820
		1.000	0.840
		1.200	0.880
		1.300	0.900
		1.700	0.960
		1.900	0.980
		3.8	1.000

Table 10-12
Data Used to Obtain Recommended Limiting Growth Distribution for Indications in Deplugged Tubes

BOC Volts	Growth Volts/EFPY	BOC Volts	Growth Volts/EFPY	BOC Volts	Growth Volts/EFPY
0.28	0.161	0.93	0.153	1.28	0.092
0.37	0.161	0.95	0.490	1.29	1.302
0.39	0.092	0.95	1.731	1.31	0.697
0.45	0.153	0.95	0.452	1.31	0.735
0.5	0.268	0.95	0.008	1.31	0.245
0.56	0.253	0.96	0.268	1.32	1.891
0.56	0.046	0.97	0.145	1.32	0.904
0.58	0.161	1.02	0.245	1.32	0.015
0.61	0.038	1.02	0.038	1.39	0.230
0.65	0.054	1.04	0.061	1.39	0.436
0.65	0.345	1.07	0.107	1.4	0.850
0.66	0.819	1.09	1.899	1.43	0.237
0.69	0.069	1.09	0.092	1.46	0.123
0.69	0.100	1.11	0.145	1.48	0.582
0.69	0.100	1.11	0.413	1.48	1.126
0.7	0.329	1.12	0.651	1.49	0.337
0.72	0.100	1.12	0.620	1.55	0.168
0.72	0.008	1.13	0.452	1.57	0.184
0.73	0.161	1.13	0.214	1.59	0.796
0.75	0.207	1.14	0.391	1.59	0.398
0.76	0.184	1.15	0.322	1.6	0.429
0.76	0.130	1.16	0.858	1.66	0.467
0.77	0.253	1.16	0.161	1.66	0.107
0.79	0.191	1.17	0.199	1.7	0.184
0.79	0.100	1.2	0.375	1.71	0.965
0.81	0.184	1.2	0.130	1.73	0.345
0.82	0.100	1.21	1.646	1.78	0.482
0.82	0.299	1.22	0.613	1.83	0.796
0.83	0.260	1.22	0.574	1.87	0.781
0.84	0.115	1.22	0.222	1.89	3.706
0.89	0.168	1.24	0.766	1.91	1.608
0.89	-0.008	1.24	0.360	1.98	0.505
0.9	0.015	1.26	0.038	1.99	1.195
0.9	0.176	1.26	0.283	2	0.651
0.91	0.299	1.26	0.054	2.19	1.669
0.91	0.276	1.27	0.827	2.36	-0.092
0.92	0.413	1.27	0.222	2.79	0.574

Table 10-13
Comparison of Leak and Burst Results for a Cycle in which Deplugged Tubes are Returned to Service – Plant P

Case	Analysis Type	POD	No. of Indica-tions[1]	Max. Volts[2]	Burst Probability		SLB Leak Rate (gpm)
					1 Tube	1 or more Tubes	
Steam Generator A							
1	Based on actual measured voltages	1	1241	2.5[3]	9.7×10^{-5}	9.7×10^{-5}	2.4
2	Projections based on prior cycle data Same growth rate applied for indications in both active and deplugged tubes	0.6	1513.5	2.9	1.2×10^{-4}	1.2×10^{-4}	4.3
3	Projections using plant-specific growth rates observed for deplugged tubes returned to service[4]	POPCD	1383.5	2.9	1.3×10^{-4}	1.3×10^{-4}	4.0
Steam Generator B							
4	Based on actual measured voltages	1	914	1.8[3]	3.7×10^{-5}	3.7×10^{-5}	1.9
5	Projections based on prior cycle data Same growth rate applied for indications in both active and deplugged	0.6	1235.8	3.7	1.8×10^{-4}	1.8×10^{-4}	4.5
6	Projections using plant-specific growth rates observed for deplugged tubes returned to service[4]	POPCD	1122.7	3.0	1.9×10^{-4}	1.9×10^{-4}	4.8

Table 10-14
Listing of Extreme Growth Values (Data Through Spring 2004, M = 115,179 Total Bobbin Indications)

Index	Tube Dia.	Plant	Cycle	Insp. Date	EFPY	Temp. °F	SG	Ind. in SG	Ind. in all SGs	Tube Row & Column	EOC Bobbin Volts	EOC RPC Volt	EOC RPC L(in.)	EOC[1] RPC Dmax	BOC Bobbin Volts	BOC RPC Volt	BOC RPC L(in.)	BOC[1] RPC Dmax	ΔV_2 600°F	ΔV_2 603°F	ΔV_2 610°F	ΔV_2 620°F
2	7/8	A-1	14	Apr-97	1.320	610.9	C	1140	3074	R2C85	13.74	4.9	0.71	100%	1.36	NA	NA	NA	*7.22*	*7.77*	*9.18*	*11.62*
11	7/8	A-1	15	Nov-98	1.290	610.9	C	1362	3502	R20C42	10.15	10.52	0.73	100%	1.23	NA	NA	NA	*5.32*	*5.72*	*6.77*	*8.57*
40	7/8	A-1	15	Nov-98	1.290	610.9	B	1101	3502	R2C75	7.17	3.92	0.69	100%	1.43	NA	NA	NA	*3.43*	*3.68*	*4.36*	*5.51*
20	3/4	AA-1	4	May-94	1.147	609.0	A	706	2731	R45C41	8.33	8.25	0.40	100%	1.66	NA	NA	NA	*4.68*	*5.04*	*5.96*	*7.54*
37	3/4	AA-1	4	May-94	1.147	609.0	A	706	2731	R18C23	5.54	6.72	0.48	100%	0.50	NA	NA	NA	*3.54*	*3.81*	*4.50*	*5.69*
3	3/4	AA-1	4	May-94	1.147	609.0	D	694	2731	R37C34	10.44	8.62	NA	100%	0.68	NA	NA	NA	*6.86*	*7.37*	*8.71*	*11.03*
9	3/4	AA-1	4	May-94	1.147	609.0	D	694	2731	R23C12	8.82	8.78	NA	100%	0.76	NA	NA	NA	*5.66*	*6.09*	*7.20*	*9.11*
21	3/4	AA-1	5A	Sep-95	0.714	609.0	C	1526	3935	R15C73	5.13	4.89	0.73	100%	1.01	1.17	0.43	76%	*4.65*	*5.00*	*5.91*	*7.48*
13	3/4	AA-1	6	Apr-97	1.035	614.0	A	1770	6784	R41C65	8.94	6.07	0.42	100%	1.47	NA	NA	NA	*5.16*	*5.55*	*6.57*	*8.31*
14	3/4	AA-1	6	Apr-97	1.035	614.0	A	1770	6784	R15C74	8.55	5.04	0.41	100%	1.23	NA	NA	NA	*5.06*	*5.44*	*6.43*	*8.14*
7	3/4	AA-1	6	Apr-97	1.035	614.0	C	2104	6784	R16C41	9.82	9.30	0.43	100%	1.52	1.64	0.609	83%	*5.74*	*6.17*	*7.29*	*9.23*
8	3/4	AA-1	6	Apr-97	1.035	614.0	C	2104	6784	R11C108	10.48	9.37	0.43	100%	2.19	1.99	0.601	86%	*5.73*	*6.16*	*7.29*	*9.22*
22	3/4	AA-1	6	Apr-97	1.035	614.0	C	2104	6784	R16C76	7.41	7.06	0.55	100%	0.89	NA	NA	NA	*4.51*	*4.85*	*5.73*	*7.25*
26	3/4	AA-1	6	Apr-97	1.035	614.0	C	2104	6784	R13C73	9.15	7.84	0.39	100%	2.94	2.76	0.547	92%	*4.29*	*4.62*	*5.46*	*6.91*
27	3/4	AA-1	6	Apr-97	1.035	614.0	C	2104	6784	R15C69	7.31	6.61	0.45	100%	1.13	NA	NA	NA	*4.27*	*4.59*	*5.43*	*6.87*
30	3/4	AA-1	6	Apr-97	1.035	614.0	C	2104	6784	R27C79	7.83	7.21	0.41	100%	1.85	NA	NA	NA	*4.13*	*4.45*	*5.26*	*6.65*
28	3/4	AA-1	6	Apr-97	1.035	614.0	D	2102	6784	R15C7	8.82	7.38	0.44	100%	2.64	3.34	0.538	96%	*4.27*	*4.59*	*5.43*	*6.87*
25	3/4	AB-1	6	Sep-94	1.277	608.0	A	802	3075	R3C3	7.64	5.74	NA	100%	0.93	NA	NA	NA	*4.34*	*4.66*	*5.51*	*6.97*
33	3/4	AB-1	6	Sep-94	1.277	608.0	A	802	3075	R20C7	7.10	3.69	NA	97%	1.14	NA	NA	NA	*3.85*	*4.14*	*4.89*	*6.19*
4	3/4	AB-1	6	Sep-94	1.277	608.0	C	899	3075	R20C7	10.95	4.59	NA	100%	1.09	NA	NA	NA	*6.37*	*6.85*	*8.10*	*10.25*
29	3/4	AB-1	7B	May-96	0.240	609.0	A	1023	5719	R13C4	3.49	2.31	NA	89%	2.23	0.58	0.376	63%	*4.23*	*4.55*	*5.38*	*6.80*
5	3/4	AB-1	7B	May-96	0.240	609.0	B	1791	5719	R21C103	3.33	1.24	NA	77%	1.47	NA	NA	NA	*6.24*	*6.71*	*7.94*	*10.04*
10	3/4	AB-1	7B	May-96	0.240	609.0	B	1791	5719	R14C109	3.44	3.53	NA	97%	1.83	NA	NA	NA	*5.40*	*5.81*	*6.87*	*8.69*
15	3/4	AB-1	7B	May-96	0.240	609.0	B	1791	5719	R19C104	4.45	2.16	NA	88%	2.95	0.91	0.502	72%	*5.04*	*5.41*	*6.40*	*8.10*
6	3/4	AB-1	7B	May-96	0.240	609.0	C	2040	5719	R12C16	2.38	NA	NA	NA	0.64	NA	NA	NA	*5.84*	*6.28*	*7.42*	*9.40*
16	3/4	AB-1	7B	May-96	0.240	609.0	C	2040	5719	R24C28	2.23	NA	NA	NA	0.73	NA	NA	NA	*5.04*	*5.41*	*6.40*	*8.10*
17	3/4	AB-1	7B	May-96	0.240	609.0	C	2040	5719	R40C79	2.72	NA	NA	NA	1.24	NA	NA	NA	*4.97*	*5.34*	*6.32*	*7.99*
24	3/4	AB-1	7B	May-96	0.240	609.0	C	2040	5719	R38C81	2.21	2.15	NA	88%	0.91	NA	NA	NA	*4.36*	*4.69*	*5.55*	*7.02*

Table 10-14 (continued)
Listing of Extreme Growth Values (Data Through Spring 2004, M = 115,179 Total Bobbin Indications)

Index	Tube Dia.	Plant	Cycle	Insp. Date	EFPY	Temp. °F	SG	Ind. in SG	Ind. in all SGs	Tube Row & Column	EOC Bobbin Volts	EOC RPC Volt	EOC RPC L(in.)	EOC[1] RPC Dmax	BOC Bobbin Volts	BOC RPC Volt	BOC RPC L(in.)	BOC[1] RPC Dmax	ΔV_2 600°F	ΔV_2 603°F	ΔV_2 610°F	ΔV_2 620°F
34	3/4	AC-2	8	Mar-01	1.254	620.0	A	611	3580	R23C24	8.05	7.03	0.63	100%	0.38	NA	NA	NA	*3.80*	*4.09*	*4.83*	*6.12*
39	3/4	AC-2	8	Mar-01	1.254	620.0	A	611	3580	R20C80	7.32	6.47	0.67	100%	0.39	NA	NA	NA	*3.44*	*3.69*	*4.37*	*5.53*
41	3/4	AC-2	8	Mar-01	1.254	620.0	A	611	3580	R22C78	7.05	5.40	0.66	100%	0.22	NA	NA	NA	*3.39*	*3.64*	*4.30*	5.45
47	3/4	AC-2	8	Mar-01	1.254	620.0	A	611	3580	R22C30	6.95	5.61	0.61	100%	0.61	NA	NA	NA	*3.14*	*3.38*	*4.00*	*5.06*
19	3/4	AC-2	8	Mar-01	1.254	620.0	B	1229	3580	R15C89	9.72	7.61	0.71	100%	0.18	NA	NA	NA	*4.73*	*5.08*	*6.01*	*7.61*
44	3/4	AC-2	8	Mar-01	1.254	620.0	B	1229	3580	R20C48	6.93	4.90	0.44	100%	0.20	NA	NA	NA	*3.34*	*3.59*	*4.24*	*5.37*
31	3/4	AC-2	8	Mar-01	1.254	620.0	C	972	3580	R20C106	8.16	7.19	0.58	100%	0.30	NA	NA	NA	*3.90*	*4.19*	*4.95*	*6.27*
32	3/4	AC-2	8	Mar-01	1.254	620.0	C	972	3580	R20C73	8.07	7.43	0.61	100%	0.28	0.86	NA	79%	*3.86*	*4.15*	*4.91*	*6.21*
36	3/4	AC-2	8	Mar-01	1.254	620.0	C	972	3580	R19C79	7.69	6.88	0.46	100%	0.53	NA	NA	NA	*3.55*	*3.82*	*4.51*	*5.71*
42	3/4	AC-2	8	Mar-01	1.254	620.0	C	972	3580	R22C92	7.36	7.20	0.55	100%	0.54	NA	NA	NA	*3.38*	*3.64*	*4.30*	*5.44*
12	3/4	AC-2	8	Mar-01	1.254	620.0	D	768	3580	R24C47	11.06	9.05	0.37	100%	0.34	NA	NA	NA	*5.31*	*5.71*	*6.76*	*8.55*
18	3/4	AC-2	8	Mar-01	1.254	620.0	D	768	3580	R10C109	10.37	5.05	0.62	100%	0.44	NA	NA	NA	*4.92*	*5.29*	*6.26*	*7.92*
35	3/4	AC-2	8	Mar-01	1.254	620.0	D	768	3580	R25C72	7.45	4.62	0.68	100%	0.27	NA	NA	NA	*3.56*	*3.83*	*4.52*	*5.73*
38	3/4	AC-2	8	Mar-01	1.254	620.0	D	768	3580	R24C68	7.85	4.93	0.7	100%	0.85	NA	NA	NA	*3.47*	*3.73*	*4.41*	*5.58*
43	3/4	AC-2	8	Mar-01	1.254	620.0	D	768	3580	R25C47	7.21	6.07	0.54	100%	0.47	NA	NA	NA	*3.34*	*3.59*	*4.25*	*5.37*
45	3/4	AC-2	8	Mar-01	1.254	620.0	D	768	3580	R24C46	7.06	6.71	0.58	100%	0.39	NA	NA	NA	*3.31*	*3.56*	*4.20*	*5.32*
46	3/4	AC-2	8	Mar-01	1.254	620.0	D	768	3580	R23C42	6.82	6.12	0.57	100%	0.30	NA	NA	NA	*3.23*	*3.48*	*4.11*	*5.20*
23	7/8	W-2	12	Nov-03	1.373	609.7	3	307	1545	R8C58	9.76	8.56	0.75	100%	1.98	NA	NA	NA	*4.49*	*4.83*	*5.71*	*7.22*
1	7/8	Y-2	11	Feb-03	1.643	603.0	4	982	1873	R44C55	21.5	12.24	0.75	100%	2.00	2.47	0.71	100%	*11.04*	*11.87*	*14.04*	*17.77*

Notes:

1) Maximum depth calculated from amplitude sizing for Plus Point coil volts by applying a correlation based on 2.75 Plus Point coil volts for 100 percent depth. When volts are pancake coil data (Plants AA and AB), pancake coil volts are adjusted by factors of 0.65 for 3/4 inch tubing (Reference: EPRI Topical Report 1007904, Section B.10.2), respectively, to estimate Plus Point coil volts.

