Steam Generator Management Program: Steam Generator Integrity Assessment Guidelines—Revision 5 – Public Version

1
INTRODUCTION

1.1 Objective

This document presents high-level information for meeting the objectives of steam generator (SG) tube integrity assessments including:

1. Identification and characterization of degradation mechanisms within SGs that require assessment

2. Application of appropriate nondestructive examination (NDE) technology to address existing and potential degradation.

3. Application of integrity assessment methods for use in evaluating component integrity at the end of an inspection interval and ensuring component integrity during the subsequent inspection interval

4. Secondary side inspection and maintenance

Developing a methodology to meet the above objectives will help ensure that SG integrity will be maintained for each degradation mechanism during the full range of normal operating conditions and applicable design basis accidents.

1.2 Scope

This document offers high-level information regarding the evaluation used to determine tube integrity. It also provides information for developing a methodology for performing SG degradation assessments (DA), condition monitoring (CM), operational assessment (OA), and secondary side assessments.

1.3 Basic Methodology of Steam Generator Integrity Assessments

This section summarizes the details of SG integrity assessments. These assessments apply to SG components which are part of the primary pressure boundary (e.g., tubing, tube plugs, sleeves and other repairs).

The essential elements of SG integrity assessments are presented in Figure 1-1. Three critical elements, the DA, CM, and OA, provide assurance that the SGs will continue to satisfy the appropriate performance criteria.

The DA is the planning process that identifies and documents information about plant-specific SG degradation. The overall purpose of the DA is to prepare for an upcoming SG inspection through the identification of the appropriate examinations and techniques and preparation of the

requisite information for integrity assessments is obtained. Discussion of the DA is provided in Section 6.

Condition monitoring is backward looking, in that its purpose is to confirm that adequate SG tube integrity has been maintained during the previous inspection interval. Condition monitoring involves an evaluation of the as-found condition of the tubing relative to integrity performance criteria. The tubes are inspected with qualified techniques and procedures. Structural and leakage integrity assessments are performed, and results compared to their respective performance criteria. Condition monitoring results are then evaluated with respect to the previous OA. Discussion of the CM is provided in Section 7.

The OA differs from the CM assessment in that it is forward looking rather than backward looking. Its purpose is to demonstrate that the tube integrity performance criteria will be met throughout the next inspection interval. The results of the OA determine the allowable run time for the upcoming inspection interval. Discussion of the OA is provided in Section 8.

The SG integrity assessment process considers the potential for foreign objects or degradation of secondary side components to affect structural and leakage integrity of the primary pressure boundary. Section 10 discusses recommended actions to address secondary side component impact on SG tube integrity.
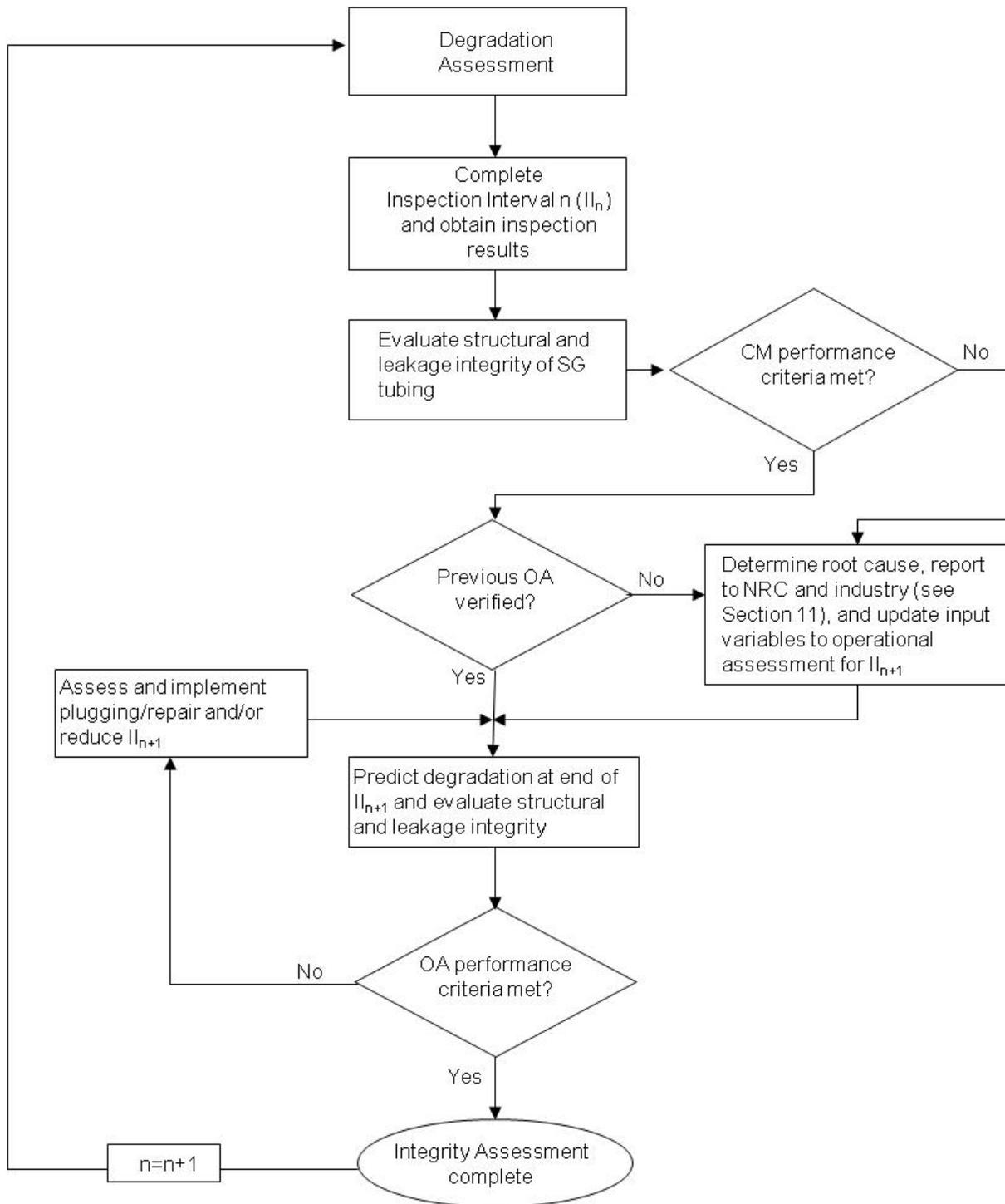
Figure 1--1
SG Reactor Coolant System Pressure Boundary Assessment; DA, CM and OA

2
TUBE INTEGRITY CRITERIA

2.1   Introduction

This section presents acceptance criteria and safety factors for structural integrity and through-wall leakage associated with degraded SG tubing.

For structural integrity performance criteria (SIPC), there are two requirements to be satisfied.

First, structural integrity needs to be satisfied under normal full power operation and under design-based accident conditions as discussed in Section 2.2. The SIPC defines the safety factors to be applied in maintaining adequate tube integrity against gross failure by either burst or plastic collapse. The technical bases for the SIPC follow from the design margins implied in Section III of the ASME Boiler and Pressure Vessel Code. This margin requirement is usually controlled by the specified safety factor to be applied to the normal steady state operating pressure differential. This requirement only applies to full power steady state operation and is not to be applied to any normal operating transient condition.

