Steam Generator Integrity Assessment Guidelines

Revision 2

Non-Proprietary Version

1012987

Final Report, July 2006

EPRI Project Manager
E. Fuller

ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1395 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

DISCLAIMER OF WARRANTIES AND LIMITATION OF LIABILITIES

THIS DOCUMENT WAS PREPARED BY THE ORGANIZATION(S) NAMED BELOW AS AN ACCOUNT OF WORK SPONSORED OR COSPONSORED BY THE ELECTRIC POWER RESEARCH INSTITUTE, INC. (EPRI). NEITHER EPRI, ANY MEMBER OF EPRI, ANY COSPONSOR, THE ORGANIZATION(S) BELOW, NOR ANY PERSON ACTING ON BEHALF OF ANY OF THEM:

(A) MAKES ANY WARRANTY OR REPRESENTATION WHATSOEVER, EXPRESS OR IMPLIED, (I) WITH RESPECT TO THE USE OF ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT, INCLUDING MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE, OR (II) THAT SUCH USE DOES NOT INFRINGE ON OR INTERFERE WITH PRIVATELY OWNED RIGHTS, INCLUDING ANY PARTY'S INTELLECTUAL PROPERTY, OR (III) THAT THIS DOCUMENT IS SUITABLE TO ANY PARTICULAR USER'S CIRCUMSTANCE; OR

(B) ASSUMES RESPONSIBILITY FOR ANY DAMAGES OR OTHER LIABILITY WHATSOEVER (INCLUDING ANY CONSEQUENTIAL DAMAGES, EVEN IF EPRI OR ANY EPRI REPRESENTATIVE HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES) RESULTING FROM YOUR SELECTION OR USE OF THIS DOCUMENT OR ANY INFORMATION, APPARATUS, METHOD, PROCESS, OR SIMILAR ITEM DISCLOSED IN THIS DOCUMENT.

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

Aptech Engineering

AREVA NP

Electric Power Research Institute

Steve Brown

Tennessee Valley Authority

Westinghouse Electric Company LLC

NOTE

For further information about EPRI, call the EPRI Customer Assistance Center at 800.313.3774 or e-mail askepri@epri.com.

CITATIONS

This report was prepared under the guidance of the Integrity Assessment Guidelines Committee.

<u>Committee Members</u>

Helen Cothron	Tennessee Valley Authority
James Begley	AREVA NP
Steve Brown	Consultant
Russell Cipolla	Aptech Engineering
Robert Keating	Westinghouse
David Ayres	Westinghouse
Richard Coe	Southern California Edison
Joseph Mathew	Omaha Public Power District
William Moore	Southern Nuclear Operating Company
Stephen Leshnoff	Exelon
Brad Corder	Ameren UE
Alan Redpath	Progress Energy
Daniel Mayes	Duke Power
Steve Swilley	EPRI
Edward Blandford	EPRI
Edward Fuller	EPRI

This report describes research sponsored by the Electric Power Research Institute (EPRI).

The report is a corporate document that should be cited in the literature in the following manner:

Steam Generator Integrity Assessment Guidelines: Revision 2. EPRI, Palo Alto, CA: 2006. 1012987.

REPORT SUMMARY

This report provides guidance for evaluating the condition of steam generator (SG) tubes based on nondestructive examination (NDE) or in situ pressure testing. This integrity assessment is normally performed during a reactor refueling outage. Nuclear power plant licensees who follow this document's guidelines will have satisfied their requirements for condition monitoring and operational assessment as defined in the Nuclear Energy Institute (NEI) initiative, *Steam Generator Program Guidelines*, NEI 97-06.

Background
Damage to steam generator tubing can impair its ability to adequately perform required safety functions in terms of both structural integrity and leakage integrity. Therefore, assessing tube integrity is an important component of a steam generator program, which is required by NEI-97-06. This program establishes a framework for structuring and strengthening existing steam generator programs. The fundamental elements that are needed represent a balance of prevention, inspection, evaluation, repair, and leakage monitoring measures.

Objectives
- To help licensees support implementation of NEI 97-06.
- To help licensees meet the integrity assessment performance criteria described in NEI 97-06.
- To define requirements and describe in detail implementation procedures for a successful steam generator integrity assessment.

Approach
An ad-hoc committee of licensee experts and additional industry specialists developed these integrity assessment guidelines. This document presents common industry practices for integrity assessment that are achievable with current technology. Any revisions to these guidelines are implemented through the Steam Generator Management Program consensus process, which requires adherence to a formal industry review, comment, and approval protocol. Interim guidance will be provided to the industry whenever necessary between guideline revisions.

Results
This document describes acceptable methods for degradation assessments, condition monitoring, operational assessments, and secondary-side assessments. Condition monitoring refers to assessing the status of steam generator tubes during an outage to ensure that they maintained adequate safety margins for the previous operating period. Operational assessment is intended to ensure that steam generator tubes will maintain adequate safety margins during the upcoming

operating period. There are other acceptable methods for integrity assessment; however, they require technical justification for their application.

This document is a major rewrite of Revision 1 of the integrity assessment guidelines. The report has been completely reorganized. There is more detail in each chapter, there are many fewer appendices, and much new material is included. A great deal of emphasis is placed on providing examples of how to carry out the essential steps of an integrity assessment. Methods for determining probability of detection (POD) of flaws are provided, as are methods for estimating flaw sizes and how large they might grow over an operating interval. There also is a new chapter on secondary-side integrity.

Since Revision 1 was published, there have been five occasions when interim guidance was issued. These are as follows:

- *Interim Guidance on New Degradation Mechanisms*, August 31, 2001;
- *Interim Guidance on Three Mile Island Tube Sever Event*, August 18, 2003;
- *Interim Guidance on Revised Structural Performance Criteria*, SGMP-IG-05-001, January 17, 2005;
- *Interim Guidance to Communicate Issuance of NEI 97-06 R2 and Gaps Between Revision 2 and Current Guidelines*, SGMP-IG-05-002, October 10, 2005; and
- *Interim Guidance Regarding Adverse Trend of Foreign Objects in Steam Generators*, SGMP-IG-05-04, November 18, 2005.

This document incorporates guidance for these occasions, although the wording may be slightly different. In any case, interim guidance is now superseded by this document.

EPRI Perspective

NEI 97-06 requires condition monitoring and operational assessment of steam generator tubing. These integrity assessment guidelines provide a useful description of how steam generator tubing can be shown to meet required performance criteria. Using a standard approach facilitates acceptance and review by regulatory authorities.

This document reflects current industry practices and represents an acceptable method for integrity assessment. Revisions can be expected as the industry accumulates experience with this guideline.