Table 10-15
Summary of Large V. C. Summer Indications
(FDB Elevation, 1993)

Steam Generator	Row	Column	Bobbin Amplitude	Location
B	42	43	22.32	01H + 0.00"
B	28	41	11.59	01H + 0.00"
B	33	20	9.84	01H + 0.00"
B	31	45	7.72	01H + 0.00"
B	30	45	6.02	01H + 0.00"

Table 10-16
List of Extreme Growth Values, Volts/EFPY Adjusted to 610°F

Index	Plant Name	Plant ID	Tube Size (inch)	Growth, ΔV (Volts)
1	Braidwood 1	AA1	3/4	5.26
2	Byron 1	AB1	3/4	5.38
3	Braidwood 1	AA1	3/4	5.43
4	Braidwood 1	AA1	3/4	5.43
5	Braidwood 1	AA1	3/4	5.46
6	Byron 1	AB1	3/4	5.51
7	Byron 1	AB1	3/4	5.55
8	Sequoyah 2	W2	7/8	5.71
9	Braidwood 1	AA1	3/4	5.73
10	Braidwood 1	AA1	3/4	5.91
11	Braidwood 1	AA1	3/4	5.96
12	South Texas 2	AC2	3/4	6.01
13	South Texas 2	AC2	3/4	6.26
14	Byron 1	AB1	3/4	6.32
15	Byron 1	AB1	3/4	6.40
16	Byron 1	AB1	3/4	6.40
17	Braidwood 1	AA1	3/4	6.43
18	Braidwood 1	AA1	3/4	6.57
19	South Texas 2	AC2	3/4	6.76
20	Farley 1	A1	7/8	6.77
21	Byron 1	AB1	3/4	6.87
22	Braidwood 1	AA1	3/4	7.20
23	Braidwood 1	AA1	3/4	7.29
24	Braidwood 1	AA1	3/4	7.29
25	Byron 1	AB1	3/4	7.42
26	Byron 1	AB1	3/4	7.94
27	Byron 1	AB1	3/4	8.10
28	Braidwood 1	AA1	3/4	8.71
29	Farley 1	A1	7/8	9.18
30	Diablo Canyon 2	Y2	7/8	14.04

Table 10-17
Probability of Large Extremes for Two Sample Sizes

Number of Large Extremes	Probability of Large Extremes Based on M = 100,000 & K = 20			
	Sample 500	Frequency in 100,000	Sample 1,000	Frequency in 100,000
0	$9.05 \cdot 10^{-1}$	90483	$8.19 \cdot 10^{-1}$	81871
1	$9.05 \cdot 10^{-2}$	9050	$1.64 \cdot 10^{-1}$	16378
2	$4.52 \cdot 10^{-3}$	452	$1.64 \cdot 10^{-2}$	1636
3	$1.50 \cdot 10^{-4}$	15	$1.09 \cdot 10^{-3}$	109
4	$3.73 \cdot 10^{-6}$	0	$5.43 \cdot 10^{-5}$	5
5	$7.40 \cdot 10^{-8}$	0	$2.16 \cdot 10^{-6}$	0
6	$1.22 \cdot 10^{-9}$	0	$7.18 \cdot 10^{-8}$	0

Table 10-18
Total Expected Number of Extremes

M (Total)	K (Extremes)	Pr(Extreme)	N (Indications)	Number of Sims
115,179	21	0.000182	500	100,000
z (Extremes)	Pr(z)	Pr(Not z)	Pr(≤ z)	SG Sims with z
0	0.912862	0.08714	0.91286	91286
1	0.083234	0.91677	0.99610	8323
2	0.003787	0.99621	0.99988	378
3	0.000115	0.99989	1.00000	11
4	2.60E-06	1.00000	1.00000	0
5	4.70E-08	1.00000	1.00000	0
6	7.07E-10	1.00000	1.00000	0
Extremes Limited to 7/8" Tubes				
56,874	3	0.000053	500	100,000
z (Extremes)	Pr(z)	Pr(Not z)	Pr(≤ z)	SG Sims with z
0	0.973970	0.02603	0.97397	97396
1	0.025689	0.97431	0.99966	2568
2	0.000338	0.99966	1.00000	33
3	2.96E-06	1.00000	1.00000	0
4	1.94E-08	1.00000	1.00000	0
5	1.02E-10	1.00000	1.00000	0
6	4.42E-13	1.00000	1.00000	0
Extremes Limited to 3/4" Tubes				
58,305	18	0.000309	500	100,000
z (Extremes)	Pr(z)	Pr(Not z)	Pr(≤ z)	SG Sims with z
0	0.856942	0.14306	0.85694	85694
1	0.132319	0.86768	0.98926	13231
2	0.010195	0.98980	0.99946	1019
3	0.000523	0.99948	0.99998	52
4	0.000020	0.99998	1.00000	2
5	6.14E-07	1.00000	1.00000	0
6	1.57E-08	1.00000	1.00000	0

Table 10-19
Plant P-1: Successive Cycle +Point Data for Highest Bobbin Volts, +Point Volts and Ratio of +Point to Bobbin Volts

Tube		Bobbin Volts			+Point Volts			Ratio +Point to Bobbin Volts		
SG	Row/Col	1R13	1R14	1R15	1R13	1R14	1R15	1R13	1R14	1R15
A	10/66	1.56	1.22	2.23	0.82	1.71	2.74	0.53	1.40	1.23
	31/62	1.69	1.78	1.82	1.30	1.40	NA	0.77	0.79	
	35/35	1.50	1.58	1.75	1.65	1.23	1.87	1.10	0.78	1.07
	5/59	0.30	0.35	0.54	NA	NA	1.12			2.07
	5/72	0.95	0.70	0.96	0.58	NA	1.19	0.61		1.24
	11/77	1.07	1.32	4.57	NA	0.61	2.41			0.53
	25/48	1.18	1.15	1.21	1.33	NA	NA	1.13		
B	3/71	1.24	1.29	NA	1.49	1.52	NA	1.20	1.18	
	18/68	1.32	2.04	Plugged	0.94	0.86	Plugged	0.71		
	15/31	0.26	0.38	0.32	0.52	NA	NA	2.00		
	17/28	0.19	0.28	0.36	0.26	NA	NA	1.37		
C	15/62	1.86	5.30	Plugged	0.43	2.94	Plugged	0.23	0.55	
	28/31	1.47	1.59	1.81	1.06	1.13	1.49	0.72	0.71	0.82
	31/35	1.32	1.90	1.77	1.13	0.94	NA	0.86	0.49	
	29/27	1.92	2.00	1.97	0.99	1.13	NA	0.52	0.57	
	32/28	1.59	1.66	1.74	0.94	1.19	1.58	0.59	0.72	0.91
	28/49	1.98	1.91	1.96	1.02	0.98	NA	0.52	0.51	

Table 10-20
Plant Y-1: Successive Cycle +Point Data for Highest Bobbin Volts, +Point Volts and Ratio of +Point to Bobbin Volts

Tube			Bobbin Volts			+Point Volts			Ratio +Point to Bobbin Volts		
SG	Row	Col	1R9	1R10	1R11	1R9	1R10	1R11	1R9	1R10	1R11
11	10	71	0.71	0.95	1.75	0.22	0.59	1.20	0.31	0.62	0.69
	18	31	--	0.43	1.20	--	0.15	0.17	--	0.35	0.14
	26	63	--	0.57	1.03	--	0.33	0.48	--	0.58	0.47
	27	47	0.83	1.14	2.26	0.26	0.58	1.16	0.31	0.51	0.51
12	7	49	--	0.49	1.02	--	0.19	0.16	--	0.39	0.16
	8	20	0.64	0.95	1.20	0.20	0.31	0.31	0.31	0.33	0.26
	14	30	--	0.73	1.09	--	0.29	0.32	--	0.40	0.29
	15	74	--	1.35	1.30	--	0.28	0.34	--	0.21	0.26
	16	40	0.29	0.75	1.11	0.17	0.26	0.57	0.59	0.35	0.51
	17	47	0.41	0.72	1.48	0.19	0.54	1.03	0.46	0.75	0.70
	25	85	--	0.68	1.19	--	0.31	0.40	--	0.46	0.34
	26	52	0.59	1.19	1.76	0.17	0.48	0.40	0.29	0.40	0.23
	28	50	0.44	1.32	1.85	0.20	0.67	0.31	0.45	0.51	0.17
14	3	47	--	0.91	1.23	--	0.14	0.34	--	0.15	0.28
	4	6	1.43	1.37	1.02	0.25	0.23	0.17	0.17	0.17	0.17
	5	78	--	0.81	1.17	--	0.30	0.32	--	0.37	0.27
	8	29	--	1.73	2.33	--	0.34	0.56	--	0.20	0.24
	14	36	--	0.98	1.05	--	0.28	0.38	--	0.29	0.36

Table 10-21
Plant Y-2: Successive Cycle +Point Data for Highest Bobbin Volts, +Point Volts and Ratio of +Point to Bobbin Volts

Tube			Bobbin Volts			+Point Volts			Ratio +Point to Bobbin Volts		
SG	Row	Col	2R9	2R10	2R11	2R9	2R10	2R11	2R9	2R10	2R11
21	3	46	--	0.67	1.21	0.16	0.19	0.24	--	0.28	0.20
	12	68	--	0.51	1.21	0.27	0.26	0.41	--	0.51	0.34
	13	39	0.20	0.66	0.93	0.27	0.30	0.45	1.35	0.45	0.48
	30	52	0.26	0.45	0.82	--	0.59	1.02	--	1.31	1.24
22	7	82	--	1.10	1.92	--	1.10	1.63	--	1.00	0.85
23	12	8	--	0.69	1.12	--	0.47	0.81	--	0.68	0.72
	17	34	--	0.62	1.60	--	0.37	1.16	--	0.60	0.73
	18	48	--	0.71	1.08	--	0.32	0.47	--	0.45	0.44
	20	32	--	0.53	1.18	--	0.47	0.91	--	0.89	0.77
	39	45	--	1.19	1.55	--	0.30	0.41	--	0.25	0.26
	44	42	--	0.71	1.00	--	0.23	0.37	--	0.32	0.37
24	2	47	0.26	0.53	1.06	--	0.28	0.44	--	0.53	0.42
	4	40	0.90	1.04	2.00	0.38	--	1.61	0.42	--	0.81
	4	68	1.01	1.97	2.37	0.26	--	0.95	0.26	--	0.40
	12	38	0.97	1.90	6.20	0.45	--	4.25	0.46	--	0.69
	13	66	1.05	1.71	1.96	0.89	1.60	1.86	0.85	0.94	0.95
	13	76	0.91	1.19	5.27	0.21	--	1.76	0.23	--	0.33
	15	45	--	0.45	0.68	--	0.93	1.37	--	2.07	2.01
	19	84	1.22	2.00	5.00	--	0.94	2.69	--	0.47	0.54
	22	47	--	0.73	1.09	--	0.13	0.19	--	0.18	0.17
	24	73	1.62	1.77	1.83	1.14	1.08	1.07	0.70	0.61	0.58
	30	20	1.22	1.75	2.17	0.81	--	1.15	0.66	--	0.53
	34	43	--	1.12	1.73	0.31	0.40	0.72	--	0.36	0.42
	44	45	0.49	2.00	21.50	--	2.97	12.12	--	1.25	0.56

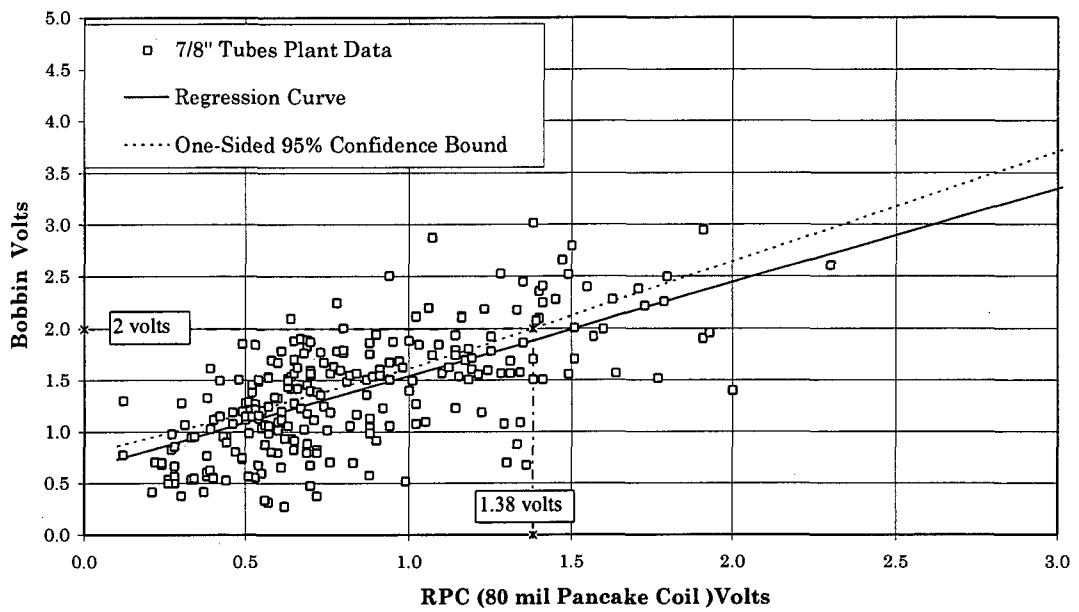


Figure 10-1
Bobbin to RPC Voltage Correlation for an Example Case Bobbin Volts vs. 80 mil Mid Range Pancake RPC Volts

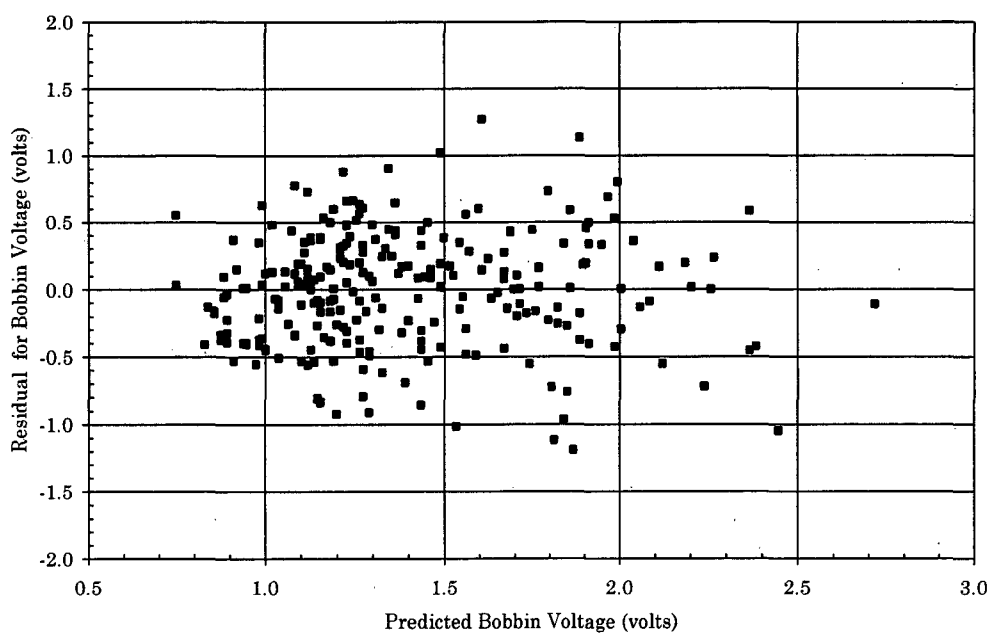


Figure 10-2
Bobbin to RPC Voltage Correlation for an Example Case Scatter Plot of Residuals – Linear Bobbin vs. Linear RPC