Second, for normal operating conditions, structural integrity needs to be satisfied to prevent general yielding of the tube under primary membrane stress. The safety factor to be applied on operating pressure differential is 1.0. This requirement only applies to normal operating transient events under Service Level A and B. Prevention of tube yielding is often referred to as the "no-yield" criterion with the purpose of limiting plastic deformation during normal operating conditions. As discussed in Section 2.5.4, meeting the SIPC safety factors for tube burst or collapse will provide reasonable assurance that general elastic behavior will be maintained such that gross yielding in the degraded region of a tube during normal operating conditions is mitigated.

The leakage performance criteria address the allowable leakage limits for tubing. They are defined separately for operational and accident-induced conditions. The operational leakage performance criterion (OLPC) applies to normal plant operating conditions and is specific to a given plant. The accident-induced leakage performance criterion (AILPC) applies to calculated leakage for postulated accident events and is also site-specific. Section 2.3 discusses the requirements for leakage integrity.

Tube integrity is demonstrated by satisfying the structural and leakage integrity performance criteria defined in Section 2.3 in conjunction with the performance acceptance standards described in Section 2.4.

2.2　Structural Integrity Performance Criterion

The SIPC provides the margins of safety for tube integrity against tube burst or collapse. The SIPC is:

> All in-service steam generator tubes shall retain structural integrity over the full range of normal operating conditions (including startup, operation in the power range, hot standby, and cool down and all anticipated transients included in the design specification) and design basis accidents. This includes retaining a safety factor of 3.0 against burst under normal steady state full power operation primary-to-secondary pressure differential and a safety factor of 1.4 against burst applied to the design basis accident primary-to-secondary pressure differentials. Apart from the above requirements, additional loading conditions associated with the design basis accidents, or combination of accidents in accordance with the design and licensing basis, shall also be evaluated to determine if the associated loads contribute significantly to burst or collapse. In the assessment of tube integrity, those loads that do significantly affect burst or collapse shall be determined and assessed in combination with the loads due to pressure with a safety factor of 1.2 on the combined primary loads and 1.0 on axial secondary loads.

The SIPC is based on loading definitions and an evaluation framework consistent with the ASME Code and past regulatory guidelines. The logic of the SIPC illustrating the key assessments for integrity is given in Figure 2-1, including a determination of significant accident loads that can contribute to burst or collapse, where normal operating pressure differential (NOPD) is the normal steady state full power operation primary-to-secondary pressure differential, limiting accident pressure differential (LAPD) is the limiting accident pressure differential, PL is a primary load, and ASL is axial secondary load. Section 6.7.1 discusses establishment of NOPD and assessment of plant changes for impact on SIPC.
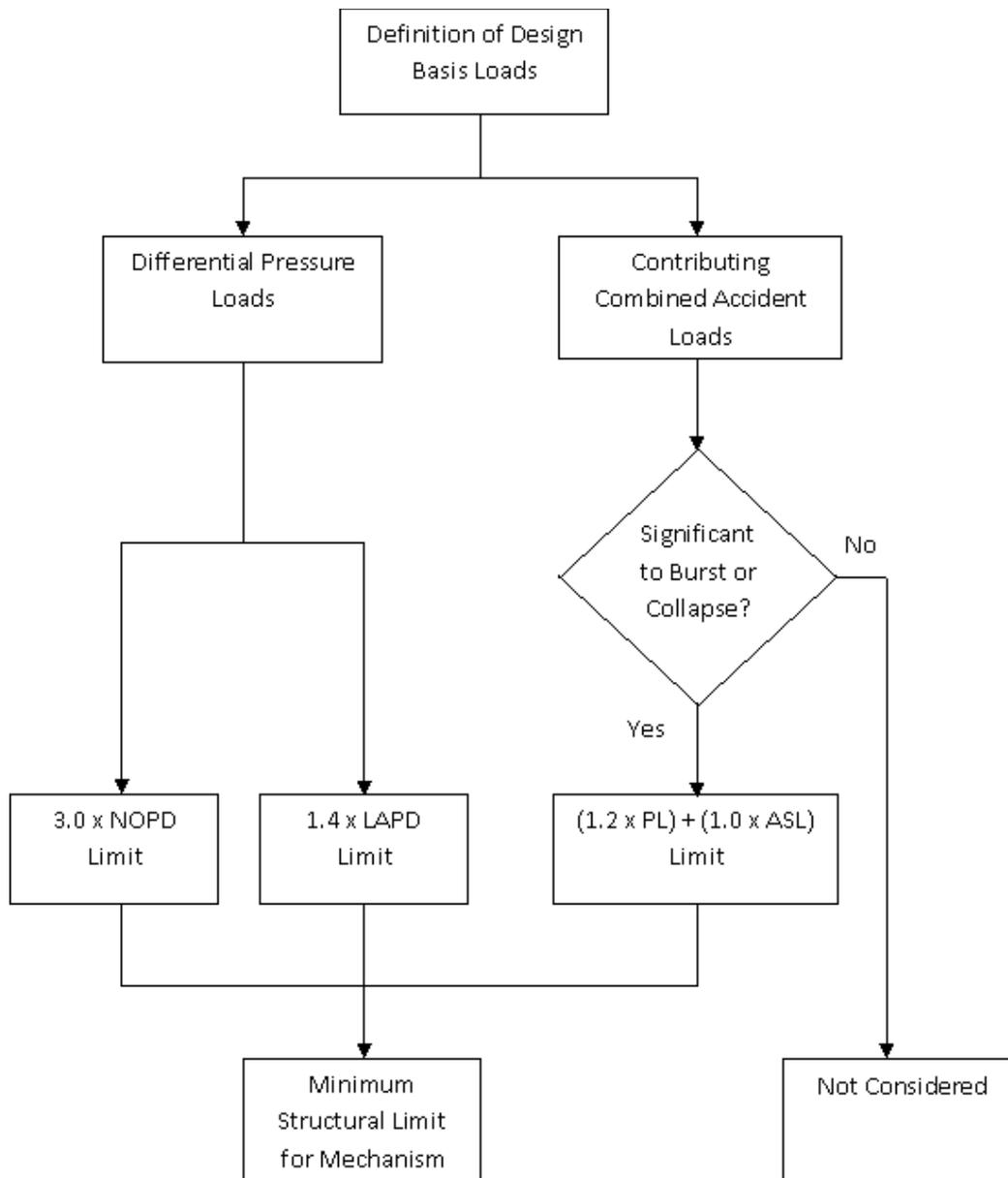
Figure 2--1
SIPC Implementation Logic

2.3 Leakage Integrity Performance Criteria

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

> The Reactor Coolant System (RCS) operational primary-to-secondary leakage through any one steam generator shall be limited to 150 gallons per day.

Note: The operational leakage performance criterion is contained in the plant's Technical Specifications and may be less than 150 gallons per day.

The AILPC is:

> The primary to secondary accident induced leakage rate for any design basis accident, other than a steam generator tube rupture, shall not exceed the leakage rate assumed in the accident analysis in terms of total leakage rate for all steam generators and leakage rate for an individual steam generator.

Note: The site-specific AILPC is contained in the plant's Technical Specifications Bases based on the site-specific accident analysis.

Determining the site-specific AILPC involves a review of site accident analyses.