Keywords

Nuclear steam generators
Degradation assessment
Condition monitoring
Operational assessment
Secondary-side integrity assessment
Integrity assessment

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

1.1 Objective

These guidelines present requirements and implementation procedures for meeting the objectives of steam generator tube integrity assessments including:

1. Identification and characterization of degradation forms within steam generators that require assessment,
2. Application of appropriate NDE technology, consistent with the expected degradation and in accordance with the EPRI Steam Generator Examination Guidelines [1].
3. Application of integrity assessment methods, consistent with the expected degradation and required safety factor, for use in evaluating integrity at the end of an inspection interval and to ensure integrity during the subsequent inspection interval.

Successful implementation of the above objectives will help ensure that steam generator integrity will be maintained for each degradation form during operation and applicable design basis accidents.

Licensees should use this document to demonstrate the condition of their steam generators relative to performance criteria used for condition monitoring and operational assessment as defined in the NEI initiative, Steam Generator Program Guidelines NEI 97-06 [2].

1.2 Scope

As required by NEI 97-06, this document offers guidance and requirements for the evaluation methods, margin, and uncertainty considerations used to determine tube integrity. It also provides guidance for performing steam generator degradation assessment (DA), condition monitoring (CM), operational assessment (OA), and secondary side assessment. Assessment of steam generator tube integrity requires an evaluation of both burst and leakage throughout an operational plant cycle. Information on how to carry out these assessments is provided in the body of this document with supplemental examples in the appendices. Other approaches may be used with technical justification.

1.3 Basic Methodology of Steam Generator Integrity Assessment

This section summarizes the details of steam generator integrity assessment. This assessment applies to steam generator components which are part of the primary pressure boundary (e.g., tubing, tube plugs, sleeves and other repairs). It also applies to foreign objects and secondary side structural supports (e.g., tube support plates) that may, if severely degraded, compromise pressure-retaining components of the steam generator.

Figure 1-1
Steam Generator RCS Pressure Boundary Assessment; Condition Monitoring and Operational Assessment

1.4 Compliance Responsibilities

This document presents a general approach and examples for demonstrating steam generator tube integrity. Plant specific programs should consider plant design, materials, steam generator corrosion experience, and operating philosophy. Performing the assessments herein will help plant personnel understand what inspections and repairs are necessary and the appropriate length of operation between inspections. To meet this goal, an effective corporate policy and monitoring program are essential and should be based on the following:

1.5 Contractor Oversight

2
TUBE INTEGRITY CRITERIA

2.1 Introduction

This chapter presents analysis margins and acceptance criteria for structural integrity and through-wall leakage associated with degraded steam generator tubing.

2.2 Structural Integrity Performance Criterion

The SIPC provides the margins for tube integrity against tube burst or collapse. The structural integrity performance criterion is:

Figure 2-1
SIPC Implementation Logic

2.3 Leakage Integrity Performance Criteria

The leakage integrity performance criteria provide requirements for both operational and accident leakage.

2.4 Performance Acceptance Standards

The performance acceptance standards for assessing tube integrity to the structural integrity and accident leakage performance criteria apply to both condition monitoring and operational assessments. The acceptance standard for structural integrity is:

The acceptance standard for accident leakage integrity is:

2.5 Discussion of Structural Margins and Bases

2.5.1 Assessment Factors

2.5.2 Burst Definition

Steam generator tubes exhibit a low probability of burst under normal operating conditions and accident conditions. The definition of tube burst is:

2.5.3 Collapse Definition

2.5.4 Limits on Yield Strength

2.6 Pressure Load Definitions

Normal steady-state full power operation as defined in NEI 97-06 [2], and discussed in Appendix A, is:

> The conditions existing during MODE 1 operation at the maximum steady state reactor power as defined in the design or equipment specification. Changes in design parameters such as plugging or sleeving levels, primary or secondary modifications, or T_{hot} should be assessed and their effects on differential pressure included if significant.

The limiting accident pressure differential is the maximum or largest pressure differential across the tube wall for the design basis accidents (Service Levels C and D). For most plants, this is the pressure differential during a main steam line break. Apart from pressure loading, other contributing loads that can occur during the postulated accidents shall be evaluated to determine if these loads contribute significantly to tube burst. Such loads are discussed in Section 2.5.1, Section 3.7.2, and in Appendix A.

3
TUBE INTEGRITY ASSESSMENT LIMITS

3.1 Introduction

This chapter presents the general requirements for establishing the tube integrity and repair limits associated with steam generator tubing, such that the tube integrity performance criteria and the performance acceptance standards defined in Chapter 2 are satisfied during operation. Tube integrity limits are defined for each degradation mechanism.

3.2 Tube Integrity Limits

3.2.1 Condition Monitoring Limit

Condition monitoring is the assessment of the current state of the steam generator tubing, and is performed at the conclusion of each steam generator inspection. The purpose of condition monitoring is to confirm that both the structural integrity and accident-induced leakage performance criteria were satisfied during the past inspection interval.

3.2.2 Operational Assessment Limit

An operational assessment is a forward-looking prediction of the steam generator tube conditions at the next inspection.

Figure 3-1
Condition Monitoring Elements of Tube Integrity Assessment

Figure 3-2
Operational Assessment Elements of Tube Integrity
(Repair on Sizing)

Figure 3-3
Operational Assessment Elements of Tube Integrity
(Repair on Detection)

3.3 Material Properties

3.4 Repair Limit

3.5 Technical Specification Repair Limit

3.6 Special Considerations for Tube Integrity Assessment

3.7 Determination of Structural Integrity Limits

3.7.1 Tube Burst Event

3.7.2 Significant Contributing Loads

Figure 3-4
Logic for Screening Contributing Loads

3.7.3 Tube Collapse Event

4
NDE MEASUREMENT UNCERTAINTIES

4.1 Introduction

This chapter addresses NDE system performance measures and their uncertainties associated with tube bundle examination for tube integrity applications. Two aspects of performance are considered: 1) degradation detection, quantified by Probability of Detection (POD), and 2) degradation sizing, quantified by linear correlations of true-versus-measured values of structural quantities of interest, such as length and depth of degradation.

Table 4-1
Steam Generator Tube Wall Degradation

4.2 Probability of Detection

4.2.1 Requirements and Limitations for Tube Integrity Applications

4.2.2 POD Modeling

A POD model is a functional measure of the ability of an NDE system to detect degradation.