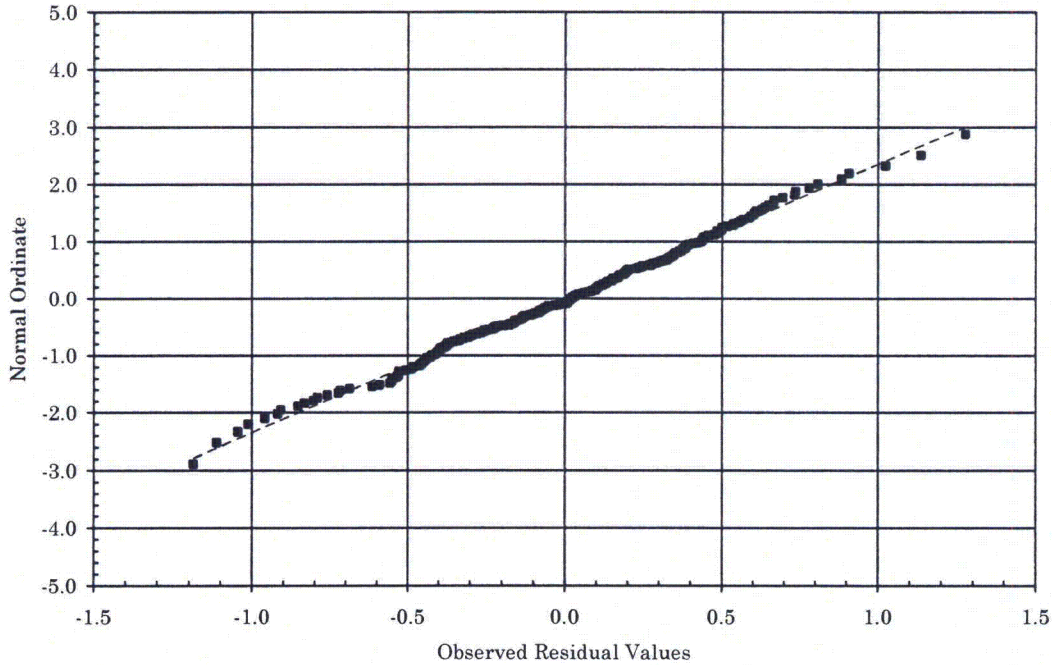


Figure 10-3
Bobbin to RPC Voltage Correlation for an Example Case Normal Plot of Residuals – Linear Bobbin vs. Linear RPC

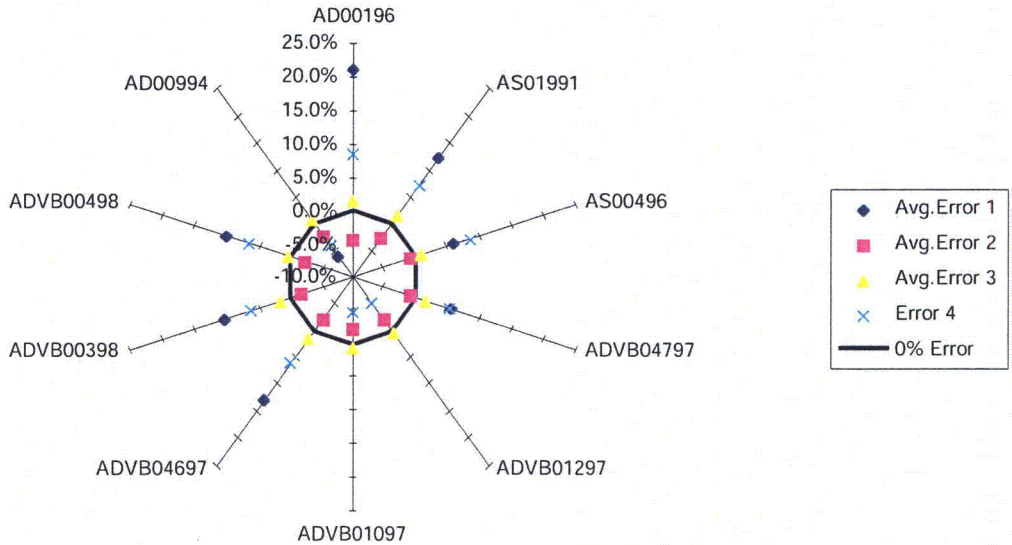


Figure 10-4
Plot of Average Errors

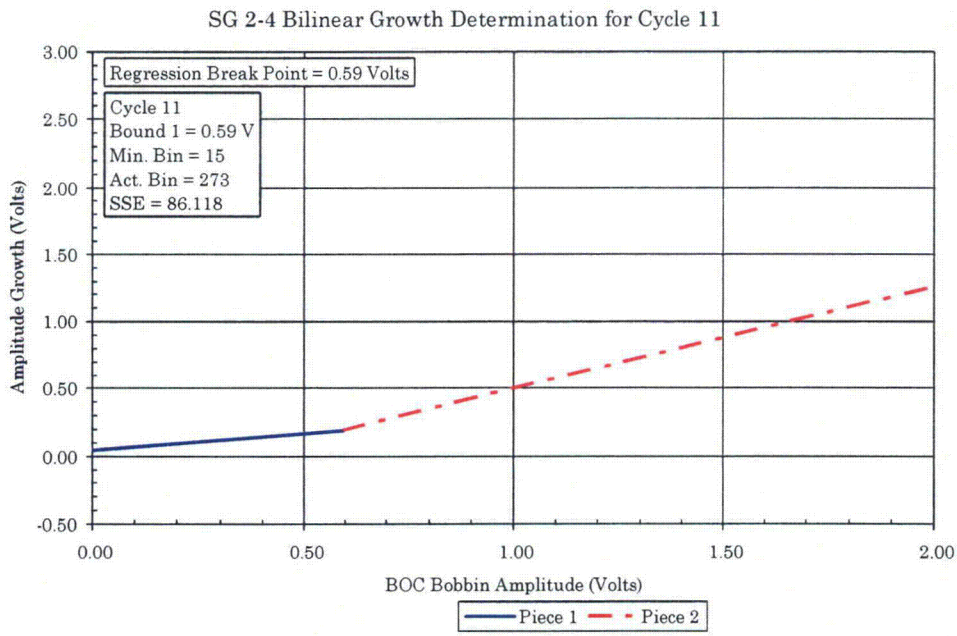


Figure 10-5
Bilinear Regression Line Illustration

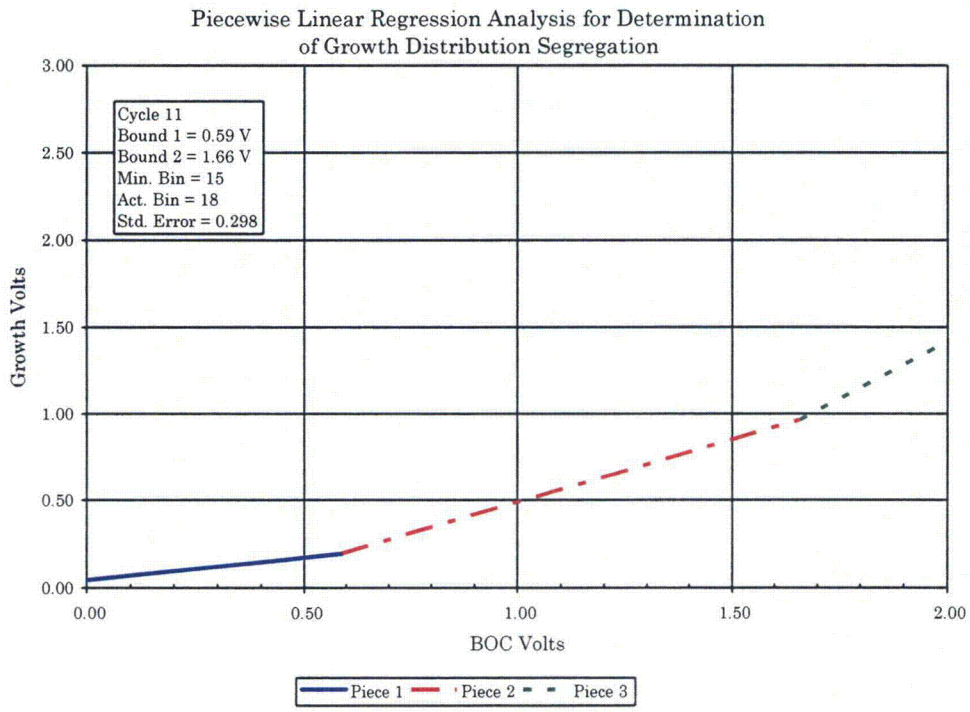


Figure 10-6
Trilinear Regression Line Illustration

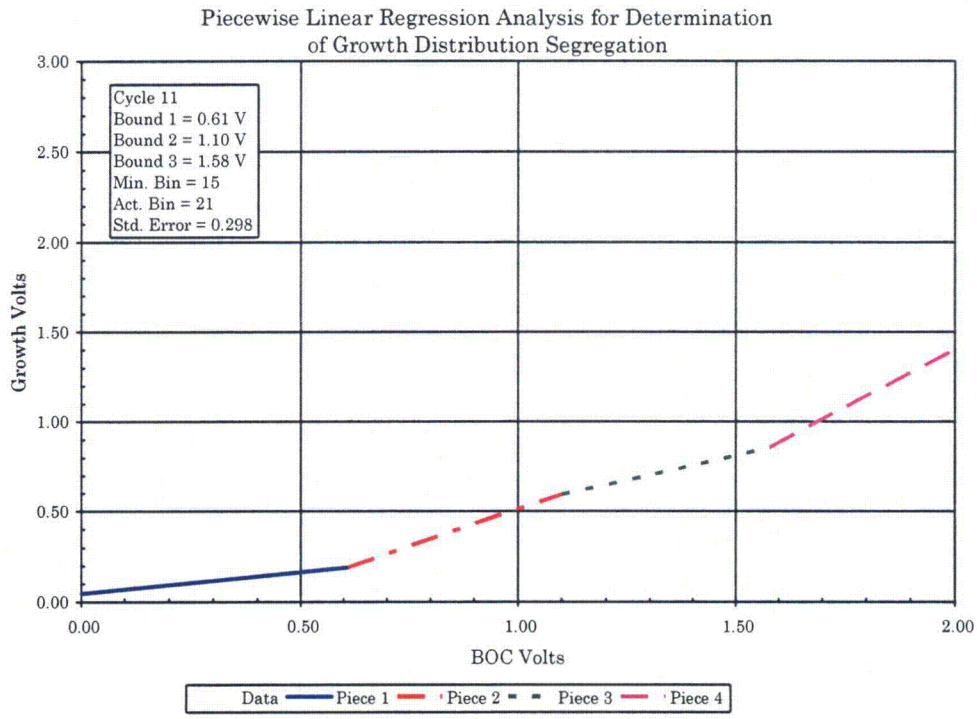
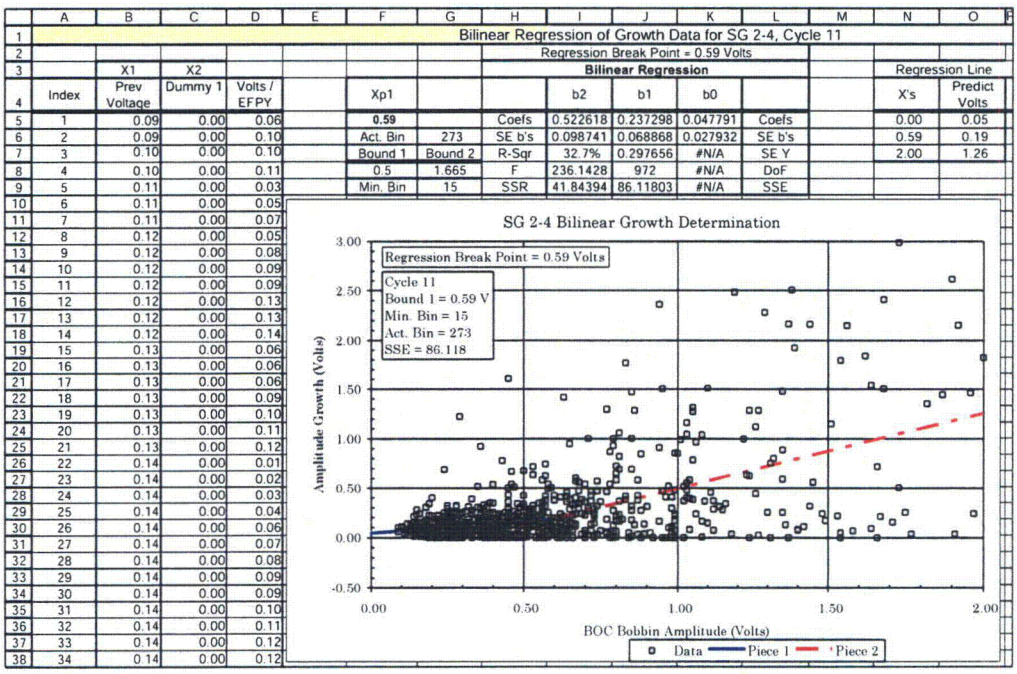


Figure 10-7
Quadrilinear Regression Line Illustration



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Bilinear Regression of Growth Data for SG 2-4, Cycle 11														
2								Regression Break Point = 0.59 Volts							
3		X1	X2					Bilinear Regression						Regression Line	
4	Index	Prev Voltage	Dummy 1	Volts / EFPY		Xp1			b2	b1	b0			X's	Predict Volts
5	1	0.09	0.00	0.06		0.59		Coefs	0.522618	0.237298	0.047791	Coefs		0.00	0.05
6	2	0.09	0.00	0.10		Act. Bin	273	SE b's	0.098741	0.068868	0.027932	SE b's		0.59	0.19
7	3	0.10	0.00	0.10		Bound 1	Bound 2	R-Sqr	32.7%	0.297656	#N/A	SE Y		2.00	1.26
8	4	0.10	0.00	0.11		0.5	1.665	F	236.1428	972	#N/A	DoF			
9	5	0.11	0.00	0.03		Min. Bin	15	SSR	41.84394	86.11803	#N/A	SSE			
10	6	0.11	0.00	0.05											
11	7	0.11	0.00	0.07											
12	8	0.12	0.00	0.05											
13	9	0.12	0.00	0.08											
14	10	0.12	0.00	0.09											
15	11	0.12	0.00	0.09											
16	12	0.12	0.00	0.13											
17	13	0.12	0.00	0.13											
18	14	0.12	0.00	0.14											
19	15	0.13	0.00	0.06											
20	16	0.13	0.00	0.06											
21	17	0.13	0.00	0.06											
22	18	0.13	0.00	0.09											
23	19	0.13	0.00	0.10											
24	20	0.13	0.00	0.11											
25	21	0.13	0.00	0.12											
26	22	0.14	0.00	0.01											
27	23	0.14	0.00	0.02											
28	24	0.14	0.00	0.03											
29	25	0.14	0.00	0.04											
30	26	0.14	0.00	0.06											
31	27	0.14	0.00	0.07											
32	28	0.14	0.00	0.08											
33	29	0.14	0.00	0.09											
34	30	0.14	0.00	0.09											
35	31	0.14	0.00	0.10											
36	32	0.14	0.00	0.11											
37	33	0.14	0.00	0.12											
38	34	0.14	0.00	0.12											