If the probability of leakage exceeding the AILPC from all sources is less than 5%, the AILPC is met. However, if the probability is greater than 5%, a leakage calculation would determine if the performance criteria are exceeded. The flow rate, pressure and temperature conditions used in the determination of the accident induced leakage rate shall be consistent with those assumed in the accident analysis for the plant.

2.4 Performance Acceptance Standards

The performance acceptance standards for assessing tube integrity to the SIPC and AILPC apply to both CM and OA. The acceptance standard for structural integrity is:

> The worst-case degraded tube for each existing degradation mechanism shall meet the SIPC requirements with at least a probability of 0.95 at 50% confidence.

The worst-case degraded tube for each existing degradation mechanism is established from the estimation of lower extreme values of structural performance parameters (e.g., burst pressure) representative of all degraded tubes in the bundle.

The acceptance standard for accident leakage integrity is:

> The probability of satisfying the limit requirements of the AILPC shall be at least 0.95 at 50% confidence.

The analysis technique for assessing the above conditions may be either deterministic or fully probabilistic in calculation form or a combination of the two. General discussion of the determination of tube assessment limits for CM and OA is given in Section 3.

2.5 Discussion of Structural Safety Factors and Bases

2.5.1 Assessment Factors

Margins of safety against burst or collapse failure provided by the SIPC are consistent with the design margins implicit in the stress limit criteria of the ASME Code. The safety factor is three times the Normal Operating Pressure Differential (3 NOPD), or 1.4 times the Limiting Accident Pressure Differential (1.4 LAPD) across the tube wall, whichever is higher. Licensees shall ensure that loadings associated with all normal plant conditions, including startup, operation in the power range, hot standby, cool down and all anticipated transients do not produce a primary membrane stress in excess of the yield stress.

Historically, a minimum burst pressure of 3 NOPD has been used as the limiting loading guideline for a structural limit. A tube degraded to the structural limit must also be able to

survive postulated conditions that include the largest primary-to-secondary differential pressure for design basis accidents. When the 3 NOPD criterion is satisfied, accident loadings are typically found to be acceptable (i.e., not limiting).

The structural performance evaluation also includes an assessment of potential contributing loading conditions for the postulated accident events defined in the design and license basis as illustrated in Figure 2-1. The assessment of these additional conditions is to assure that the associated loading conditions that can significantly contribute to tube burst or collapse are addressed. An accident loading condition other than differential pressure is considered significant when the addition of such loads in the assessment of the SIPC causes a lower structural limit or limiting burst/collapse condition to be established. This general assessment is needed to ensure that the structural integrity performance objectives are adequately satisfied, given that there are design-specific as well as plant-specific situations that cannot be generically addressed.

2.5.2   Burst Definition

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

> Tube burst is the gross structural failure of the tube wall. The condition typically corresponds to an unstable opening displacement (e.g., opening area increased in response to constant pressure) accompanied by ductile (plastic) tearing of the tube material at the ends of the degradation.

2.5.3   Collapse Definition

Steam generator tubes must also exhibit a low probability of failure by net-section collapse under accident conditions. Tube collapse refers to the failure condition where a tube forms a plastic hinge under the combined action of axial and bending loads. For purposes of this document, the definition of tube collapse is defined as:

> For the load displacement curve for a given structure, collapse occurs at the top of the load versus displacement curve where the slope of the curve becomes zero.

On a generic basis, plastic collapse of a tube under accident loads has been shown not to be a relevant failure mode for tubing for current operating steam generator designs. It is expected that a tube burst condition will occur prior to collapse. Therefore, tube burst will be the limiting failure mode in the determination of structural limits.

2.5.4   Limits on Yield Strength

Tube integrity be maintained for the full range of reactor operation including startup, operation in the power range, hot standby, cool down, and all anticipated transients that are included in the design specification. This "no yield" criterion for normal operating conditions is stated in Part C.3.a.(1) of NRC Regulatory Guide 1.121:

> "Loadings associated with normal plant conditions, including startup, operation in power range, hot standby, and cooldown, as well as all anticipated transients (e.g., loss of electrical load, loss of offsite power) that are included in the design specifications for the

plant, should not produce a primary membrane stress in excess of the yield stress of the tube material at operating temperature."

In summary, the yield strength of the tubing should not be exceeded during the full range of normal reactor operating conditions, even when the tubing is degraded to the minimum acceptable wall thickness.

Hence, a key aspect of tube integrity is to ensure that degraded SG tubes are not stressed beyond the elastic range of the tube material for primary membrane loads for normal operating conditions (i.e., gross yielding of the tube is prevented during normal operation). In this context, tube integrity for all expected operating scenarios (i.e., the full range of reactor operation including startup, operation in the power range, hot standby, and cool down (including plant coast down), and all anticipated transients) is demonstrated if the associated primary membrane stresses are below the yield strength of the tube material for Service Levels A and B (normal and upset) conditions. As it is not practical to verify a yield strength criterion in a field application, the safety factor requirements of the SIPC on pressure loads have been crafted to ensure the yield strength criterion is also satisfied. In general, meeting the structural requirements of the SIPC will limit the primary membrane stress such that gross yielding in the degraded region is prevented in current operating steam generator designs.

2.6   Pressure Load Definitions

The important loading condition for structural integrity performance assessments is the pressure differential across the tube wall during normal steady state operation and accident conditions as defined in the SIPC. For normal plant operation, the pressure across the SG tube is the primary-to-secondary pressure differential occurring at normal full power operation.

Normal steady-state full power operation as defined in NEI 97-06 is:

> The conditions existing during MODE 1 operation at normal steady state full power operation.

3
TUBE INTEGRITY ASSESSMENT LIMITS

3.1   Introduction

This section presents the high-level information regarding the establishment of the tube integrity and plugging limits associated with SG tubing, such that the tube integrity performance criteria and the performance acceptance standards defined in Section 2 are satisfied during operation. Tube integrity limits are defined for each existing and potential degradation mechanism.

Determination of tube integrity limits includes identifying an acceptable structural parameter, such as loss of wall thickness or degradation length, which can be related to tube integrity and can be measured by NDE technology.

3.2   Tube Integrity Limits

The focus of this section is on the determination of structural limits to prevent tube burst. A structural limit is established from the mean (best estimate) regression relationship for tube failure for the conditions defined by the SIPC. The CM limit is obtained by modifying the structural limit to account for the uncertainties associated with the tube failure regression model, material properties, and the NDE system. The plugging limit (OA limit) is obtained by further modification to consider degradation growth and require that flaws on tubes remaining in service at the beginning of cycle satisfy the SIPC over the next inspection interval.

The structural parameter may be defined explicitly in terms of a mechanical variable, such as crack length and/or depth, or by percent degraded area (PDA). Alternatively, this structural parameter may be defined in terms of an implicit variable that is empirically related to the strength of the tube (e.g., eddy current bobbin voltage, RPC voltage, etc.).

USNRC Regulatory Guide 1.121 provides another acceptable methodology to establish structural limits.

3.2.1   Condition Monitoring Limit

Condition monitoring is the assessment of the current state of the SG tubing and is performed at the conclusion of each SG inspection. The purpose of the CM is to confirm that both the SIPC and AILPC were satisfied during the past inspection interval. The assessment involves a comparison of the as-found inspection results against the performance acceptance standards for structural integrity and accident leakage. Because the detected indications, in terms of the distribution of either indication voltages or measured flaw sizes, reflect a conservative estimate of the in-service population of (detected and non-detected) flaws at the end of the cycle (EOC), monitoring the as-found condition will provide a conservative evaluation of the current condition of the tube bundle, including the flaws that remain undetected after inspection. In this situation,

the performance acceptance standard can be applied to the detected population to verify the SGs met the SIPC during the previous inspection interval.