Figure 4-1
Generating a POD Model Using Binary Hit-Miss Data

Figure 4-2
Different POD Models Resulting from the Same Hit-Miss Data

4.2.3 GLM Calculation of POD and its Uncertainties

4.2.4 Experimental Determination of System POD

Figure 4-3
Accounting for Data Analyst Uncertainty using a GLM Weighted Average POD

4.2.5 Model-Assisted POD Development

Figure 4-4
Model-Assisted Example POD Calculations Using Data for Volumetric Degradation at Tube Support Plate Center and Edges

4.3 Sizing Requirements and Limitations for Tube Integrity Applications

Figure 4-5
Regression Plot Format Used for Determining NDE Sizing Errors – Cold Leg Thinning Data

Table 4-2
Correlation Coefficient, r*, at 95% confidence level for a positive correlation [19]

4.4 Extension of Qualified NDE Techniques for Tube Integrity Applications

Table 4-3
Examples of Extended Applicability of Qualified Techniques

5
DEGRADATION GROWTH RATES

5.1 Introduction

In this chapter methods are presented to determine degradation growth rates from NDE inspection information. This chapter also provides specific growth rate information from industry service experience that may be used when plant-specific data are limited.

5.2 Background

5.3 Data Evaluation Procedures

The following procedures can be used to characterize distributions of growth rates for use in Operational Assessments. Two methods are presented. The first method is a simplified approach that provides a conservative estimate for growth since it includes sizing uncertainties. In some situations, this method may result in a very conservative value for growth rate distribution, in which case a second, more refined method, may be used to give a more realistic estimate for growth rate by explicitly accounting for sizing uncertainties.

5.3.1 Conservative Estimate of the Growth Rate Distribution

5.3.2 Realistic Estimate of the Growth Rate Distribution

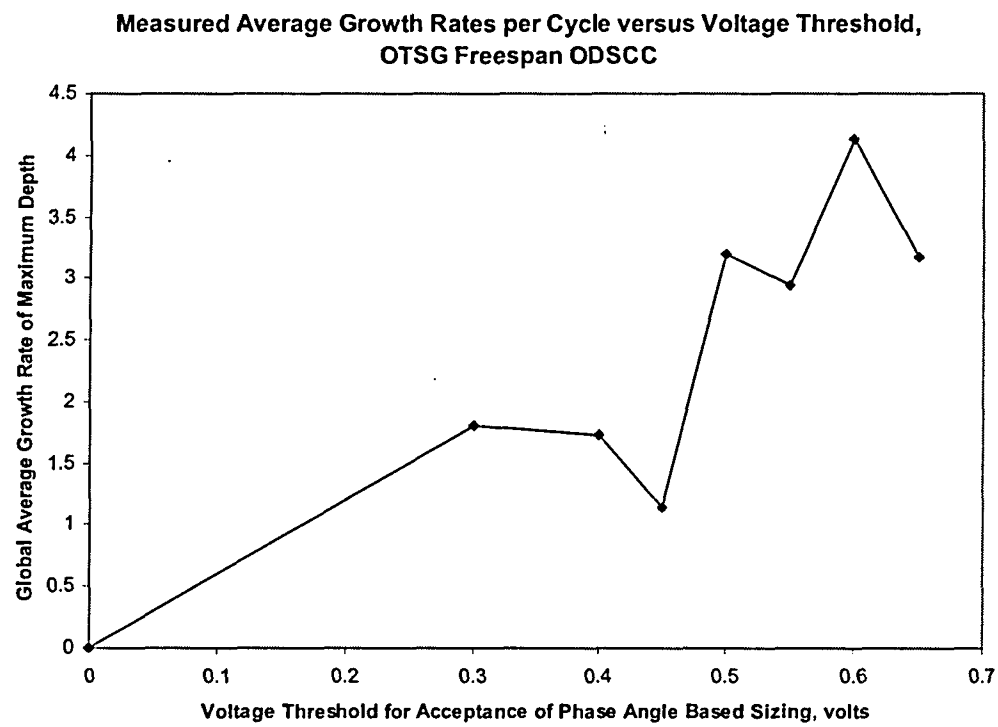

Figure 5-1
Global Average Growth rate of Maximum Depth as Voltage Threshold of Acceptable Sizing Data is Increased

5.4 Illustrations of Estimations of Actual Growth Rate Distributions

Three examples of estimating actual physical growth rates from NDE measurements of degradation growth are presented below. The first two examples are for plug on sizing repair scenarios and the third is for a plug-on-detection degradation mechanism.

5.4.1 Example 1: AVB Wear Plug on Sizing

Figure 5-2
Comparison of NDE Measured Growth Rates, Actual Physical Growth Rates and Computer Simulation of NDE Measured Growth Rates for Wear Depth Growth.

5.4.2 Example 2: Axial PWSCC at Dented Intersections Plug-on-Sizing

Figure 5-3
Distribution of NDE Measured Average Depth Growth Rates of PWSCC Indications Left In Service under an ARC

Figure 5-4
Distribution of NDE Measured Length Growth Rates of PWSCC Indications Left In Service under an ARC

5.4.3 Example 3: Axial ODSCC in OTSG Tubes Plug on Detection

5.5 Default Growth Rate Distributions

5.5.1 Axial Stress Corrosion Cracking

Figure 5-5
Comparison of NDE Measured Growth Rates, Actual Physical Growth Rates and Computer Simulation of NDE Measured Growth Rates for Axial PWSCC

Figure 5-6
Deceleration Factor for ODSCC and PWSCC Growth Rates Compared to 611°F

Figure 5-7
Comparison of NDE Measured Growth Rate Distribution with Computer Simulation Result of NDE Measured Growth Rate Distribution, OTSG Axial ODSCC/IGA.

Figure 5-8
Comparison of NDE Measured Growth Rate Distribution with Best Estimate Physical Growth Rates Distribution, OTSG Axial ODSCC/IGA.

Figure 5-9
Cumulative Distributions of Average Depth Growth Rates of Axial ODSCC/IGA
(curve on the left is a best estimate distribution, others include NDE sizing uncertainties)

5.5.2 Circumferential Stress Corrosion Cracking

6 DEGRADATION ASSESSMENT

6.1 Introduction

Degradation assessment is the process of identifying and documenting existing and potential degradation in planning for an upcoming outage, including inspection plans and related actions for the primary and secondary sides of the steam generator.

6.2 Purpose

The overall purpose of the degradation assessment is to ensure that appropriate inspections are performed during the upcoming outage, and that the requisite information for integrity assessment is provided.