Figure 10-8
Excel Screen for Bilinear Regression Analysis

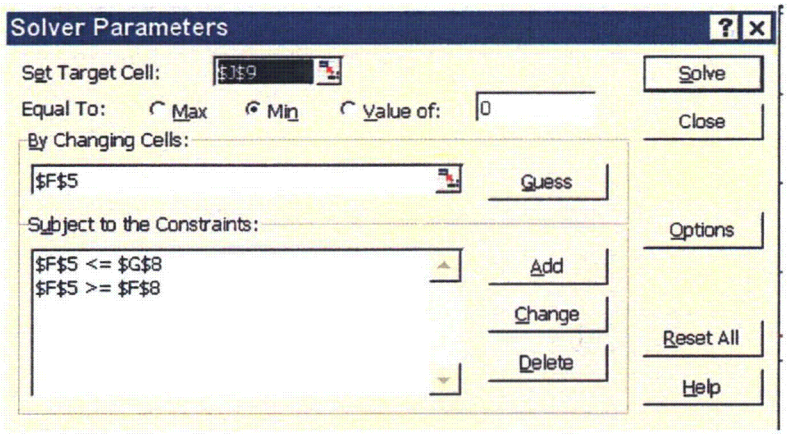


Figure 10-9
Excel Solver Screen for Bilinear Regression Analysis

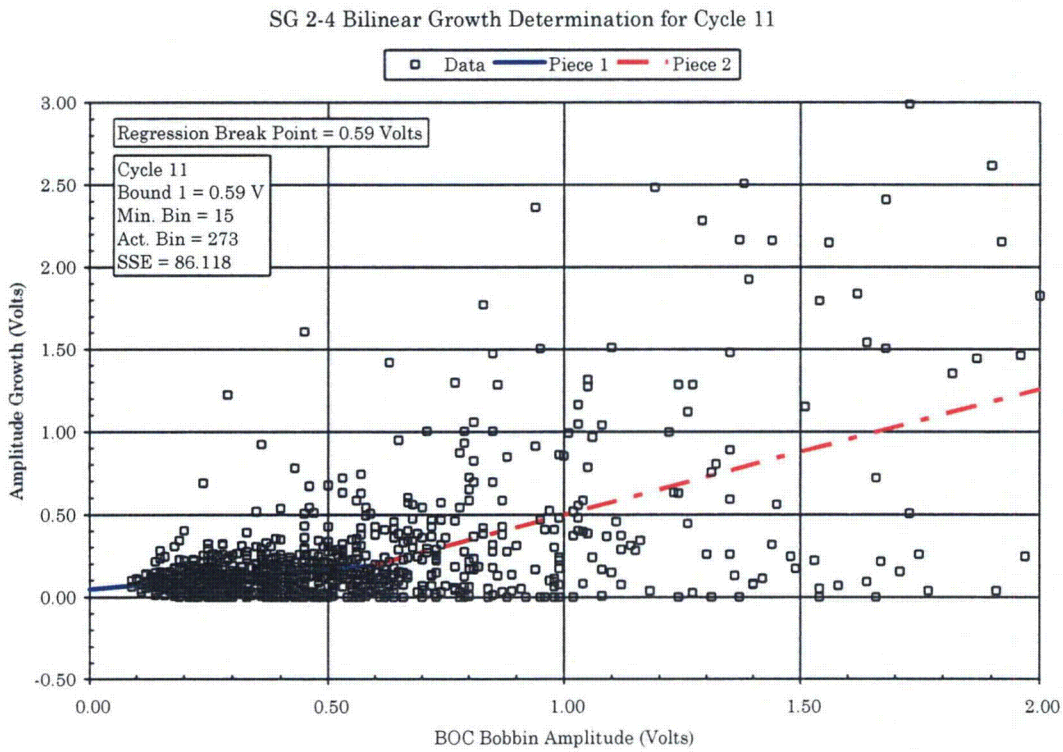


Figure 10-10
Bilinear Regression Lines for SG 2-4 Cycle 11 Growth Data

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Trilinear Regression of Growth Data for SG 2-4, Cycles 10 & 11														
2															
3		X1	X2	X3		Count	1005	Trilinear Regression						Regression Line	
4	Index	Prev Voltage	Dummy 1	Dummy 2	Volts / EFPY	Xp1	Xp2	Item	b3	b2	b1	b0	Item	X's	Predict Volts
5	1	0.09	0.00	0.00	0.06	**0.59**	**1.66**	Coefs	0.52884	0.50898	0.23727	0.047797	Coefs	0.00	0.05
6	2	0.09	0.00	0.00	0.10	Upper	19	SE b's	0.447836	0.111546	0.075824	0.030508	SE b's	0.59	0.19
7	3	0.10	0.00	0.00	0.10	Bound 1	Bound 2	R-Sqr	33.8%	0.322637	#N/A	#N/A	SE Pred	1.66	0.99
8	4	0.10	0.00	0.00	0.11	0.5	1.709	F	170.6574	1001	#N/A	#N/A	DoF	2.00	1.42
9	5	0.11	0.00	0.00	0.03	Min Bin	15	SSR	53.29344	104.1985	#N/A	#N/A	SSE		
10	6	0.11	0.00	0.00	0.05										
11	7	0.11	0.00	0.00	0.07										
12	8	0.12	0.00	0.00	0.05										
13	9	0.12	0.00	0.00	0.08										
14	10	0.12	0.00	0.00	0.09										
15	11	0.12	0.00	0.00	0.09										
16	12	0.12	0.00	0.00	0.13										
17	13	0.12	0.00	0.00	0.13										
18	14	0.12	0.00	0.00	0.14										
19	15	0.13	0.00	0.00	0.06										
20	16	0.13	0.00	0.00	0.06										
21	17	0.13	0.00	0.00	0.06										
22	18	0.13	0.00	0.00	0.09										
23	19	0.13	0.00	0.00	0.10										
24	20	0.13	0.00	0.00	0.11										
25	21	0.13	0.00	0.00	0.12										
26	22	0.14	0.00	0.00	0.01										
27	23	0.14	0.00	0.00	0.02										
28	24	0.14	0.00	0.00	0.03										
29	25	0.14	0.00	0.00	0.04										
30	26	0.14	0.00	0.00	0.06										
31	27	0.14	0.00	0.00	0.07										
32	28	0.14	0.00	0.00	0.08										
33	29	0.14	0.00	0.00	0.09										
34	30	0.14	0.00	0.00	0.09										
35	31	0.14	0.00	0.00	0.10										
36	32	0.14	0.00	0.00	0.11										
37	33	0.14	0.00	0.00	0.12										
38	34	0.14	0.00	0.00	0.12										

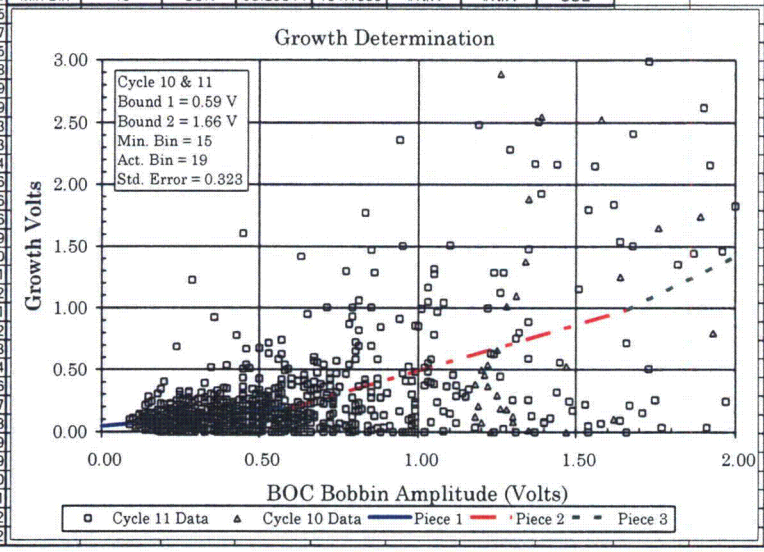


Figure 10-11
Excel Screen for Trilinear Regression Analysis

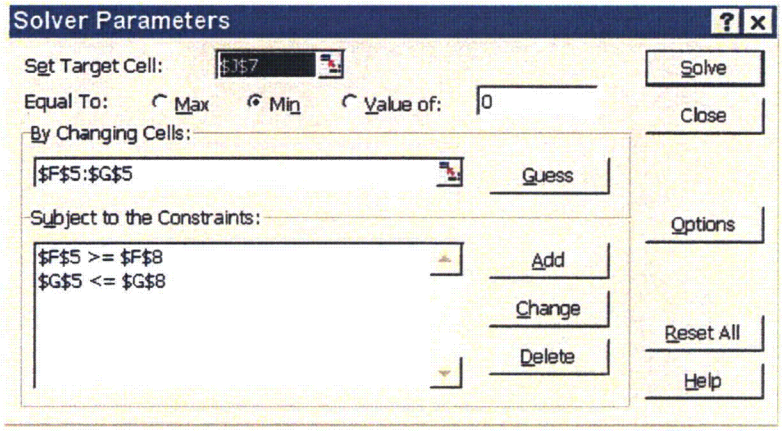


Figure 10-12
Excel Solver Screen for Trilinear Regression Analysis

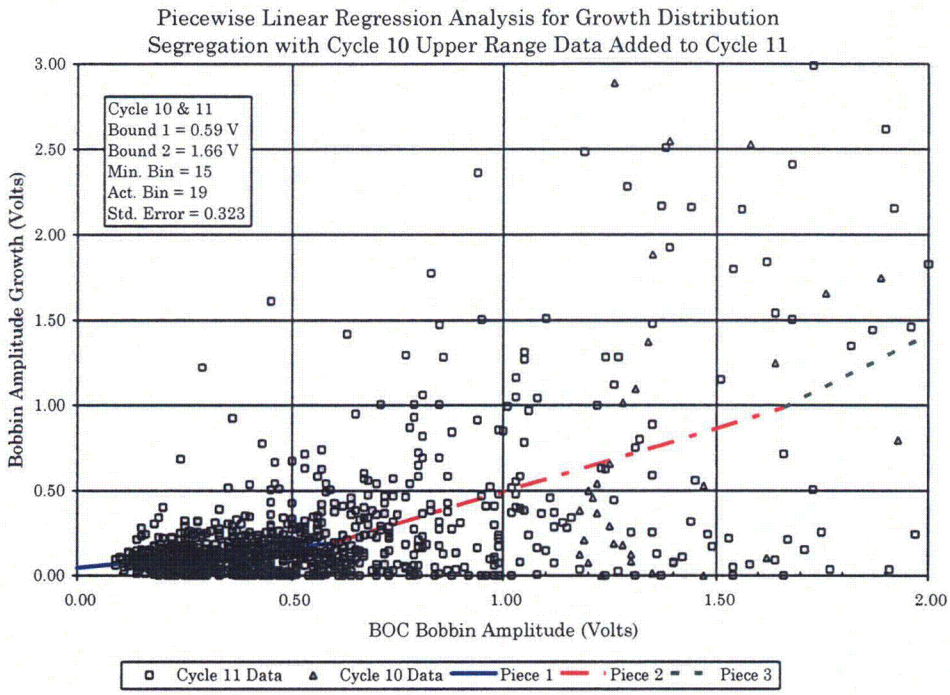


Figure 10-13
Trilinear Regression Lines for SG 2-4 Cycle 11 Growth Data

Quadrilinear Regression of Growth Data for SG 2-4, Cycle 11

								Cycle							
	X1	X2	X3	X4				11	Quadrilinear Regression						
Index	Prev Voltage	Dummy 1	Dummy 2	Dummy 3	Volts / EFPY	Xp1	Xp2	Xp3	Item	b4	b3	b2	b1	b0	Item
1	0.09	0.00	0.00	0.00	0.06	**0.61**	**1.10**	**1.58**	Coefs	0.757186	-0.27413	0.579332	0.239746	0.047118	Coefs
2	0.09	0.00	0.00	0.00	0.10		Act. Bin	21	SE b's	0.50295	0.253105	0.151708	0.071886	0.028407	SE b's
3	0.10	0.00	0.00	0.00	0.10	Bound 1	Bound 2	Bound 3	R-Sqr	32.9%	0.29762	#N/A	#N/A	#N/A	SE Y
4	0.10	0.00	0.00	0.00	0.11	0.50	1.40	1.67	F	118.6566	970	#N/A	#N/A	#N/A	DoF
5	0.11	0.00	0.00	0.00	0.03		Min. Bin	15	SSR	42.04141	85.92056	#N/A	#N/A	#N/A	SSE
6	0.11	0.00	0.00	0.00	0.05										
7	0.11	0.00	0.00	0.00	0.07										
8	0.12	0.00	0.00	0.00	0.05										
9	0.12	0.00	0.00	0.00	0.08										
10	0.12	0.00	0.00	0.00	0.09										
11	0.12	0.00	0.00	0.00	0.09										
12	0.12	0.00	0.00	0.00	0.13										
13	0.12	0.00	0.00	0.00	0.13										
14	0.12	0.00	0.00	0.00	0.14										
15	0.13	0.00	0.00	0.00	0.06										
16	0.13	0.00	0.00	0.00	0.06										
17	0.13	0.00	0.00	0.00	0.06										
18	0.13	0.00	0.00	0.00	0.09										
19	0.13	0.00	0.00	0.00	0.10										
20	0.13	0.00	0.00	0.00	0.11										
21	0.13	0.00	0.00	0.00	0.12										
22	0.14	0.00	0.00	0.00	0.01										
23	0.14	0.00	0.00	0.00	0.02										
24	0.14	0.00	0.00	0.00	0.03										
25	0.14	0.00	0.00	0.00	0.04										
26	0.14	0.00	0.00	0.00	0.06										
27	0.14	0.00	0.00	0.00	0.07										
28	0.14	0.00	0.00	0.00	0.08										
29	0.14	0.00	0.00	0.00	0.09										
30	0.14	0.00	0.00	0.00	0.09										
31	0.14	0.00	0.00	0.00	0.10										
32	0.14	0.00	0.00	0.00	0.11										
33	0.14	0.00	0.00	0.00	0.12										
34	0.14	0.00	0.00	0.00	0.12										