Condition monitoring therefore requires that the detected flaws, as determined by in-service inspection, do not exceed the appropriate CM limit for each degradation mechanism. A schematic illustration of the CM limit is shown in Figure 3-1. Its determination involves calculations with the following parameters:

1. A burst model based on regression analysis of tube failure data, including uncertainty (relational uncertainty) in the prediction of burst pressure, for a given extent of degradation,

2. Tube material strength information, including uncertainty (material properties uncertainty) in mechanical strength behavior due to material heat-to-heat and within-heat variability, and

3. Measurement uncertainty to the NDE sizing technique (NDE measurement uncertainty).
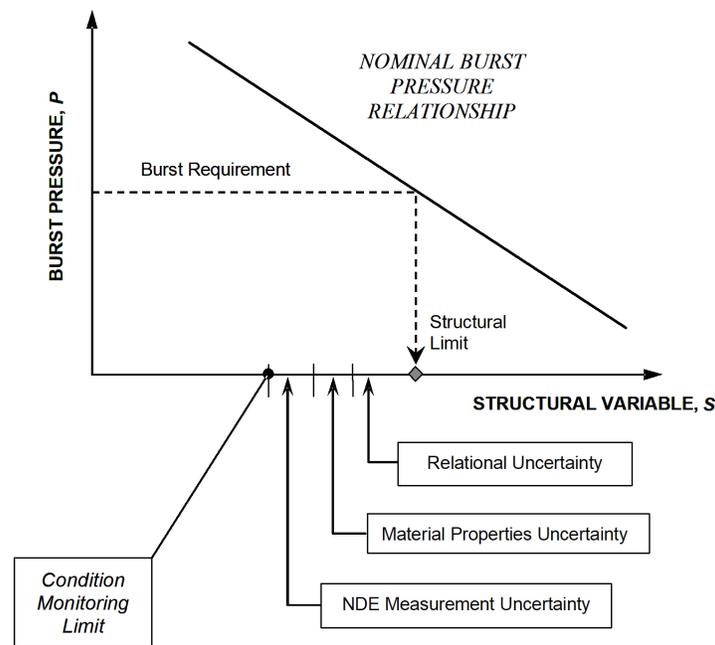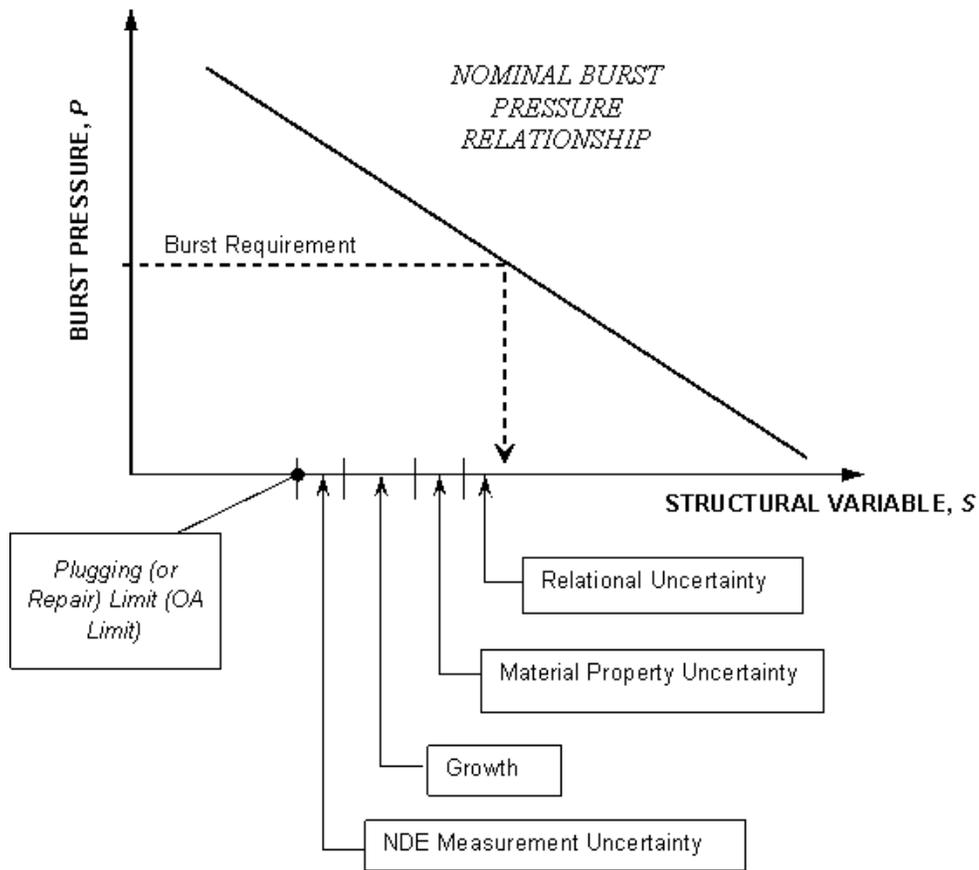

Figure 3-1-
CM Elements of Tube Integrity Assessment

3.2.2   Operational Assessment Limit

An OA is a forward-looking prediction of the SG tube conditions at the next inspection. Operational assessments require that the projected sizes of the undetected population of flaws, or detected flaws intentionally left in service as determined by analysis, do not exceed the OA limit. The OA limit is the beginning of cycle (BOC) maximum value of the degradation parameter which satisfies the SIPC at the next SG inspection.

Operational assessment requires that the degree of degradation of any flaw remaining in service does not exceed the appropriate OA limit for any degradation mechanism. A schematic illustration of an OA is shown in Figure 3-2 for plug on NDE sizing and Figure 3-3 for plug on

3-2

detection. The plugging limit and OA limit are similar in nature in that they provide the BOC structural parameter to meet the SIPC at EOC, depending on whether one is using sizing or probability of detection (POD) to establish the BOC requirement.