Figure 6-1
Recirculating Steam Generator Degradation Mechanisms

Figure 6-2
Once Through Steam Generator Degradation Mechanisms

6.3 Sources of Information for Degradation Assessment

6.4 Identification of Potential Steam Generator Degradation Mechanisms

6.4.1 Degradation in Previously Plugged Tubes

6.4.2 Types of Degradation

6.4.2.1 Intergranular Attack and Outside Diameter Stress Corrosion Cracking

6.4.2.2 Primary Water Stress Corrosion Cracking and Intergranular Attack

6.4.2.3 Tube Fretting and Wear

6.4.2.4 Other Wear Damage

6.4.2.5 Pitting

6.4.2.6 High Cycle Fatigue

6.4.2.7 Impingement

6.4.2.8 Wastage/Thinning

6.5 Identification of NDE Techniques

6.6 Identification of Inspection Sample Plan

6.7 Integrity Assessment and Repair Limits

6.8 Secondary Side Considerations

6.9 Actions Upon Finding Unexpected Degradation

7 CONDITION MONITORING

7.1 Introduction

Condition monitoring (CM) involves the evaluation of inspection results at the end of the inspection interval to determine the state of the steam generator tubing for the most recent period of operation relative to structural and leakage integrity performance criteria. This chapter provides guidance on performing structural assessments.

7.2 Condition Monitoring Evaluation Procedure

7.3 Structural Integrity Evaluation using Inspection Results

7.3.1 Probabilities and Percentiles

7.3.2 Arithmetic Strategy for Combining Uncertainties

Table 7-1
Condition Monitoring Uncertainty Treatment for Structural Integrity

7.3.3 Simplified Statistical Strategy for Combining Uncertainties

7.3.4 Monte Carlo Strategy for Combining Uncertainties

7.3.5 Strategy Comparison

7.3.5.1 Arithmetic Evaluation

7.3.5.2 Simplified Statistical Evaluation

7.3.5.3 Monte Carlo Evaluation

Figure 7-1
Condition Monitoring Structural Limit Curves for Axial PWSCC Per ETSS 96703.1 at 4155 psi Using Three Strategies for Combining Uncertainties

7.4 Signal Amplitude Approaches to Structural Integrity

Figure 7-2
Condition Monitoring Plot for Freespan Axial ODSCC/IGA in OTSG Tubing at 4050 psi

7.5 Role of In Situ Pressure Testing

7.6 Verification

8 OPERATIONAL ASSESSMENT

8.1 Introduction

Operational Assessment (OA) involves projecting the condition of the SG tubes to the time of the next scheduled inspection outage and determining their acceptability relative to the tube integrity performance criteria of NEI 97-06 [2].

8.2 Projection of Worst Case Degraded Tube

8.3 Fully Probabilistic Operational Assessment Methods

8.3.1 Repair on Detection

8.3.2 Repair on NDE Sizing

8.4 Repair on NDE Sizing: General Considerations

Table 8-1
Operational Assessment Uncertainty Treatment for Structural Integrity for Repair on NDE Sizing

Table 8-1 (continued)
Operational Assessment Uncertainty Treatment for Structural Integrity for Repair on NDE Sizing

8.4.1 Arithmetic Strategy for Repair on NDE Sizing

8.4.2 Simplified Statistical Strategy for Repair on NDE Sizing

8.4.3 Mixed Arithmetic/Simplified Statistical Strategy for Repair on NDE Sizing

8.4.4 Monte Carlo Strategy for Repair on NDE Sizing

8.4.5 Strategy Comparison for Repair on NDE Sizing

8.4.5.1 Example: Cold Leg Thinning at Drilled Tube Support Plates

Figure 8-1
Cumulative Distribution of Cold Leg Thinning Depth Growth Rate NDE Measurements, Computer Simulation of NDE Measurements, and Best Estimate Growth Rate Distribution

8.4.5.2 Arithmetic Strategy

8.4.5.3 Mixed Arithmetic/Simplified Statistical/Monte Carlo Strategy

8.4.5.4 Simplified Statistical Strategy

8.4.5.5 Monte Carlo Strategy

8.5 Repair on Detection General Considerations

Table 8-2
Operational Assessment Uncertainty Treatment for Structural Integrity for Repair on Detection

Table 8-2 (continued)
Operational Assessment Uncertainty Treatment for Structural Integrity for Repair on Detection

8.5.1 Arithmetic Strategy for Repair on Detection

8.5.2 Simplified Statistical Strategy for Repair on Detection

8.5.3 Mixed Arithmetic/ Simplified Statistical Strategy for Repair on Detection

8.5.4 Monte Carlo Strategies for Repair on Detection

8.5.5 Comparison of Strategies for Repair on Detection

8.5.5.1 Example Equation

8.5.5.2 Arithmetic Strategy

8.5.5.3 Mixed Arithmetic/Simplified Statistical Strategy

8.5.5.4 Simplified Statistical Strategy

8.5.5.5 Monte Carlo Strategy

8.6 Signal Amplitude Based Operational Assessment

Figure 8-2
Signal Amplitude-Based Operational Assessment for Freespan Axial ODSCC/IGA at OTSG Plants Voltage Illustrated

8.7 Verification

9
PRIMARY-TO-SECONDARY LEAKAGE ASSESSMENT

9.1 Introduction

This chapter provides requirements for primary-to-secondary leakage assessment and documents methods to calculate leakage.

9.2 Accident Induced Leakage

9.3 Operational Leakage

9.4 Leak Rate Calculation Methodologies

9.5 Validation of Leak Rate Equations

Figure 9-1
Calculated and Measured Leak Rates for Axial Cracks in Alloy 600 Tubing at Normal Operating Conditions

9.6 Condition Monitoring Evaluation for Leakage Integrity

9.7 Operational Assessment Evaluation for Leakage Integrity

9.8 Actions upon Failure to Meet Leakage Integrity Performance Criteria

10
MAINTENANCE OF SECONDARY SIDE INTEGRITY

10.1 Introduction

10.2 Purpose

10.3 Secondary Side Assessments

Figure 10-1
Process of Recording, Monitoring, and Assessing Data

10.4 Secondary Side Cleaning

10.5 Secondary Side Visual Inspections

10.6 Upper Internals Inspections

Figure 10-2
Contingency Planning for Secondary Side Inspection with no Planned Primary Side Inspection

11
REPORTING

11.1 External Reporting

Required reporting to the NRC is addressed in each licensee's technical specification and in NEI 97-06. The NRC report includes the results of the condition monitoring performed during a SG inspection.