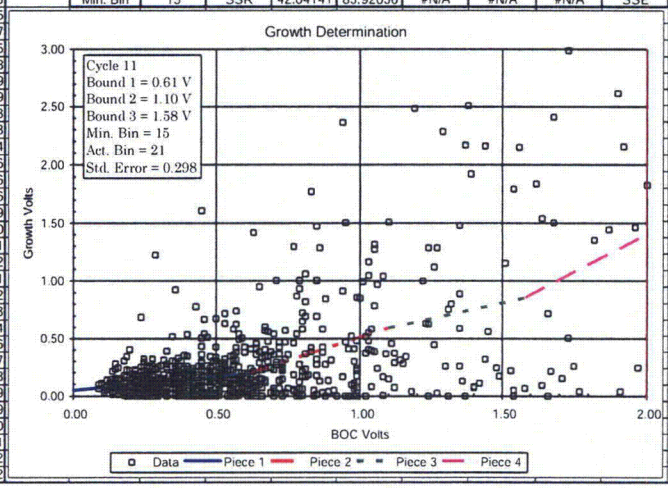


Figure 10-14
Excel Screen for Quadrilinear Regression Analysis

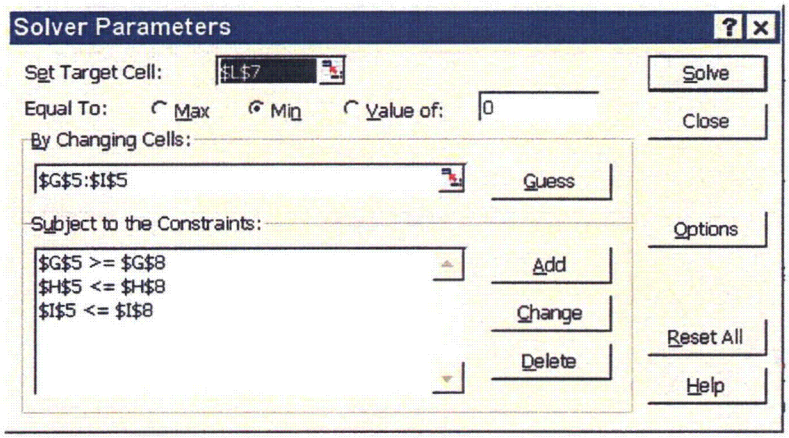


Figure 10-15
Excel Solver Screen for Quadrilinear Regression Analysis

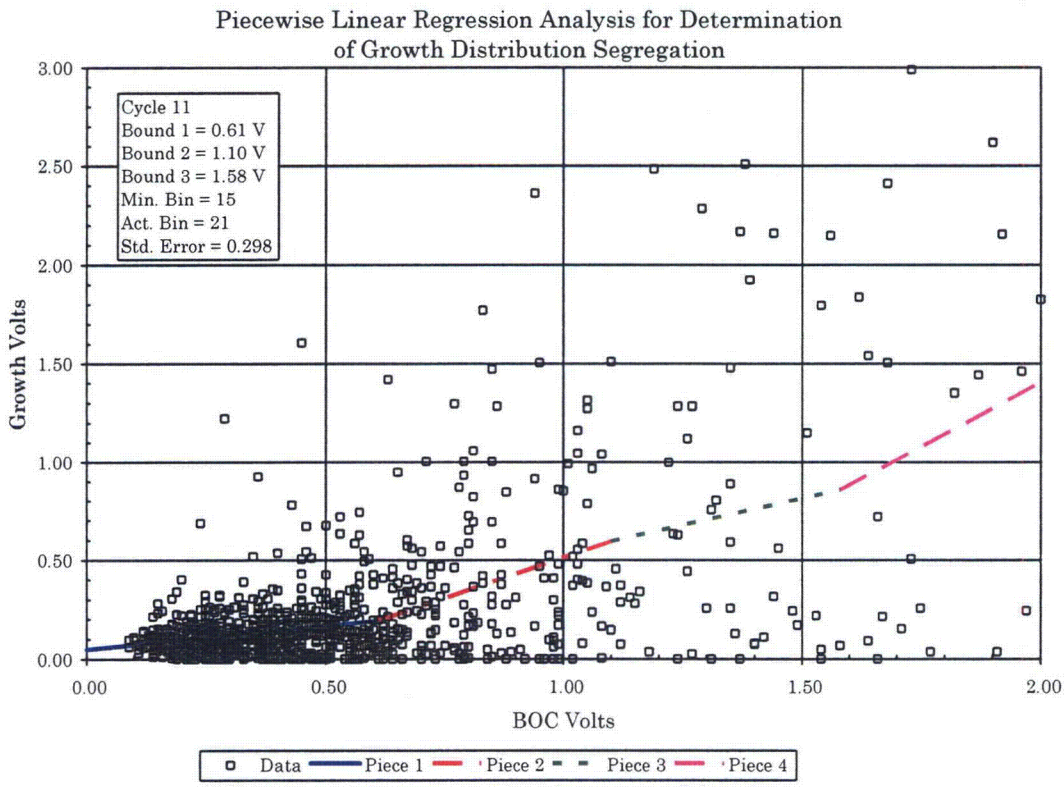


Figure 10-16
Quadrilinear Regression of SG 2-4 Cycle 11 Growth Data

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O
1	Trilinear Regression of Growth Data for SG 2-4, Cycle 10														
2															
3		X1	X2	X3				Tri-Linear Regression						Regression Line	
4	Index	Prev Voltage	Dummy 1	Dummy 2	Volts / EFPY	Xp1	Xp2		b3	b2	b1	b0		X's	Predict Volts
5	1	0.09	0.00	0.00	0.19	**0.69**	**1.17**	Coefs	0.75179	0.57116	0.11249	0.092858	Coefs	0.00	0.09
6	2	0.12	0.00	0.00	0.10	Element	30	SE b's	0.28264	0.17758	0.07993	0.035554	SE b's	0.69	0.17
7	3	0.12	0.00	0.00	0.41	Bound 1	Bound 2	R-Sqr	33.2%	0.25584	#N/A	#N/A	SE Pred	1.17	0.50
8	4	0.13	0.00	0.00	0.05	0.50	1.28	F	80.0806	484	#N/A	#N/A	DoF	2.00	1.69
9	5	0.13	0.00	0.00	0.14	Min Bin	15	SSR	15.7247	31.6796	#N/A	#N/A	SSE		
10	6	0.14	0.00	0.00	0.15										
11	7	0.14	0.00	0.00	0.15										
12	8	0.14	0.00	0.00	0.16										
13	9	0.14	0.00	0.00	0.20										
14	10	0.15	0.00	0.00	0.08										
15	11	0.15	0.00	0.00	0.09										
16	12	0.15	0.00	0.00	0.21										
17	13	0.16	0.00	0.00	0.01										
18	14	0.16	0.00	0.00	0.02										
19	15	0.16	0.00	0.00	0.03										
20	16	0.16	0.00	0.00	0.06										
21	17	0.16	0.00	0.00	0.11										
22	18	0.16	0.00	0.00	0.15										
23	19	0.16	0.00	0.00	0.16										
24	20	0.17	0.00	0.00	0.00										
25	21	0.17	0.00	0.00	0.04										
26	22	0.17	0.00	0.00	0.11										
27	23	0.17	0.00	0.00	0.21										
28	24	0.18	0.00	0.00	0.06										
29	25	0.18	0.00	0.00	0.10										
30	26	0.18	0.00	0.00	0.21										
31	27	0.18	0.00	0.00	0.22										
32	28	0.19	0.00	0.00	0.03										
33	29	0.19	0.00	0.00	0.15										
34	30	0.19	0.00	0.00	0.19										
35	31	0.20	0.00	0.00	0.00										
36	32	0.20	0.00	0.00	0.03										
37	33	0.20	0.00	0.00	0.03										
38	34	0.20	0.00	0.00	0.04										

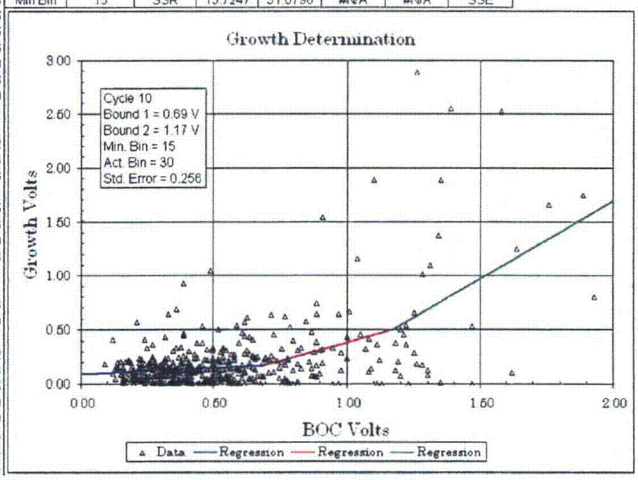


Figure 10-17
Excel Screen for SG 2 4 Cycle 10 Growth Data

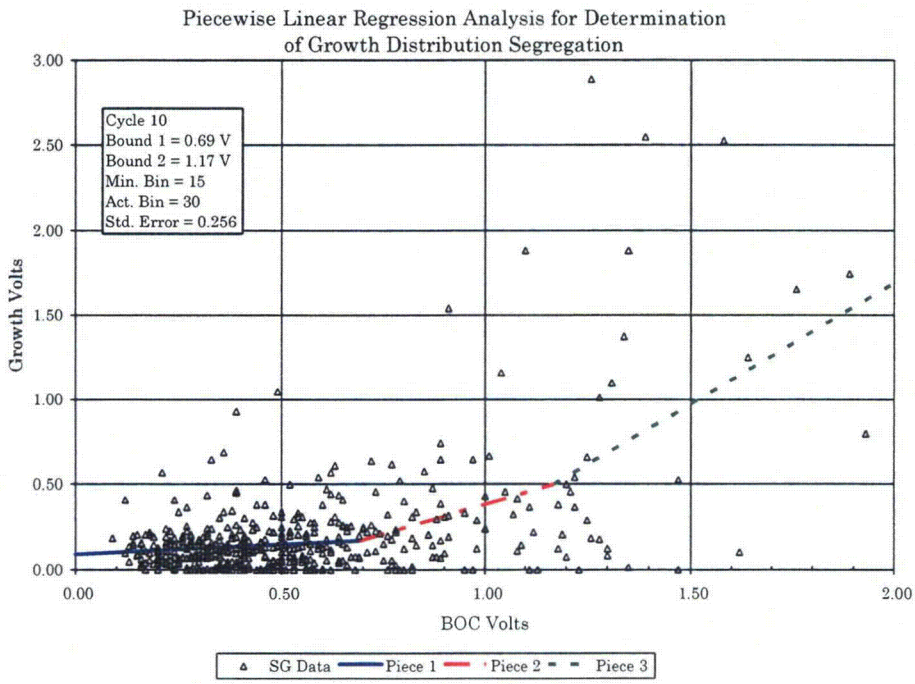


Figure 10-18
Quadrilinear Regression without a Data Limit on Piece 3

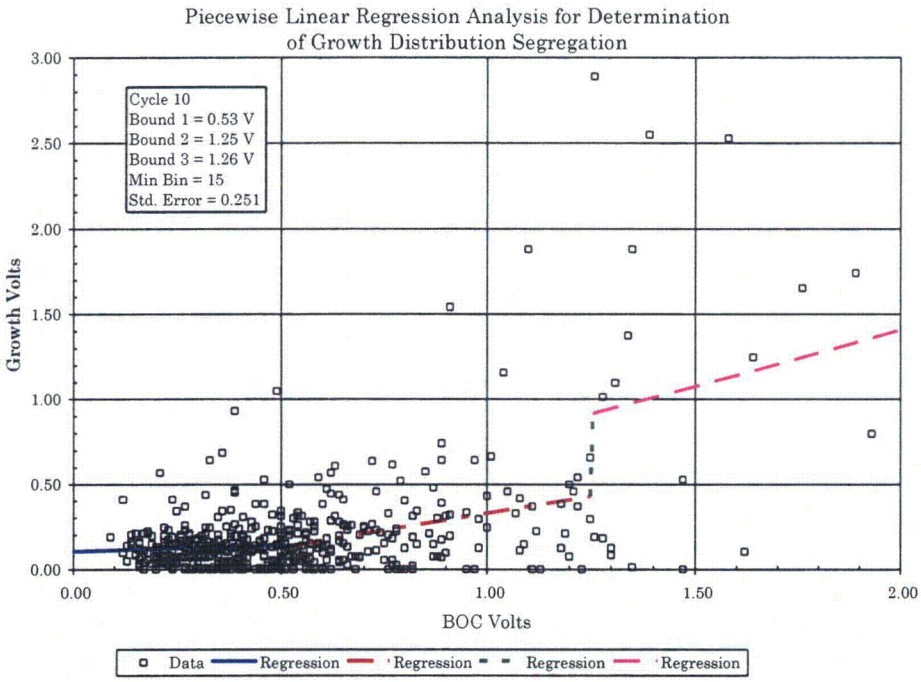


Figure 10-19
Trilinear Regression of SG 2-4 Cycle 10 Growth Data
(Illustration of an unsatisfactory analysis result)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R
1	Quadrilinear Regression of Growth Data for SG 2-4, Cycle 10																	
2																		
3		X1	X2	X3	X4							Quad-Linear Regression					Regression Line	
4	Index	Prev Voltage	Dummy 1	Dummy 2	Dummy 3	Volts / EFPY	Xp1	Xp2	Xp3		b4	b3	b2	b1	b0		X's	Predict Volts
5	1	0.09	0.00	0.00	0.00	0.19	**0.56**	**1.13**	**1.28**	Coefs	-1.4124	2.071103	0.348747	0.075907	0.104244	Coefs	0.00	0.10
6	2	0.12	0.00	0.00	0.00	0.10	Act Bin	15	15	SE b's	0.788419	0.686082	0.181235	0.101476	0.041105	SE b's	0.56	0.15
7	3	0.12	0.00	0.00	0.00	0.41	Bound 1	Bound 2	Bound 3	R-Sqr	33.6%	0.255333	#N/A	#N/A	#N/A	SE Y	1.13	0.39
8	4	0.13	0.00	0.00	0.00	0.05	0.50	1.13	1.28	F	61.02917	483	#N/A	#N/A	#N/A	DoF	1.28	0.76
9	5	0.13	0.00	0.00	0.00	0.14	Min Bin	15	15	SSR	15.91518	31.48917	#N/A	#N/A	#N/A	SSE	2.00	1.54
10	6	0.14	0.00	0.00	0.00	0.15												
11	7	0.14	0.00	0.00	0.00	0.15												
12	8	0.14	0.00	0.00	0.00	0.16												
13	9	0.14	0.00	0.00	0.00	0.20												
14	10	0.15	0.00	0.00	0.00	0.08												
15	11	0.15	0.00	0.00	0.00	0.09												
16	12	0.15	0.00	0.00	0.00	0.21												
17	13	0.16	0.00	0.00	0.00	0.01												
18	14	0.16	0.00	0.00	0.00	0.02												
19	15	0.16	0.00	0.00	0.00	0.03												
20	16	0.16	0.00	0.00	0.00	0.06												
21	17	0.16	0.00	0.00	0.00	0.11												
22	18	0.16	0.00	0.00	0.00	0.15												
23	19	0.16	0.00	0.00	0.00	0.16												
24	20	0.17	0.00	0.00	0.00	0.00												
25	21	0.17	0.00	0.00	0.00	0.04												
26	22	0.17	0.00	0.00	0.00	0.11												
27	23	0.17	0.00	0.00	0.00	0.21												
28	24	0.18	0.00	0.00	0.00	0.06												
29	25	0.18	0.00	0.00	0.00	0.10												
30	26	0.18	0.00	0.00	0.00	0.21												
31	27	0.18	0.00	0.00	0.00	0.22												
32	28	0.19	0.00	0.00	0.00	0.03												
33	29	0.19	0.00	0.00	0.00	0.15												
34	30	0.19	0.00	0.00	0.00	0.19												
35	31	0.20	0.00	0.00	0.00	0.00												
36	32	0.20	0.00	0.00	0.00	0.03												
37	33	0.20	0.00	0.00	0.00	0.03												
38	34	0.20	0.00	0.00	0.00	0.04												
39	35	0.20	0.00	0.00	0.00	0.06												
40	36	0.20	0.00	0.00	0.00	0.07												
41	37	0.20	0.00	0.00	0.00	0.08												