Figure 3-2-
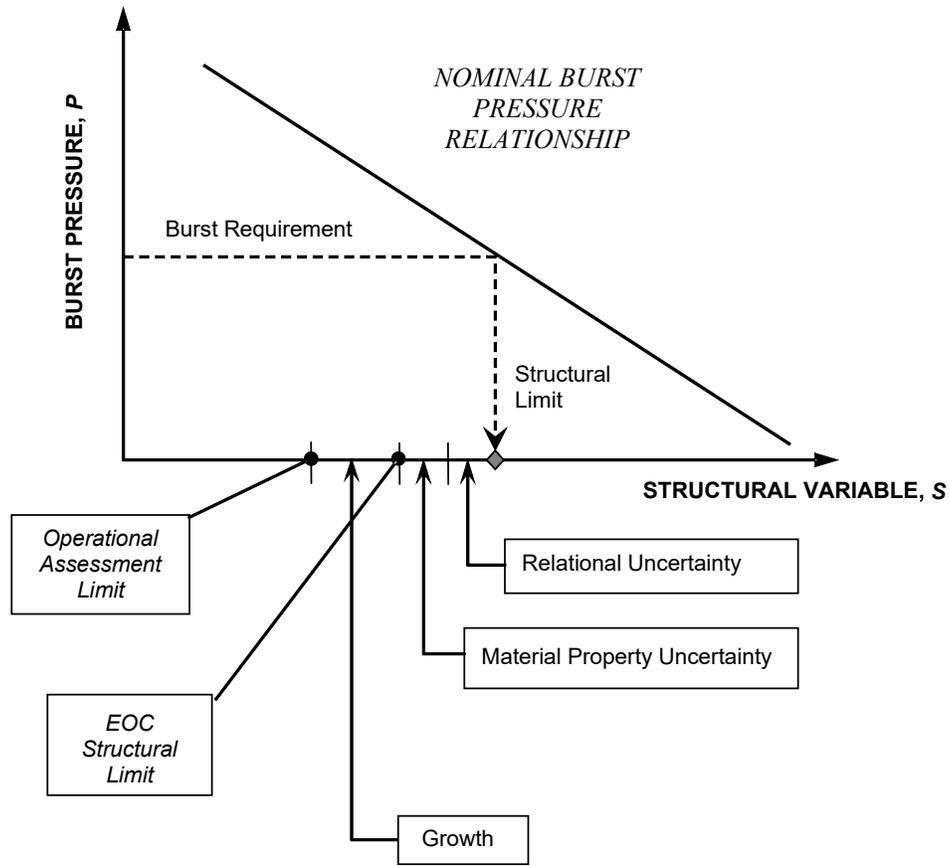**OA Elements of Tube Integrity Plug (or Repair) on Sizing**

Figure 3--1
OA Elements of Tube Integrity Plug (or Repair) on Detection

Determination of the plug and OA limits involve calculations with the following:

1. A burst model based on regression analysis of tube failure data including uncertainty (relational uncertainty) in the prediction of burst pressure for a given extent of degradation

2. Tube material strength information including uncertainty (material property uncertainty) in mechanical strength behavior due to material heat-to-heat variability

3. Degradation growth during future operation (growth uncertainty)

4. For plug on NDE sizing, measurement uncertainty associated with the sizing technique (NDE measurement uncertainty)

The plug and OA limits are sometimes referred to as the BOC Allowable Limit.

3.2.3   Application of Uncertainties in Integrity Assessments

When performing CM assessments, NDE sizing results are evaluated to determine if structural and leakage integrity requirements have been met. When performing OAs, projections are made concerning the size of the degradation at the next scheduled inspection and then compared to structural and leakage integrity requirements.

For CM, the uncertainties determine how accurately the NDE results can estimate the actual degradation dimensions and how accurately the probability of burst and leakage can be calculated. Thus, the CM uncertainties include:

1. NDE sizing uncertainties

2. Material property uncertainties

3. Burst equation (relational) uncertainties

4. Leakage equation uncertainties

There are two scenarios for projecting the size of degradation when performing an OA: plug on sizing and plug on detection. The determination of the BOC worse-case flaw is different in each case. For the plug on sizing, NDE results are used to determine the BOC flaw size, therefore, sizing uncertainties are added. For the plug on detection an estimate is determined by the POD for that degradation. No NDE results are used; therefore, no sizing uncertainties are necessary. The next step is to determine the growth of the degradation for the upcoming inspection interval. This degradation growth allowance can be considered as an uncertainty. Thus, the OA uncertainties include:

1. Material property uncertainties

2. Burst equation uncertainties (relational uncertainties)

3. Leakage equation uncertainties

4. Plug on Sizing Scenario

    a. NDE sizing uncertainties

    b. Growth allowance uncertainty

5. Plug on Detection Scenario

    a. Growth allowance uncertainty

3.3   Material Properties

The structural limit depends upon the flow strength of the material, which is a function of both the yield and ultimate tensile strengths for the tubing. The integrity assessment limits include adjustments to account for statistical distributions associated with tube material properties. Both CM and OA limits reflect the uncertainty in strength determined at the operating temperature for the as-fabricated generator.

3.4   Plugging Limit

The plugging limit is the NDE measured parameter at or beyond which the tube is to be removed from service by plugging. It is recommended that plugging limits for existing degradation mechanisms be established prior to the inspection. The plugging limit is defined such that the performance criteria will be met at the end of the inspection interval. If a Technical Specification plugging limit is defined, the more limiting value shall be used.

3.5   Technical Specification Plugging (or Repair) Limit

A plant's Technical Specification plugging limit is determined from bounding values of NDE sizing uncertainty and degradation growth rate in conjunction with a conservative safety factor. Flaws that are smaller than the plugging limit may be left in service when technically justified by the OA. Historically, the plugging limit has been derived by subtracting allowances for NDE uncertainty and degradation growth from a structural limit. The plugging limit is based on maximum measured depth.

3.6   Determination of Structural Integrity Performance Criteria Limits

3.6.1   Tube Burst Event

In applying the SIPC, structural limits for allowable tube wall degradation are determined for three sets of postulated conditions, as illustrated in Figure 2-1. The conditions for determining allowable burst pressure, or allowable structural limits on degradation, are defined by separate analyses. The limits for accident conditions are determined from a tube failure model that considers pressure differentials and combined primary loads (bending plus pressure) and axial secondary loads and their synergistic effect on burst pressure and/or plastic collapse.

The structural limit for a given degradation mechanism is the maximum degradation size that satisfies all three requirements. In most situations, the structural limits are set by the safety factor of three imposed on full power steady state operating pressure. In some situations, the establishment of the structural limit will be governed by accident conditions. This will be dependent on plant design, the specific degradation mechanism and location, and the applicable set of transient parameters for the plant under consideration. In a few situations, contributing non-pressure loads may be significant.

3.6.2   Significant Contributing Loads

Potential contributing non-pressure primary loads created during accident conditions would be those bending loads resulting from dynamic conditions. Dynamic conditions include cross flow and other hydraulic and inertia forces from a loss of coolant accident (LOCA) and seismic events. Both RSGs and OTSGs are subjected to these types of primary bending loads.

Contributing axial secondary loads during accident conditions are generally the result of differential thermal conditions. For OTSGs, the largest contributors of axial load in the tubes are the difference in temperature between the tubes and shell, and the difference in coefficient of thermal expansion between the tube and shell materials. Since the tubes have a larger coefficient of thermal expansion than the shell, even without a temperature difference between tubes and shell, the tube will experience a compressive thermal load under normal (steady-state) operating conditions when the tube and shell are at the same temperature. The axial load associated with thermal expansion can be significant because the temperature difference that may develop between the tubes and shell is coupled with more rapid heating or cooling of the tubes than the shell during a transient condition. Due to different transient response systems at each of the OTSG plants, the resulting accident tube loads are plant specific.

For RSGs, in the event that a tube becomes locked at a support plate, it is possible that differential temperatures between the tube and the wrapper or other neighboring structures can

create secondary axial loads in the locked tube. The magnitude of the axial loads is a function of the number of tubes that are locked and their location in the bundle. During normal operation, the tubes that become locked will have a fixed axial stress, which is simply the stress due to the pressure load in an unlocked tube. Once locked, the axial stress may vary during transients that impose a differential displacement between the locked tubes and adjacent structures.