Required reporting to the industry is addressed in NEI 97-06. It is important the licensees share experiences with the industry in a timely manner through the SGMP and/or the INPO OE process. If a performance criterion is exceeded or if a new industry degradation mechanism is identified, this information should be sent to appropriate SGMP representatives as soon as possible via e-mail so that lessons learned can be disseminated quickly to the industry. All appropriate tables in the EPRI Steam Generator Database shall be completed within 120 days after startup.

11.2 Internal Reporting

The reporting discussed in this section is not meant to cover all required internal reporting or documentation. This section is concerned with required reporting for integrity assessments. Refer to other EPRI Guidelines for additional internal reporting requirements.

11.2.1 The Degradation Assessment Report

11.2.2 The Condition Monitoring Report

11.2.3 The Operational Assessment Report

12
REQUIREMENTS

12.1 Introduction

12.2 Tube Integrity Criteria

12.3 Tube Integrity Assessment Limits

12.4 NDE Measurement Uncertainties

12.5 Degradation Growth Rates

12.6 Degradation Assessment

12.7 Condition Monitoring

12.8 Operational Assessment

12.9 Primary-to-Secondary Leakage Assessment

12.10 Maintenance of SG Secondary Side Integrity

12.11 Reporting

13
GLOSSARY

14
LIST OF ABBREVIATIONS AND ACRONYMS

AILPC	Accident-Induced Leakage Performance Criterion
ARC	Alternate Repair Criteria
ASL	Axial Secondary Loads
ASME	American Society of Mechanical Engineers
AVB	Anti-Vibration Bar
AVT	All Volatile Treatment
BOC	Beginning of Cycle
BP	Burst Pressure
B&W	Babcock and Wilcox
CAF	Corrosion-Assisted Fatigue (High Cycle Fatigue)
CDF	Cumulative Distribution Function
CE	Combustion Engineering
CEOG	Combustion Engineering Owners' Group
CFR	Code of Federal Regulations
CLT	Cold Leg Thinning
CM	Condition Monitoring
CMTR	Certified Mill Test Report
DA	Degradation Assessment
ECT	Eddy Current Testing
EDF	Empirical Distribution Function
EFPY	Equivalent Full-Power Years
EOC	End of Cycle
EPRI	Electric Power Research Institute
ETSS	Examination Technique Specification Sheet
FDA	Fractional Degraded Area
FLB	Feed Line Break
FME	Foreign Material Exclusion
FOSAR	Foreign Object Search and Retrieval
FS	Free Span
FSAR	Final Safety Analysis Report

GDC	General Design Criteria
GLM	Generalized Linear Modeling
GPD	Gallons Per Day
GR	Growth Rate
IAGL	Integrity Assessment Guidelines
ICC	Intergranular Cellular Corrosion
ID	Inside Diameter
IGA	Intergranular Attack
IDIGA	Inside Diameter Intergranular Attack
IGSCC	Intergranular Stress Corrosion Cracking
INPO	Institute for Nuclear Power Operations
ISI	In-Service Inspection
LAPD	Limiting Accident Pressure Differential
LCO	Limiting Condition Operation
LOCA	Loss of Coolant Accident
LR	Leak Rate
LTL	Lower Tolerance Limit
MAPOD	Model-Assisted Probability of Detection
MD	Maximum Depth
MSLB	Main Steam Line Break
NDE	Nondestructive Examination
NEI	Nuclear Energy Institute
NMP	NDE Measurement Parameter
NOP	Normal Operating Pressure
NOPD	Normal Operating Pressure Differential
NRC	United States Nuclear Regulatory Commission
NSSS	Nuclear Steam Supply System
OA	Operational Assessment
OD	Outside Diameter
ODSCC	Outside Diameter Stress Corrosion Cracking
OE	Operating Experience
OI	Operating Interval
OTSG	Once Through Steam Generator
PDA	Percent Degraded Area
Pdf	Probability Density Function
PICEP	Pipe Crack Evaluation Program (a computer program)

PL	Primary Load
POB	Probability of Burst
POD	Probability of Detection
POL	Probability of Leak
PWR	Pressurized Water Reactor
PWSCC	Primary Water Stress Corrosion Cracking
RCPB	Reactor Coolant Pressure Boundary
RFC	Retirement for Cause
RG	Regulatory Guide
RPC	Rotating Pancake Coil
RSG	Recirculating Steam Generators
SF	Safety Factor
SG	Steam Generator
SGDD	Steam Generator Degradation Database
SGMP	Steam Generator Management Program
SGPB	Steam Generator Pressure Boundary
SGTR	Steam Generator Tube Rupture
SIPC	Structural Integrity Performance Criterion
SL	Structural Limit
SLB	Steam Line Break
SR	Stability Ratio
SRP	Standard Review Plan
SSE	Safe Shutdown Earthquake
STP	Standard Temperature and Pressure (60°F, 760 mm Hg)
S/N	Signal-to-Noise Ratio
TRM	Technical Requirements Manual
TS	Tubesheet
TSP	Tube Support Plate
TSPC	Tube Support Plate Center
TSPE	Tube Support Plate Edge
TW	Through Wall
UTS	Upper Tubesheet (in OTSGs)
W	Westinghouse

15
REFERENCES

1. Pressurized Water Reactor Steam Generator Examination Guidelines: Revision 6, Requirements. EPRI, Palo Alto, CA: 2002. 1003138.
2. "Steam Generator Program Guidelines," Nuclear Energy Institute NEI 97-06, Revision 2, Nuclear Energy Institute, Washington, DC (May 2005).
3. *Steam Generator Management Program Administrative Procedures, Revision 1*, EPRI, Palo Alto, CA: 2004. 1011274.
4. *Steam Generator Degradation Specific Management Flaw Handbook*, EPRI, Palo Alto, CA: 2001. 1001191
5. *Impacts of the Structural Integrity Performance Criterion on Steam Generator Tube Integrity Evaluations*, EPRI, Palo Alto, CA: 2004. TR-1009541
6. Annis. C., "Measuring the Reliability of Nondestructive Evaluation Systems." American Institute of Aeronautics and Astronautics, AIAA-94-1399-CP. 1994.
7. Statistical Engineering Webpage, http://www.stastisticalengineering.com
8. Myers, R.H. and D. Montgomery. "A Tutorial on Generalized Linear Models." Journal of Quality Technology, Vol. 29, No. 3, July 1997.
9. Meyers, R., et al., "Generalized Linear Models With Applications to Engineering and the Sciences," John Wiley and Sons, New York, New York, USA, 2002.
10. Dobson, A. "An Introduction to Generalized Linear Models." Chapman & Hall/CRC 2002.
11. SG-SGDA-02-51, "Tube Integrity Tools Manual," Westinghouse Electric Company, Madison, PA, USA: December, 2002.
12. "Flaw Handbook Tools Theory Manual," Prepared for EPRI by Westinghouse Electric Company, Madison, PA, USA: July 2005.
13. *Integrity Assessment Examples Manual*, EPRI, Palo Alto, CA: 2006. 1012986.
14. *"Recombinant DNA – A New Approach to Evaluating the Effects* of Plant Noise on NDE Detection and Sizing Capabilities," EPRI SG NDE Conference, July 2002.
15. *"DQV on Eddyview – Where We Have Been and Where are We Going?," EPRI SG NDE Conference, July 2004.*
16. SG-SGDA-06-02, "Users Manual – Crystal Ball Program for Adjusting NDE Performance Test PODs for Alternate Noise Distributions, Westinghouse Electric Company, Madison PA, USA – December 2005.
17. *Users Manual – Crystal Ball Program for Predicting NDE System POD*, EPRI, Palo Alto: 2006. 1012988.