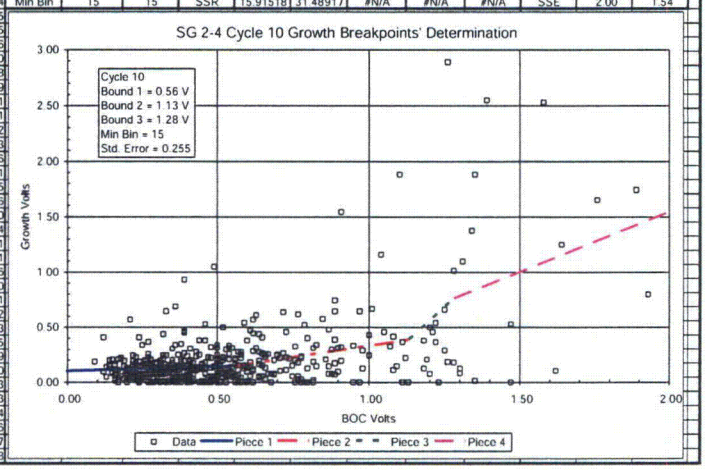


Figure 10-20
Quadrilinear Regression with a Data Limit on Piece 3

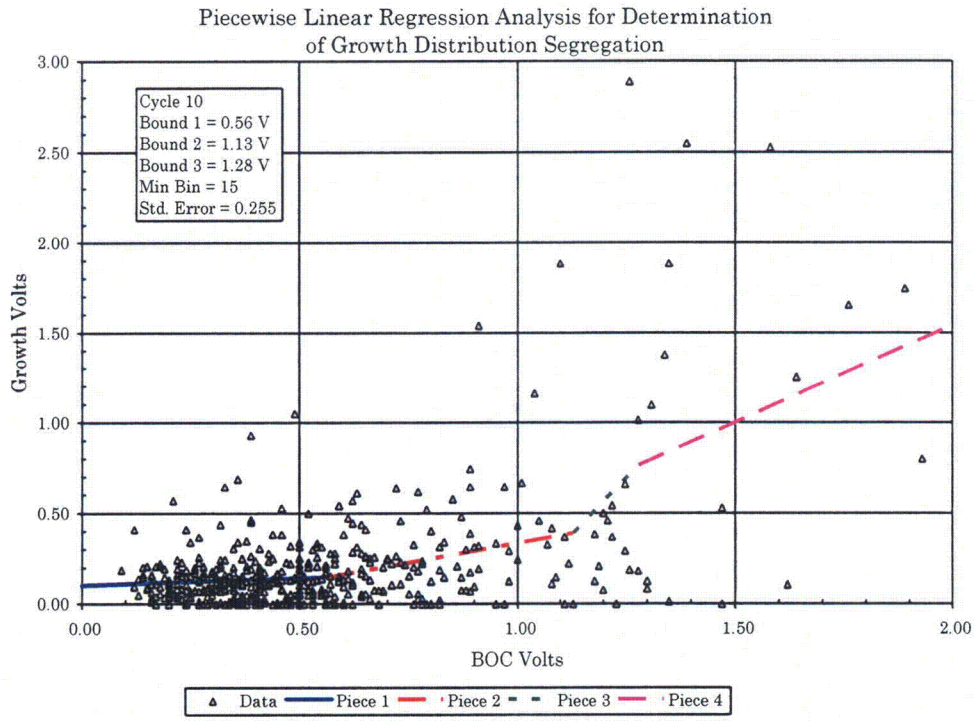


Figure 10-21
Quadrilinear Regression of SG 2-4 Cycle 10 Growth Data

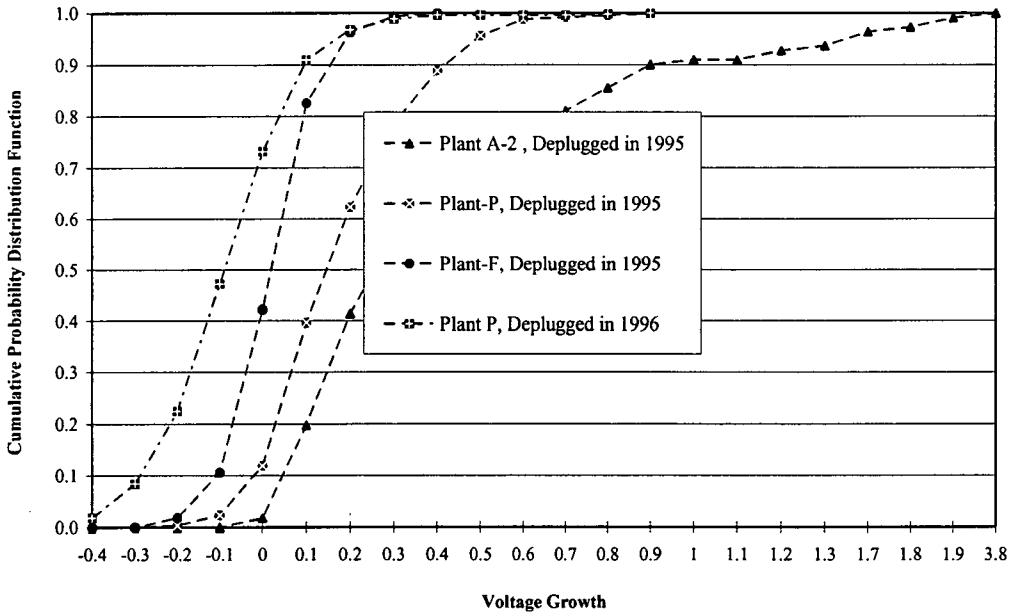


Figure 10-22
Growth Rates for Deplugged Tubes in the First Cycle After Return to Service Composite of Data from All SGs in a Plant Cumulative Probability Distributions for Growth on an EFPY Basis

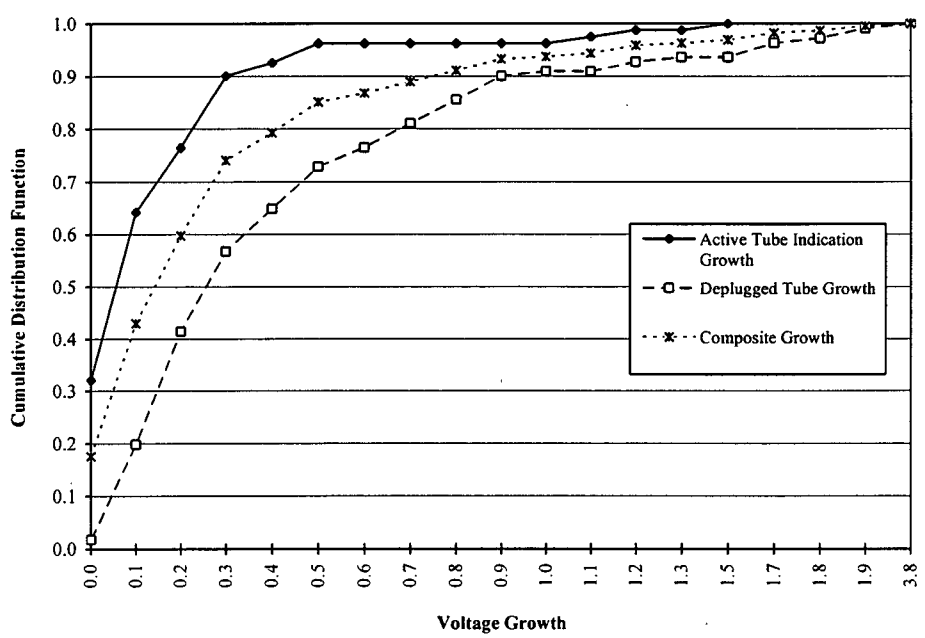


Figure 10-23
Composite Growth Distribution Based on Active and Deplugged Tube Growth Distributions

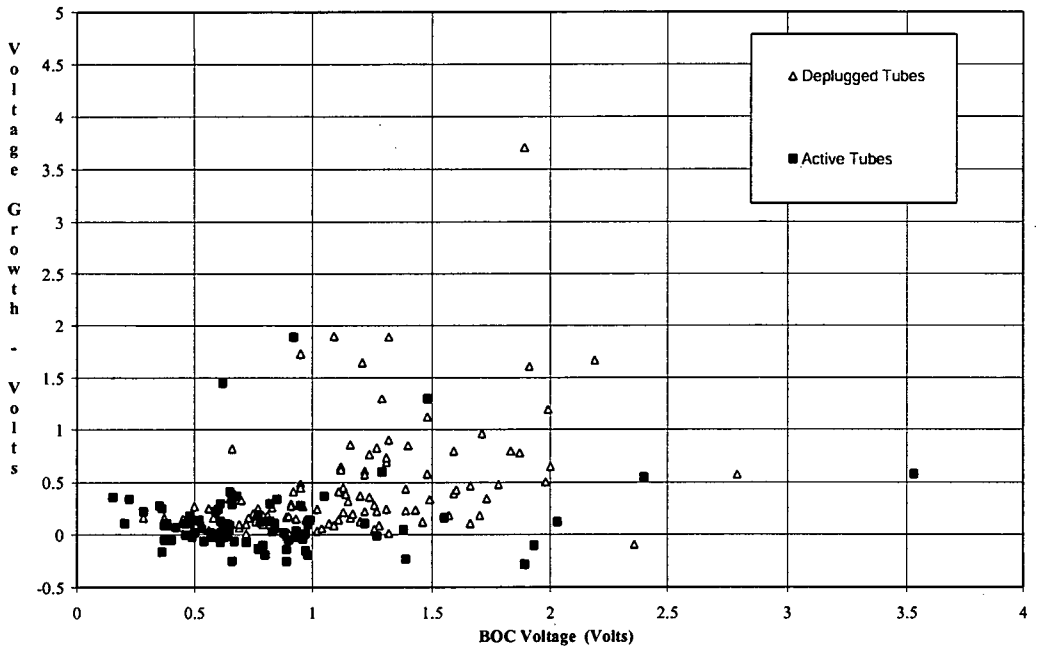


Figure 10-24
Voltage Growth vs. BOC Voltage Deplugged Tube Data is for First Cycle of Operation After Tubes Deplugged

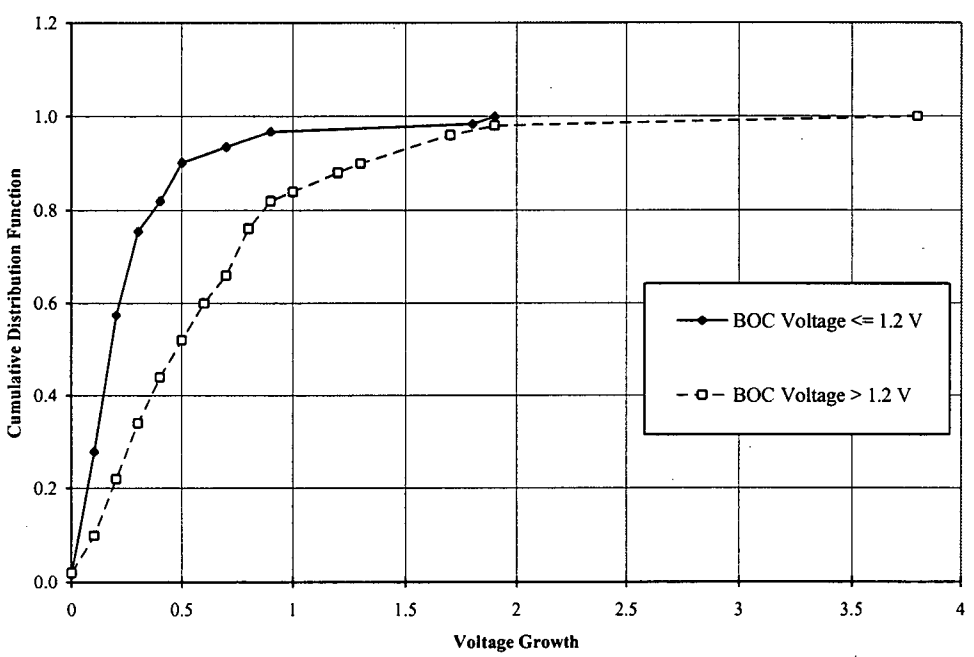


Figure 10-25
Limiting Growth Distribution Recommended for Deplugged Tube Indications Growth Considered Dependent of BOC Voltage