Locked tubes in the interior of the bundle, away from restraining structures such as the stay rods and wedge supports on the wrapper, will tend to displace the tube supports plates due to the flexibility of the plates resulting in little or no additional axial loads. This same type of behavior will occur during faulted conditions, resulting in little or no added stress for locked tubes away from restraining structures. A review of applicable loading conditions will indicate which tubes and under what conditions axial tube loads will become significant. Note that for trefoil and quatrefoil style tube holes in tube support plates (TSPs) or lattice grid bar, TSPs constructed using stainless steel that the likelihood of locked tubes at TSPs is judged extremely low.

As an overall general approach, the logic to screen loads as to their significance to affect tube burst is outlined in Figure 3-4. The significance of the non-pressure loads to tube integrity will depend on the location of degradation in the tube bundle, the degradation mechanism, and the form and magnitude of the load. The conditions for which non-pressure loads may or may not be significant will depend on the plant design.
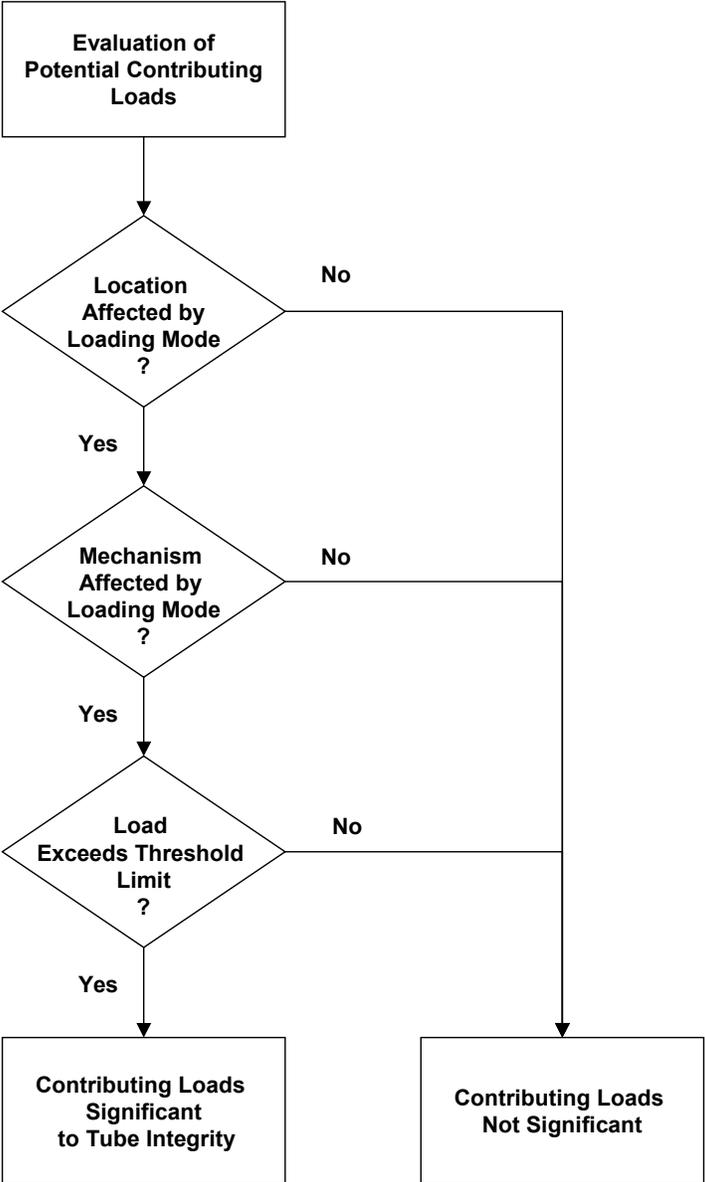
Figure 3--2
Logic for Screening Contributing Loads

3.6.3   Tube Collapse Event

Tube collapse by net section plastic failure under combined tension and bending loads has also been evaluated. Plastic collapse testing of flawed and unflawed tubing for both straight and U-bend geometries showed that plastic collapse is not a relevant failure mode for SG tubing in current operating steam generator designs. For new reactor designs, this mechanism would have to be evaluated. For straight sections of tubing, substantial bending loads cause locking in tube support structures that restricts further tube end rotation and axial displacements. This effectively prevents plastic collapse in bending. Plastic collapse of U-bends under in-plane bending leads to very large displacements. Such large displacements are restricted by interference with neighboring tubes. Therefore, tube burst is the only important failure mode for SG tube integrity for normal and accident loading conditions.

4
NDE MEASUREMENT UNCERTAINTIES AND TECHNIQUE SELECTION

4.1 Introduction

This section addresses eddy current NDE system performance measures and associated uncertainties for SG tube bundle examination and tube integrity applications. Two aspects of performance are considered: 1) degradation detection, quantified by probability of detection (POD), and 2) degradation sizing. Because the performance of various available techniques is an important input to the integrity assessment process, technique performance characteristics have an important impact on the selection of methods to be employed during an inspection.

For all existing and potential degradation mechanisms identified in the DA, total NDE system performance (technique and analyst uncertainties) should be established for detection. If noise or other factors affect the ability to apply the sizing procedure (typically only applicable to SCC sizing), tube integrity could be demonstrated through in situ pressure testing or an alternate sizing methodology provided the uncertainty basis is documented. However, it is likely that indications which approach the CM limit are of sufficient signal amplitude that external factors have a negligible impact upon sizing capability.

Section 4.2 defines POD requirements and limitations on POD for tube integrity applications and discusses POD modeling. Section 4.3 discusses sizing requirements and limitations.

4.2 Probability of Detection

4.2.1 Requirements and Limitations for Tube Integrity Applications

An NDE system is defined as the equipment, procedure and personnel used in performing an inspection. Steam generator tube examination technique qualification focuses on a portion of the system (i.e., equipment and procedure). Personnel effects, such as performance variations expected with multiple data analysts (human factors) should also be considered.

Probability of Detection information can be established using an empirical approach. A number of POD functions are available. Based on the properties of the function at the origin (See Figure 4-2), the log-logistic function was determined to be the most appropriate for generic use (equation 4-1).

$$POD(S) = \frac{1}{1+e^{-(a+b \log S)}}$$ **Eq. 4--1**

where *S* is the structural parameter (e.g., length, depth, or PDA), and *a* and *b* are model parameters to be determined. In general, these parameters are degradation mechanism and examination technique specific.

The application of the log-logistic POD function is not exclusive. The logistic POD function has also been used for tube integrity applications; this function is provided by equation 4-2. Additional POD curve fitting functions besides the log-logistic and logistic have been applied, and it is the responsibility of the tube integrity engineer to evaluate the function selected to ensure its' appropriateness.

$$POD(S) = \frac{1}{1+e^{-(a+bS)}}$$
<div align="right">**Eq. 4-2**</div>

4.2.2   POD Modeling

A POD model is a functional measure of the ability of an NDE system to detect degradation. It is one of the inputs to an OA and is used to estimate degradation remaining in service after an eddy current examination of the tube bundle is performed. As shown in Figure 4-1, a POD model is constructed using binary hit-miss data in which NDE detections and non-detections, coded as 1's and 0's respectively, are plotted using a structural parameter as the independent variable, and then non-linearly regressed using an appropriate mathematical function which is defined as the POD model. The resulting POD model is dependent on the available hit-miss data and its distribution with respect to the structural variable. Various structural parameters such as maximum depth, average depth, length, voltage, etc. can be used as the independent variable depending on the needs of the tube integrity engineer.