18. Brown, S. D., "NDE System Sizing Error Verification," Letter Report dated November, 2005.

19. Beyer, W.H "Handbook of Tables for Probability and Statistics", CRC Publications 1966.

20. "Degradation Growth Rates in OTSG Tubing," AREVA/FANP Document 51-5022969-00, September 2003.

21. "Assessment of Current Understanding of Mechanisms of Initiation, Arrest and Reinitiation of Stress Corrosion Cracks in PWR Steam Generator Tubing," NUREG/CR-5752, ANL-99/4, February 2000.

22. "Sequoyah Nuclear Plant U1C10 Steam Generator Inspection Results," TVA Presentation to NRC Staff, April 25, 2000.

23. *Three Mile Island Plugged Tube Severance: A Study of Damage Mechanisms*, EPRI, Palo Alto, CA: May 2003: 1008438.

24. "Rapidly Propagating Fatigue Cracks in Steam Generator Tubes," NRC Bulletin No. 88-02, United States Nuclear Regulatory Commission, Washington, DC, February 5, 1988.

25. *Steam Generator In Situ Pressure Test Guidelines*, EPRI, Palo Alto, CA: 2003. 1007904 Rev. 2.

26. EPRI Steam Generator Management Program, "ECT Examination Technique Specification Sheets," www.EPRIq.com

27. "Correlation of Burst Pressure with Plus Point Voltage and Length for OTSG Axial ODSCC," Framatome Calculation Note 32-5030334-00, August 2003.

28. *Technical Basis for Steam Generator Tube Integrity Performance Acceptance Standards*, EPRI, Palo Alto, CA: 2006. 1012984.

29. "Alternative Radiological Source Terms for Evaluating Design Basis Accidents at Nuclear Power Reactors," Regulatory Guide 1.183, United States Nuclear regulatory Commission, Washington, DC, July 2000.

30. *PWR Primary-To-Secondary Leak Guidelines—Revision 3*, EPRI, Palo Alto, CA: 2004. 1008219

31. *Depth Based Structural Analysis Methods for SG Circumferential Indications*, EPRI, Palo Alto, CA: 1997. 107197-P1

32. *Steam Generator Tubing Burst Testing and Leak Rate Testing Guidelines*, EPRI, Palo Alto, CA: 2002. 1006783

33. *PICEP: Pipe Crack Evaluation Program*, EPRI, Palo Alto, CA: 1987. NP-3596-SR, Rev. 1

34. *Steam Generator Tube Leakage Experiments and PICEP Calculations*, EPRI, Palo Alto, CA: 1990. NP-6897-L

35. *Depth Based Structural Analysis Methods for SG Circumferential Indications*, EPRI, Palo Alto, CA: 1997. 107197-P1

36. *Ductile Fracture Handbook, Volume 1: Circumferential Throughwall Cracks*, EPRI, Palo Alto, CA: 1989. NP-6301-DV1

37. *Ductile Fracture Handbook: Volume 2*, EPRI, Palo Alto, CA: 1990. NP-6301-DV2

38. Duffy, A. R., Eiber, R. J. and Maxey, W. A., "Recent Work on Flaw Behavior in Pressure Vessels," Proceedings of the Symposium on Fracture Toughness Concepts for Weldable Structural Steel, UKAEA, Chapman and Hall Ltd., Risley, April 1969.

39. "Pressure and Leak-Rate Tests and Models for Predicting Failure of Flawed Steam Generator Tubes," NUREG/CR-6664, ANL 99/23, August 2000.

40. *Steam Generator Foreign Object Task Force Review Material*. EPRI, Palo Alto, CA: 2006. 1012921.

A
APPENDIX A: INDUSTRY TECHNICAL BASES FOR STRUCTURAL INTEGRITY ASSESSMENT

A.1 Introduction

A.2 Definition of Burst

A.2.1 Burst Condition

A.2.2 Technical Discussion

A.2.3 Application - Condition Monitoring

A.3 Deterministic Structural Performance Criterion Pressure Loading Definition

A.3.1 Background

A.3.2 Statement of Structural Performance

Figure A-1
SIPC Implementation Logic

A.3.3 Definitions

A.3.4 Technical Discussion

A.3.5 Limits on Yield Strength

A.4 ASME Code Review

A.4.1 Minimum Wall Requirements

A.4.2 Primary Loads from Accidents Events

A.4.2.1 ASME Section III Appendix F Considerations

Table A-1
Alloy 600 Typical Properties – Mean Values

A.4.3 Secondary Loads from Accident Events

A.4.3.1 Definition of Secondary Loads

A.4.3.2 Code Practice

A.4.4 Summary of Code Considerations

A.5 Historical Perspective

A.5.1 Regulatory Perspective

A.5.2 Application of Industry Definition

A.5.2.1 Original Design

A.5.2.2 Condition Monitoring

A.5.2.3 Validation of Industry Definition

Table A-2
Typical Differential Pressures for NSSS Designs

A.6 Assessment of Contributing Loads

A.6.1 Primary Loads

A.6.2 Axial Membrane Loads in OTSG Tubing

A.6.3 Axial Membrane Loads in RSG Tubing

A.6.4 Treatment of Axial Thermal Loads

A.7 Allowable Structural Limits

A.7.1 Tube Burst Condition

A.7.2 Plastic Collapse Under Tension and Bending

A.7.3 Circumferential Degradation

A.7.4 Axial Degradation

A.8 Summary and Conclusions

A.9 References

A1 Title 10 to the Code of Federal Regulations, Part 50.

A2 "Steam Generator Program Guidelines," Nuclear Energy Institute NEI 97-06, Revision 1, Nuclear Energy Institute, Washington, DC (January 2001).