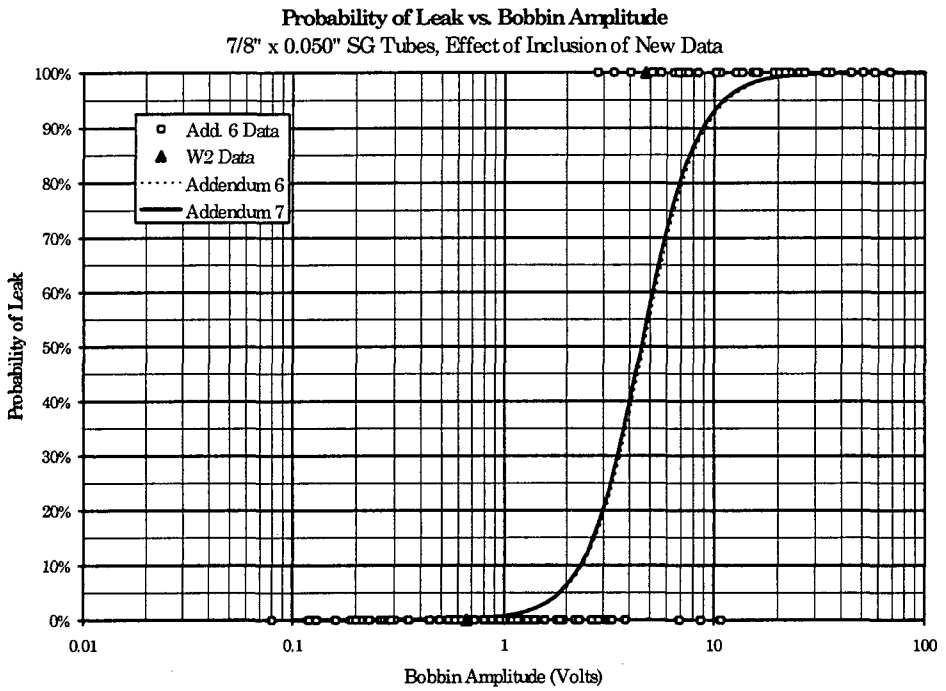


Figure 10-26
Probability of Leak for 7/8" Diameter Tubes

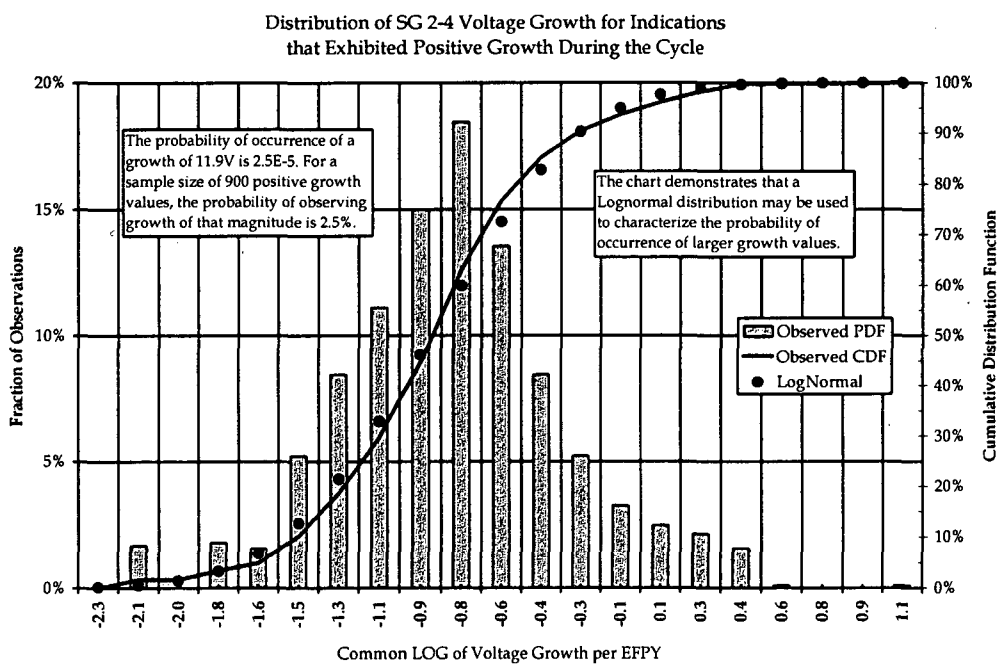


Figure 10-27
Distribution of Amplitude Growth for Cycle 11

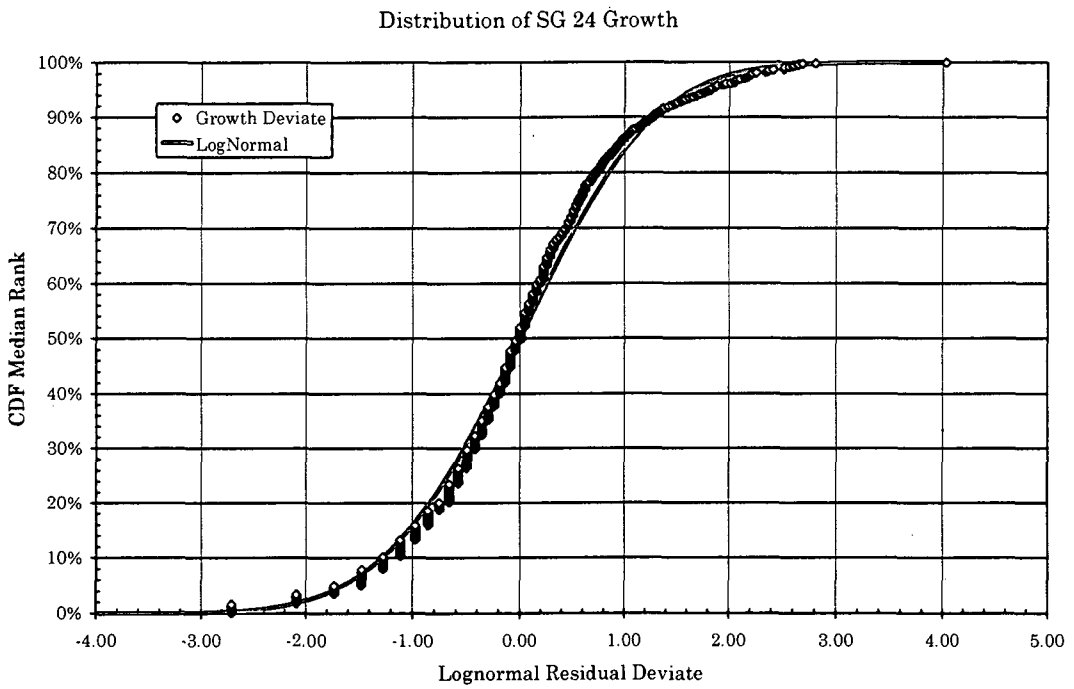


Figure 10-28
Amplitude Growth CDF vs. Lognormal CDF

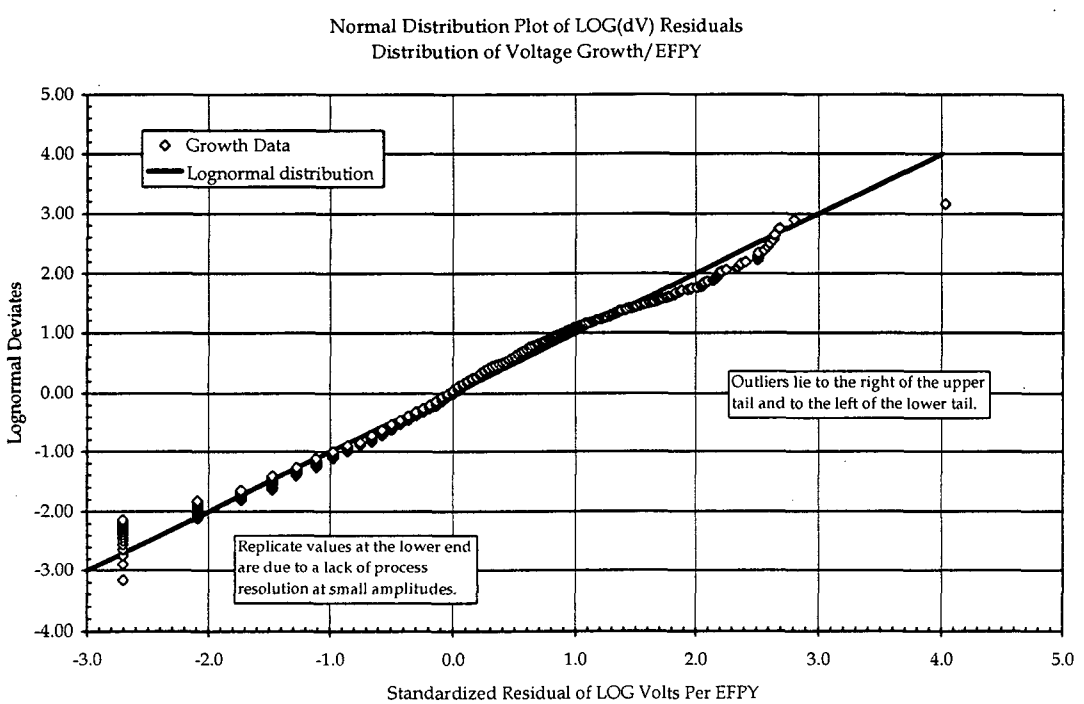


Figure 10-29
Normal Distribution Plot of Logarithm Residuals

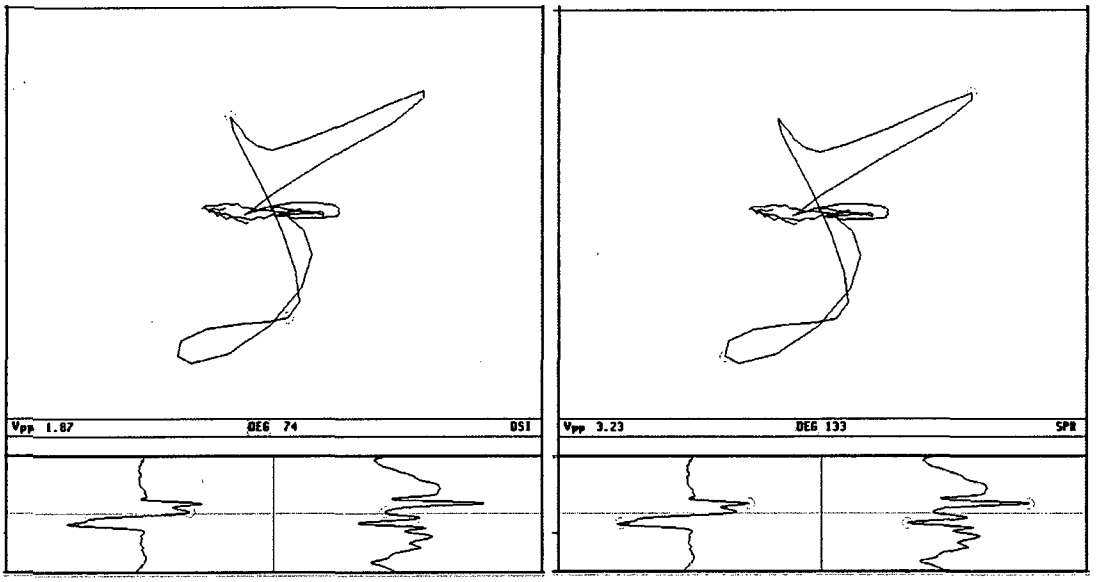


Figure 10-30
Flaw and Mix Residual (400/100 Mix) for Plant A-1 Pulled Tube R27C54-1H

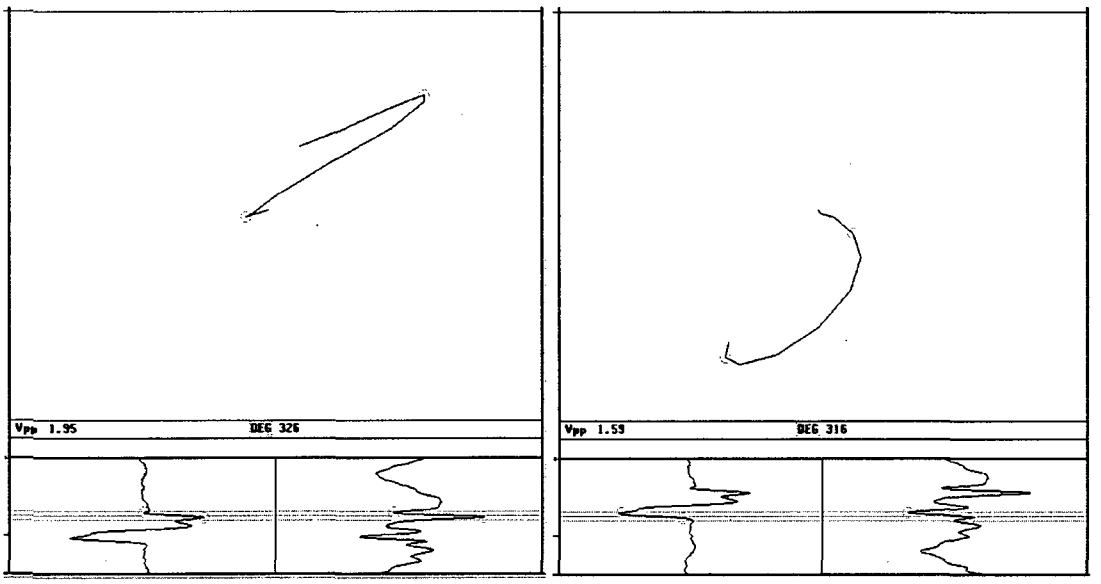


Figure 10-31
Upper and Lower TSP Noise Signals for Plant A-1 R27C54-1H
(Center 1/3 of TSP Cannot be Evaluated Due to Flaw Signal)

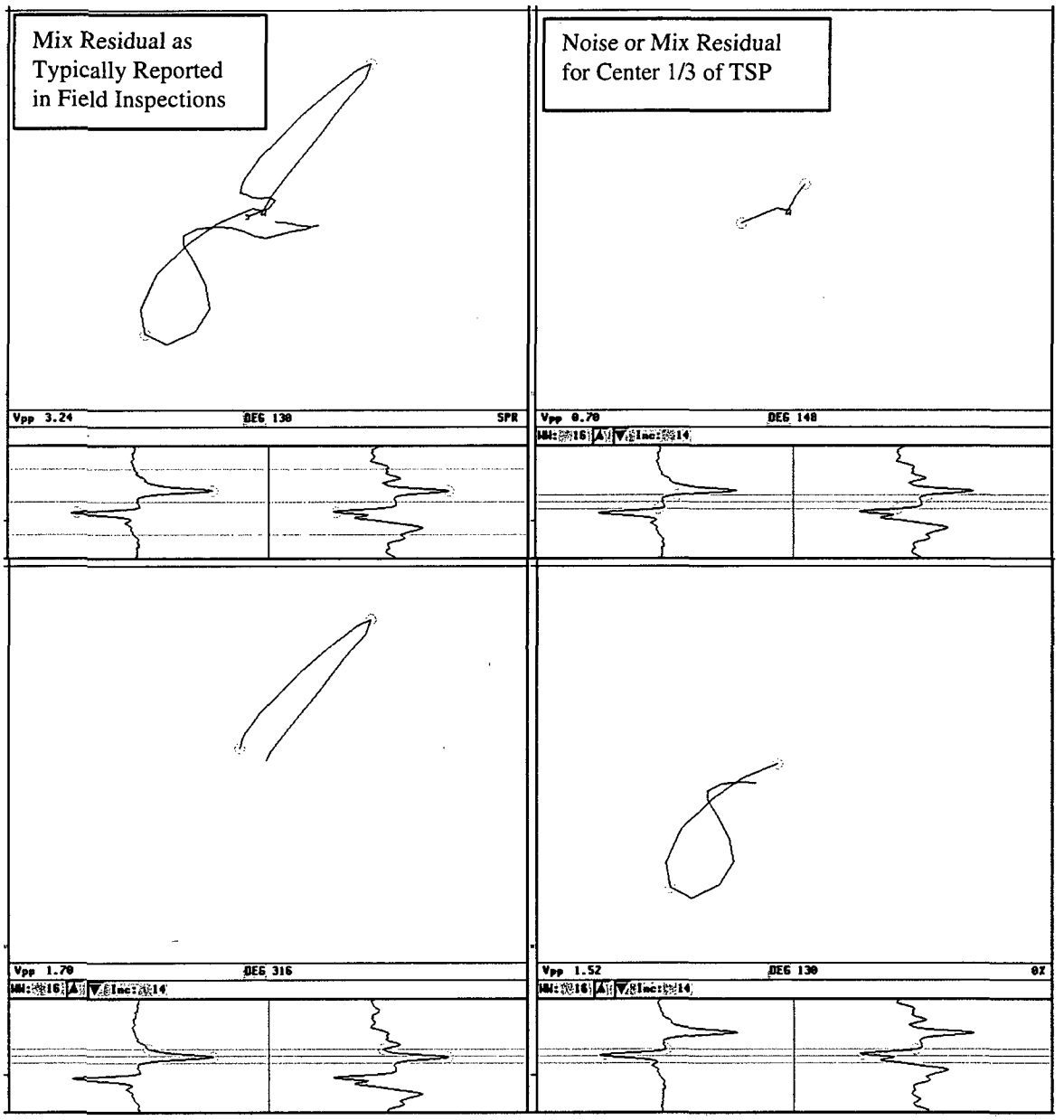


Figure 10-32
Mix Residual and Center, Upper and Lower 1/3 TSP Noise Signals (400/100 kHz Mix) for Plant A-1 R27C54 at 2H

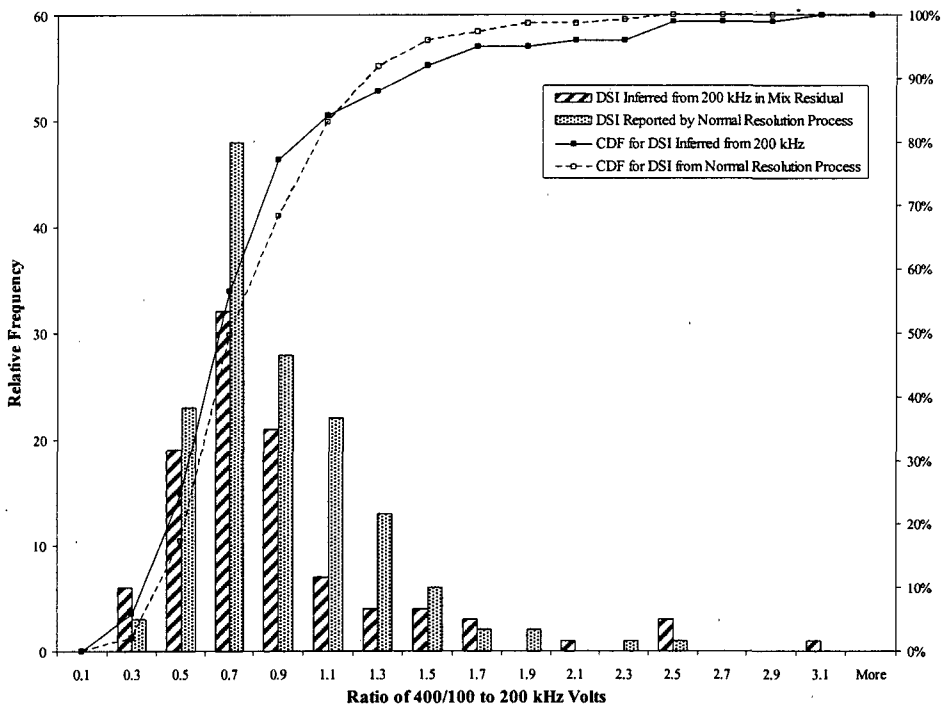


Figure 10-33
Plant P-1: TSP ODSCC 400/100 to 200 kHz Bobbin Voltage Ratios: Comparison of Ratios from Normal Resolution Process with Ratios Inferred from 200 kHz Mix Residual Analysis