Binary hit-miss data can be regressed using different non-linear functions resulting in different POD models for the same input. This point is illustrated in Figure 4-2 where the same hit-miss data have been fit using logistic and log-logistic functions. Note that for this data set, the logistic function is non-zero at the origin with a value of ~1 at the upper extreme of the independent variable whereas the log-logistic function is fixed at the origin but assumes a value <1 at the upper extreme. Numerous alternative curve fits are available, and in some cases, it could be determined that one of these alternate fits is more appropriate than either the logistic or log-logistic.
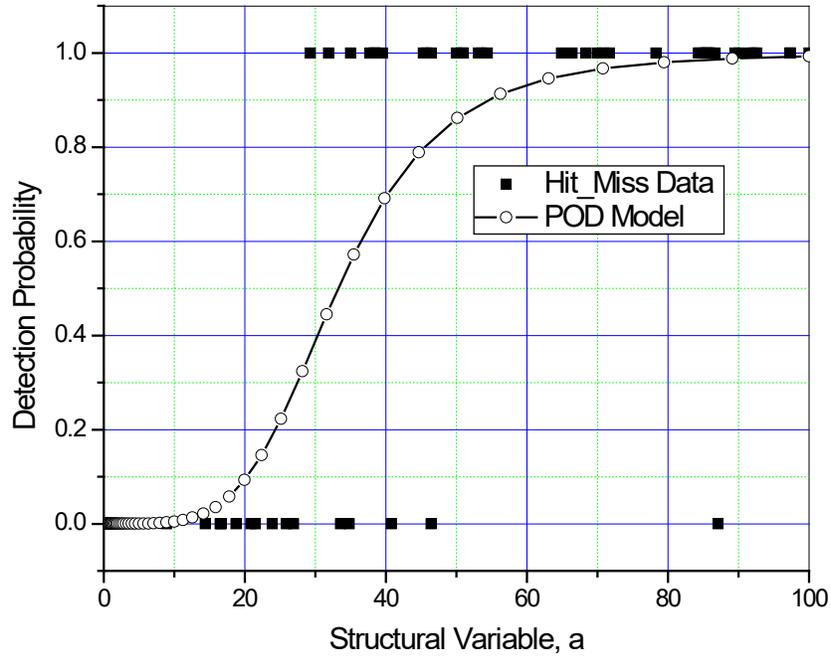
Figure 4--1
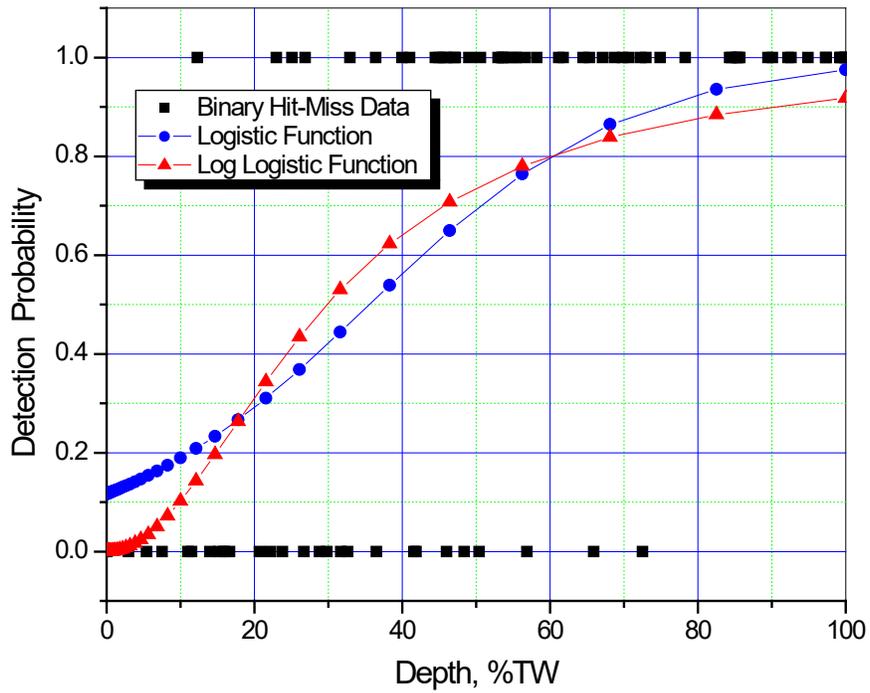**Generating a POD Model Using Binary Hit-Miss Data**

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

4.3 Sizing Requirements and Limitations for Tube Integrity Applications

NDE sizing uncertainty is based on assessing a measured NDE value with the true value of a structural variable as determined from metallography. Normally this comparison is done over the expected dynamic range of the structural variable, resulting in a paired data set consisting of measured and actual values. Sizing uncertainties are determined using standard linear regression analysis methods.

The starting point for establishing sizing uncertainties is a scatter plot of NDE measured ($NDE_{measured}$) and true structural (S) values as shown in Figure 4-3. The structural variable for this example is maximum depth in percent through-wall. The measured value is used as the independent variable with the structural value being the dependent variable. The paired data are then regressed using the linear equation

$$S = a + b * NDE_{measured}$$ **Eq. 4--2**

where S is the structural parameter used for integrity assessment, a and b are constants determined by minimizing the root mean square (RMS) error about the regression line and $NDE_{measured}$ is the NDE measured value. In general, these constants are degradation mechanism and examination technique specific. The tube integrity engineer can now determine the structural variable S, which is generally a function of the degradation mechanism being addressed, i.e., thinning, axial cracking, etc. To date, specific values for S have included maximum depth; PDA; burst effect length and burst effective depth; crack area etc.
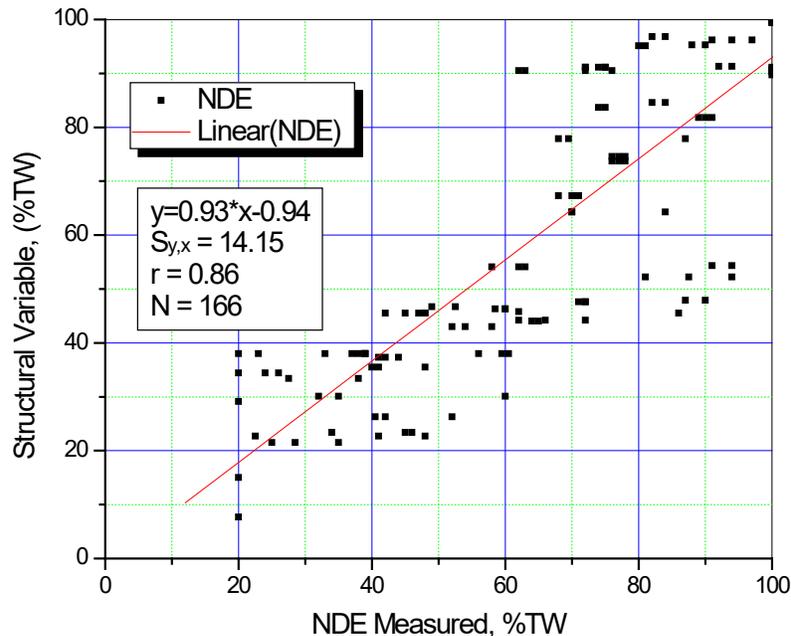

Figure 4-3-
Regression Plot Format Used for Determining NDE Sizing Errors

When using data to determine sizing performance, the technique performance test data should have a correlation coefficient that establishes with 95% confidence that a correlation does statistically exist between the measured size and what is considered to be the actual size.