A3 Testimony of James Knight before the Atomic Safety and Licensing Board, U.S. Nuclear Regulatory Commission, Washington, DC (January 1975).

A4 Draft Regulatory Guide 1.121, "Bases for Plugging Degraded PWR Steam Generator Tubes," U.S. Nuclear Regulatory Commission, Washington, DC (August 1976).

A5 ASME Boiler and Pressure Vessel Code, Section III, Division 1, Subsection NB, "Class 1 Components," 2004 Edition.

A6 "Burst Pressure Correlation for Steam Generator Tubes with Through-Wall Axial Cracks", EPRI TR-105505, Final Report, October 1997.

A7 "Safety Evaluation Report Related to the Preliminary Design of the Standard Reference System RESAR-414," NUREG-0491, Docket Number STN 50-572, United States Nuclear Regulatory Commission, November 1978.

A8 "Steam Generator In Situ Pressure Test Guidelines," EPRI Report TR-107904-R2, Electric Power Research Institute, Palo Alto, CA (August 2003).

A9 "Guidelines for Steam Generator Tube Section Removal, Test and Examination", EPRI TR-016743-V4R1 Final Report, December 1997.

A10 *Steam Generator Tubing Burst Testing and Leak Rate Testing Guidelines*, EPRI, Palo Alto, CA: 2002. 1006783

A11 Draft Regulatory Guide DG-1074, "Steam Generator Tube Integrity," March 1998.

A12 "Impacts of the Structural Integrity Performance Criterion on Steam Generator Tube Integrity Evaluations," EPRI TR-1009541, (November 2004).

A13 ASME Boiler and Pressure Vessel Code, Section XI, Rules for the Inservice Inspection of Nuclear Power Plant Components," 2004 Edition.

A14 "Evaluation of Flaws in Austenitic Steel Piping," EPRI NP-4690-SR, Special Report, (July 1986).

A15 Cipolla, R. C., D. A. Scarth, G. M. Wilkowski, and V. A. Zilberstein, "Technical Basis for Proposed Revision to Acceptance Criteria for ASME Section XI Pipe Flaw Evaluation," PVP Vol. 422, 2001 ASME Pressure Vessel and Piping Conference, Atlanta, Georgia, (July 23-26, 2001).

A16 Testimony of Raymond Maccary before the Atomic Safety and Licensing Appeal Board, U.S. Nuclear Regulatory Commission, Washington, DC (January 1976).

A17 Atomic Safety and Licensing Board, LBP-75-27, U.S. Nuclear Regulatory Commission, Washington, DC (May 1, 1975).

A18 Regulatory Guide 1.160, "Assessing and Managing Risk Before Maintenance Activities at Nuclear Power Plants," U.S. Nuclear Regulatory Commission, Washington, DC

A19 Costa, D., "Treatment of Tube Axial Thermal Loads," Report No. 51-5021407-01, AREVA.

A20 NEI letter to NRC (S.J. Collins), "Industry Steam Generator Program Initiative", dated December 17, 1998.

B

APPENDIX B: MODEL-ASSISTED POD DEVELOPMENT

B.1 Model-Assisted POD (MAPOD)

B.1.1 Ahat Modeling

Figure B-1
Ahat POD Modelling

Figure B-2
Excel™ Implementation of Ahat POD Modeling for Cold-Leg Thinning ETSS Data

Figure B-3
Excel™ Implementation of Ahat POD Modeling for Cold-Leg Thinning ETSS Data

Figure B-4
Excel™ Implementation of Ahat POD Modeling for Cold-Leg Thinning ETSS Data

B.1.2 Noise-Dependent Structural POD Modeling

B.1.2.1 Ahat (S/N) Modeling

B.1.2 2 Monte Carlo Ahat (S/N) Simulation

Figure B-5
Monte Carlo Simulation of Ahat (S/N) Data

B.1.2.3 Incorporating Human Factor or Personnel Effects

Figure B-6
Modelling Data Analyst Human Factor Effects using a (S/N) Dependent Reporting Probability

Table B-1
Example Monte Carlo POD Simulator Output Data

Figure B-7
Monte Carlo Generated Noise Dependent Structural POD Model

B.1.2.4 Illustrating the Dependency of POD on (S/N)

Figure B-8
Cumulative Noise Distributions Used for Noise-Dependent Monte Carlo POD Simulations

B.1.2.5 POD Model Prediction and Validation

Figure B-9
Monte Carlo Simulated Noise-Dependent Structural Detection Probabilities Showing the Effects of Increasing and Decreasing Noise

Figure B-10
Monte Carlo Predicted POD Compared with Technique Limit and Weighted Average POD for one the Performance Demonstration Datasets