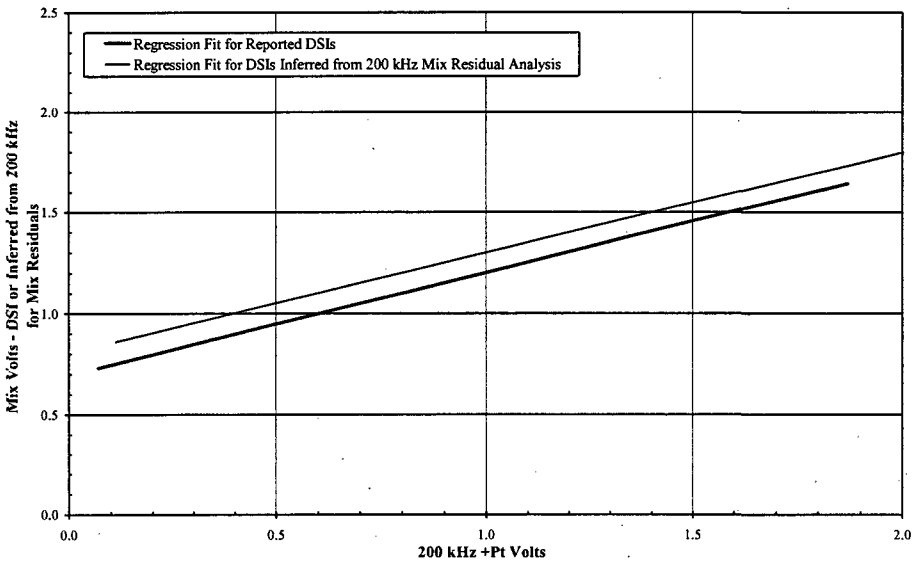


Figure 10-34
Comparison of Bobbin Flow Mix Volts for Reported DSIs and DSIs Inferred from 200 kHz Mix Residual Analysis vs. 200 kHz +Point Volts

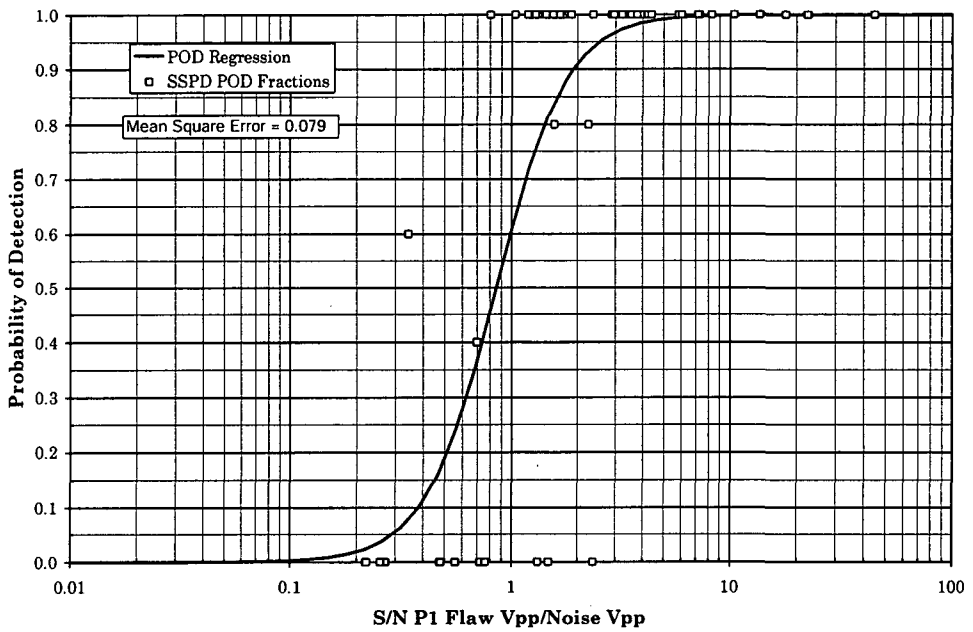


Figure 10-35
POD as Function of Mix P1 S/N (Flaw Vpp/Noise Vpp)
(Generalized Linear Model Log-logistic Solution)

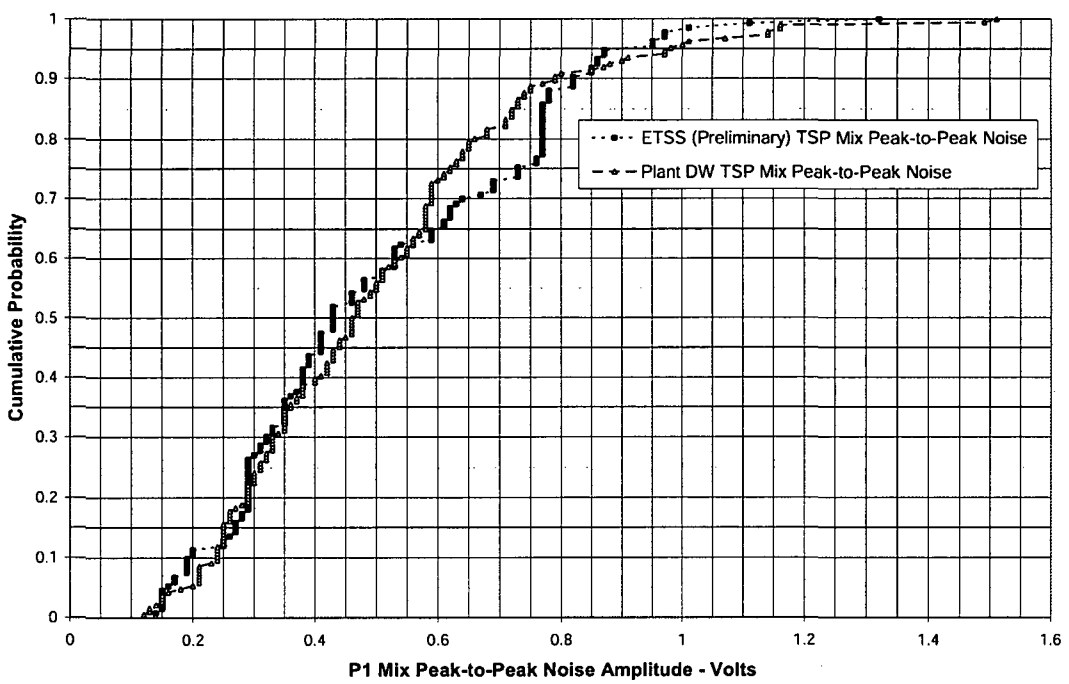


Figure 10-36
TSP Bobbin P1 Mix Peak-to-Peak Amplitude Noise Distributions Preliminary ETSS Data and Plant DW Data

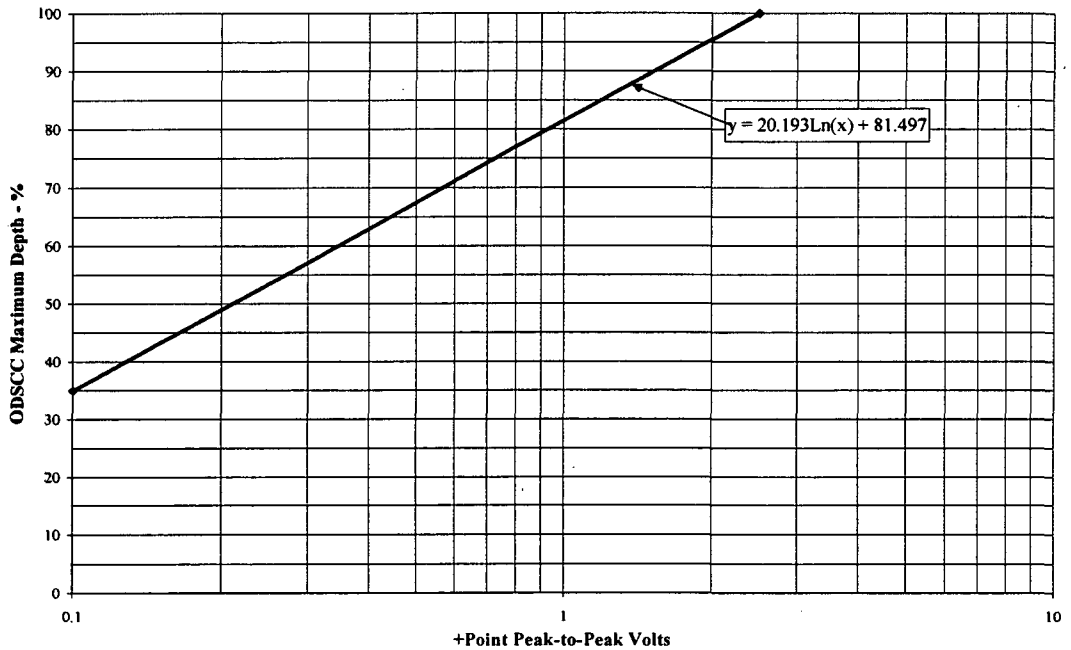


Figure 10-37
+Point Amplitude Sizing Correlation for Estimating Depths Based on Amplitude
(Logarithmic Fit to 2.5 Volts at 100% Depth and 0.1 Volt at 40% Depth)

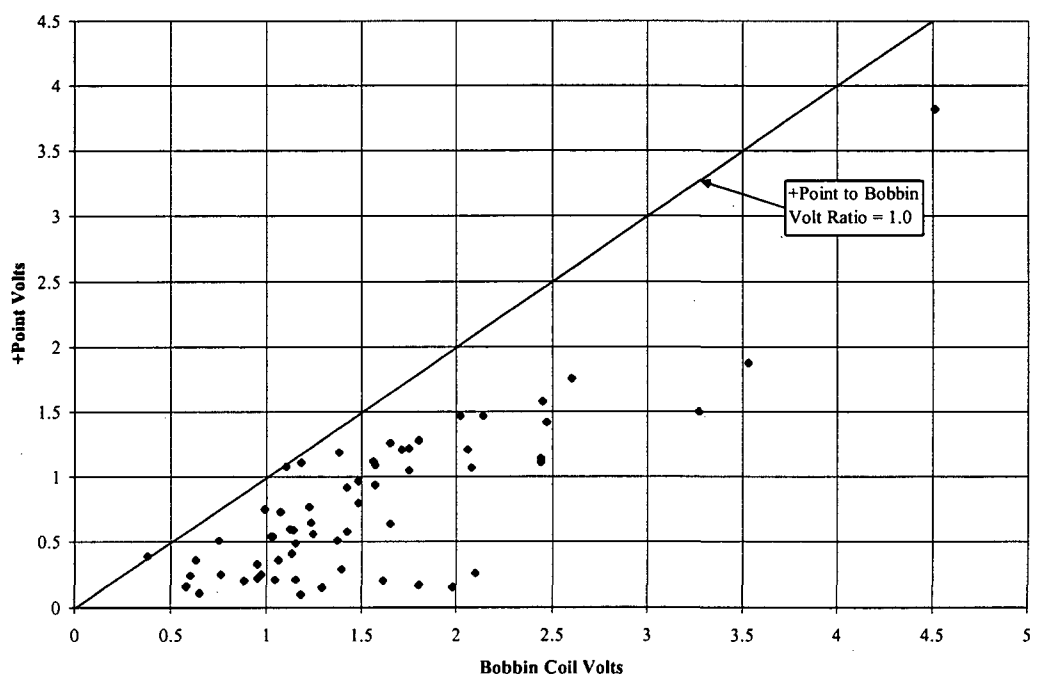


Figure 10-38
+Point DW +Point Volts versus Bobbin Coil Volts

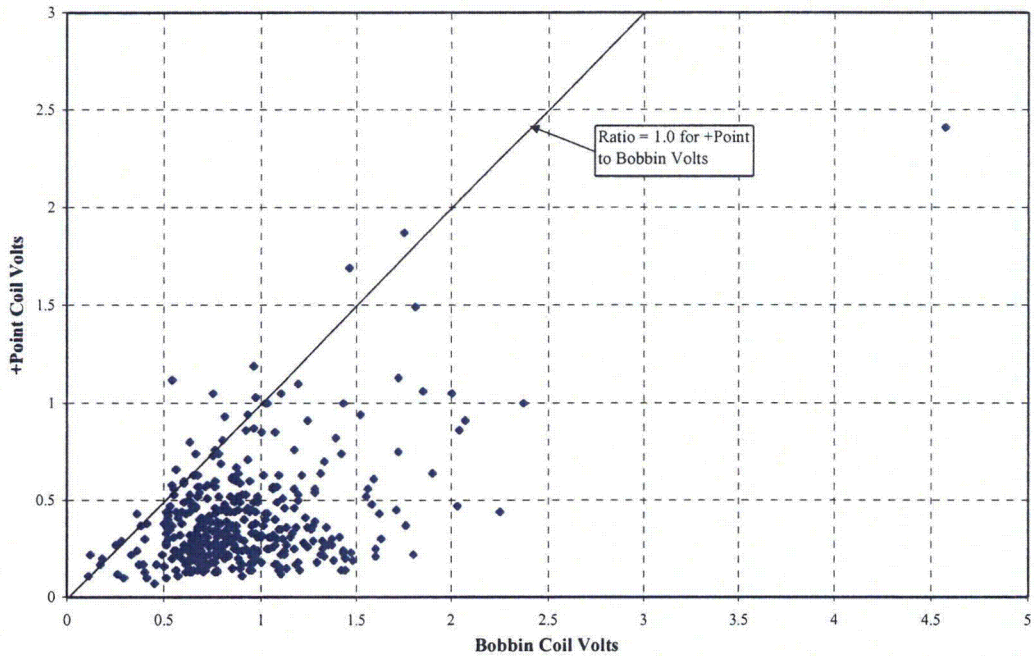


Figure 10-39
Plant P-1 1R15: +Point versus Bobbin Volts, Axial ODSCC at TSP Intersections

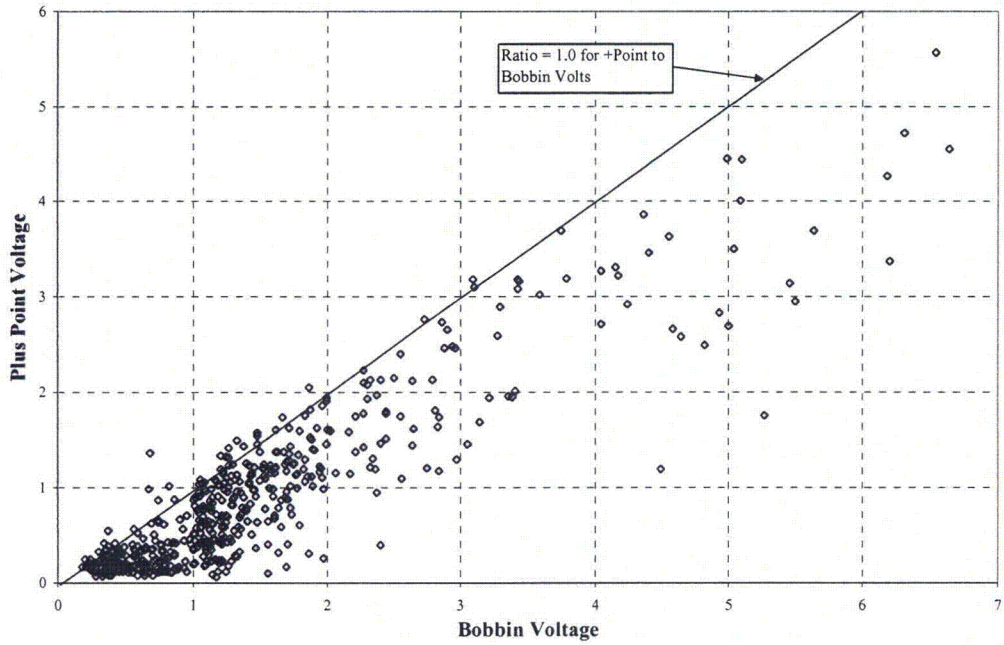


Figure 10-40
DCPP-2 All SGs, 2R11: +Point to Bobbin Voltage Comparison for ODSCC at TSPs

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