B.1.2.6 Applications

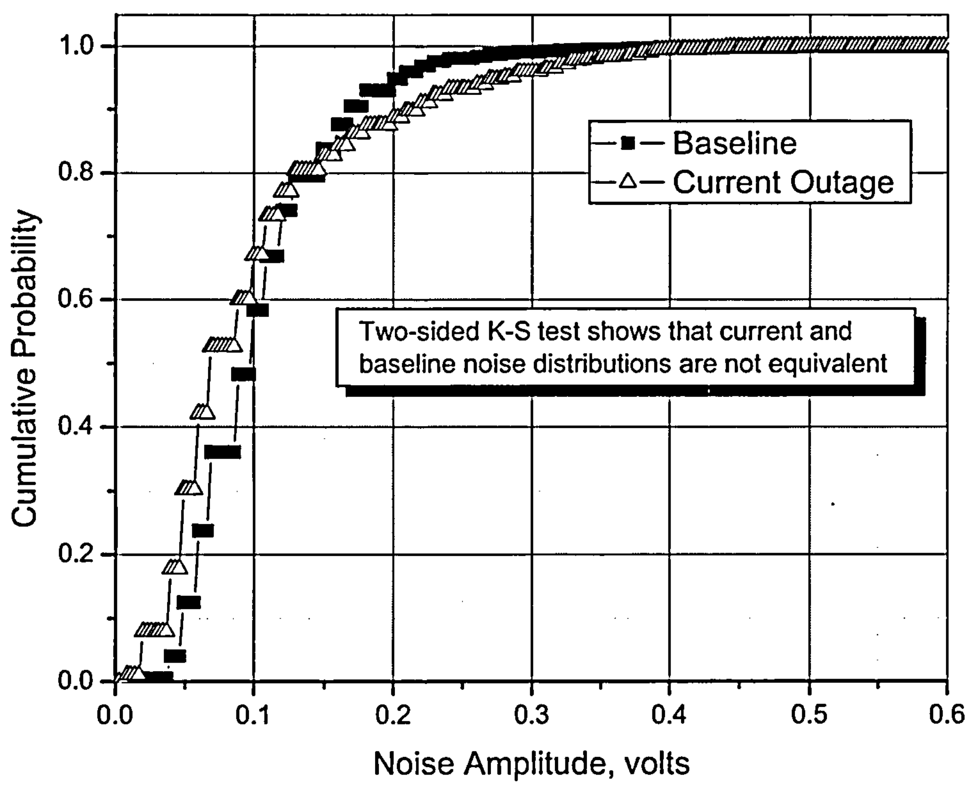

Figure B-11
Kolmogorov-Smirnov Comparison of Two Noise Distributions

Figure B-12
Kolmogorov-Smirnov Comparison of Two Noise Distributions

Figure B-13
Simulation Logic for Deriving Effective POD

Figure B-14
Simulation Outputs for +Pt Confirmation

Figure B-15
Comparison of Effective POD with Bobbin and +Pt coil PODs (+Pt Confirmation)

B.2 References

B1 Berens, A.P. and P.W. Hovey, "Evaluation of NDE Reliability Characterization," AFWAL-TR-81-4160, Vol. 1, Air Force Wright Aeronautical Laboratories, WPAFB, OH, December 1981

B2 Berens, A.P. and P.W. Hovey, "Flaw Detection Reliability Criteria, Volume 1 – Methods and Results" AFWAL-TR-84-4022, Vol. 1, Air Force Wright Aeronautical Laboratories, WPAFB, OH, April 1984

B3 Berens, A.P., "NDE Reliability Data Analysis," ASM Metals Handbook Volume 17 Nondestructive Evaluation and Quality Control, 9th Ed., American Society of Metals International, Materials Park, OH, 1989

B4 MIL-HDBK-1823, "Department of Defense Handbook - Nondestructive Evaluation System Reliability Assessment," April 1999

B5 Berens, A.P. "Probability of Detection (POD) Analysis for the Advanced retirement for Cause (RFC)/Engine Structural Integrity Program (ENSIP) Nondestructive Evaluation (NDE) System – Volume 1: POD Analysis " AFRL-ML-WP-TR-2001-4010, Air Force Research Laboratory, WPAFB, OH, January, 2000

B6 Berens, A.P. "Probability of Detection (POD) Analysis for the Advanced retirement for Cause (RFC)/Engine Structural Integrity Program (ENSIP) Nondestructive Evaluation (NDE) System – Volume 2: POD Users Manual" AFRL-ML-WP-TR-2001-4011, Air Force Research Laboratory, WPAFB, OH, January, 2000

B7 "Monte Carlo POD Simulator Users Guide" Aptech Engineering Services Report, Prepared under Task 6b of the EPRI Tools for Tube Integrity Assessment Program, Draft dated July, 2004

B8 "Guidelines for NDE and Destructive Exam Data Acceptability for NDE POD and Sizing Performance Evaluations" Westinghouse/Aptech Engineering Report prepared under Task 3 of EPRI Tools for Tube Integrity Assessment Program, July 2003

C

APPENDIX C: EXAMPLES OF CONDITION MONITORING AND OPERATIONAL ASSESSMENT LIMIT DETERMINATION

C.1 Axial Cracking Examples

C.1.1 Example of Freespan, Through-wall Axial Crack

C.1.2 Condition Monitoring Limit Using Arithmetic Method

C.1.3 Condition Monitoring Limit Using Simplified Statistical Method

C.1.4 Growth

C.1.5 Monte Carlo Analysis

Figure C-1
Burst Pressure as a Function of Critical Crack Length for the Three Methods

C.2 Circumferential Cracking Examples

C.2.1 Circumferential Cracking with Restricted Lateral Tube Motion, Pressure and Bending Loads

C.2.2 Input Parameters

C.2.3 Governing Equations

Figure C-2
Burst pressure as a function of PDA for circumferentially cracked tubes [C1]

C.2.4 Structurally Significant External Loads

C.2.5 Pressure Only

C.2.5.1 Calculation of the Structural Limit

C.2.5.2 Arithmetic Method, Pressure Only

C.2.5.3 Simplified Statistical Analysis, Pressure Only

C.2.5.4 Monte Carlo Analysis, Pressure Only

C.2.6 Pressure Plus External Bending and Axial Loads

C.2.6.1 Calculation of the Structural Limit, Pressure Plus Bending & Axial Loads

C.2.6.2 Condition Monitoring Limit, Pressure Plus Bending & Axial Loads

C.2.6.3 Arithmetic Method, Pressure Plus Bending & Axial Loads

C.2.6.4 Simplified Statistical Analysis, Pressure Plus Bending & Axial Loads

C.2.6.5 Monte Carlo Analysis, Pressure Plus Bending & Axial Loads

C.2.7 Conclusions

Table C-1
Summary of Critical FDA Results for Circumferential Crack Example

C.3 Volumetric Degradation Examples

C.3.1 Example of Uniform 360° Thinning Over a Given Axial Length

C.3.2 Structural Limit

Table C-2
Structural Limit Parameter h_{SL} Solutions for Several L Values

C.3.3 Condition Monitoring Limit

Table C-3
Relational and Material Uncertainties Calculated at the 95th Percentile

C.3.4 Growth

Table C-4
Postulated Distribution of Growth of Uniform Thinning Indications for Operational Assessment Calculations (OD = 0.875, t = 0.050)

Figure C-3
Distribution of Growth for Uniform Thinning

C.3.5 Monte Carlo Analysis

Figure C-4
Comparison of CM solutions for a burst pressure of 4.473 ksi

Figure C-5
Distribution of simulated burst pressures for a sample depth and length

C.4 References

C1 Steam Generator Degradation Specific Management Flaw Handbook, EPRI, Palo Alto, CA: January 2001. 1001191

C2 Burst Pressure Correlation for Steam Generator Tubes With Throughwall Axial Cracks, EPRI, Palo Alto, CA: 1997. TR-105505

C3 Impacts of the Structural Integrity Performance Criterion on Steam Generator Tube Integrity Evaluations, EPRI, Palo Alto, CA: 2004. 1009541

C4 McKay, M. D., R. J. Beckman, and W. J. Conover, "A Comparison of Three Methods for Selecting Values of Input Variables in the Analysis of Output from a Computer Code," Technometrics, Vol. 21, No. 2, May 1979.

C5 Pressurized Water Reactor Steam Generator Examination Guidelines: Revision 6, EPRI, Palo Alto, CA: September 1997. 1003138.