Table 4-1 provides the minimum correlation coefficient for a given number of data points to achieve this level of confidence. For example, for a sizing data set of 16 points the correlation coefficient should be greater than 0.426.

The following equation was developed to approximate the values in Table 4-1.

$$r = 1.841H^{-0.527}$$ **Eq. 4--3**

where H is the number of observed data pairs.

Table 4--1
Correlation Coefficient, r*, at 95% confidence level for a positive correlation

Number of Observed Pairs, H	Correlation Coefficient, r, (minimum)
16	0.426
20	0.378
25	0.337
30	0.306
35	0.283
40	0.264
45	0.248
50	0.235
Note: A minimum number of 16 data points will be adequate for most distributions	

* Applies to linear first-order models only

Localized conditions can also affect sizing performance. One example is wear at a Dented Trefoil/Quatrefoil Style TSP. Depth estimation from the bobbin probe can be challenging if the wear and dent are located at the same elevation. Characterization using a rotating probe or array probe can establish if the dent and wear are located on the same land. If so, the two signals can combine to form a signal resultant and sizing using amplitude could result in an overestimate of depth. If the wear and dent are located at the same elevation but on different lands, the established sizing methods remain valid.

5
DEGRADATION GROWTH RATES

5.1   Introduction

In this section a discussion is presented regarding determining degradation growth rates from NDE inspection information. Plants that have degradation within their SGs should analyze inspection data from prior outages to help develop flaw growth information. If growth rates are developed prior to current inspection, they should be updated with current inspection results in the development of an OA. Degradation growth rates can exhibit increasing or decreasing trends over time. Especially, if plant operating conditions have changed, e.g., power uprates, etc.

Flaw growth rates are necessary in order to project EOC degradation distributions when implementing an OA strategy. An empirical growth rate distribution and a 95th percentile upper bound growth rate value should be established for each existing degradation mechanism (or sub mechanism) if sufficient data exist.

5.2   Background and General Information

General Considerations:

Growth rate information is obtained from the change of NDE measurement parameters from one inspection to another. For a plug on sizing scenario, such as for wear, sizing information may be available from current and prior inspections. For a plug on detection scenario, as is typically applied to crack-like degradation, NDE sizing for the inspection prior to the detection inspection is typically based on a reevaluation of previous NDE data, i.e., a historical or look-back evaluation, using the benefit of hindsight. This naturally raises a substantial question of sizing accuracy, since look-back sizing is applied to an indication that was previously unidentified. This situation can be improved by having the same NDE analyst perform side-by-side sizing of a given indication using the data from both inspections. Growth rates obtained from plug on sizing scenarios tend to provide the most reliable growth rate data.

Degradation growth rates should be established from past site-specific results. If site specific data is not available, then industry data from similar design SGs may be considered for use with the caution that non-site-specific degradation rates are typically different due to the differences in SG operation and should be evaluated for application.

Ideally, degradation growth rates should be based on a large set of data, for example, 59 growth data points or more. A minimum of 15 site-specific growth data points is needed to avoid extrapolating to the 95% probability, 50% confidence value, a key parameter of interest. For a larger, normally distributed growth data set, the 95/50 and 95th percentile ordered growth should be approximately equal. If the 95/50 growth rate is determined by the sum of the mean growth + 1.645 times the standard deviation, it is recommended to compare this value with the ordered

(median-ranked) 95th percentile value and apply the more conservative of the two when performing deterministic OAs.

Particularly for probabilistic OA inputs, a distribution (typically the lognormal distribution but others can be used) fitted to the growth rate data can be used. The fitting process is not exclusive to probabilistic OAs. A lognormal distribution can be generated from the lognormal mean and standard deviation values however the distribution may not well represent the upper tail. It is important that the developed distribution represents the upper tail of the growth rate distribution and that the largest measured growth rate is bounded by the fitted function. Figure 5-1 presents an example of a hypothetical growth data set where the lognormal distribution generated from the mean and standard deviation of the lognormal growth data points does not represent the upper tail. The growth data and two lognormal distributions are found on Figure 5-1. The "LN Fit" distribution is the distribution calculated from the mean and standard deviation of the lognormal growth data. As seen from this figure, the distribution does not well represent the upper tail of the data. The "Developed LN Fit" distribution is developed by adjusting the lognormal mean and standard deviation such that the upper tail of the data is well represented. Additionally, but of lesser significance, the "Developed LN Fit" passes through the approximate 50th percentile of the data. Typically, it is only the upper tail which will influence burst probability thus representation of the upper tail is of most importance.

Growth results and EOC size distributions should be compared over several cycles of operation to determine if degradation growth rates are accelerating. Comparison of prior cycle projections to inspection results helps to assess growth rate and methodology adequacy. Growth rates from several cycles of operation should only be combined if the NDE sizing procedure is essentially the same and substantially accelerating growth rates are not an issue. This is not a typical problem unless significant chemistry upsets are known to have occurred, operating or support conditions have dramatically changed in the case of wear degradation. If high growth rates are identified in one or more inspections followed by one inspection with low degradation growth rates, the higher growth rates should be used until a decreasing trend is confirmed.

Actual degradation growth rates are confounded by NDE sizing errors. Each measured growth rate contains two measurement errors; that is, the error associated with the current measurement, and the error associated with the prior measurement of a given flaw.

Conservative estimates of degradation growth rates are useful in cases where structural integrity margins are relatively large and a quick, effective simplistic type of OA strategy is all that is required to demonstrate tube integrity performance criteria are met. A conservative distribution of growth rates is obtained if NDE sizing errors are included and negative growth rates are set equal to zero. This strategy should only be followed if 15 or more NDE estimated growth rates are available. Overly conservative growth rates are obtained if only positive NDE estimated growth rates are considered. Overly conservative growth rates may also result from look-back sizing of only the largest EOC NDE measured degradation dimensions. For simplistic type OAs, the upper 95th percentile growth rate is the parameter of interest. When structural integrity margins are small, more realistic degradation growth rates are necessary to demonstrate tube integrity performance criteria are met.

When determining a growth rate where the prior inspection period included three or more operating cycles simply averaging the growth rate over the inspection period could dilute the upper tail of the per cycle growth rate. The growth is random for each operating cycle. It is

recommended that a multi-cycle assessment of growth be performed to identify the appropriate per cycle growth rate.

SCC Considerations:

For SCC degradation mechanisms, growth rates are dependent on the RCS temperature and can vary over the tube length (e.g., hot leg versus cold leg or elevation dependent, that is bottom TSP versus top TSP). In these cases, if RCS temperature changes, or if growth rate data from multiple plants with different temperatures are being combined, then the combined data should be normalized to a common temperature using the Arrhenius equation and appropriate activation energy constants.

The Arrhenius equation is written in general terms as:

$$Rate = A \exp\left(\frac{-\Delta H}{RT}\right)$$

where A is a constant, ΔH is the activation energy, R is the ideal gas constant and T is the absolute temperature. If the temperature increases the rate increases. If ΔH is expressed in units of cal/mol then R is 1.985 cal/(mol K) and T is the absolute temperature in Kelvin. This concept can also be applied within a SG to estimate the SCC growth rate variation from specific hot leg to cold leg locations.

Experience has shown that very large apparent growth rates arising from indications without prior detection likely represent a detection issue not a growth rate issue. Assigning a starting degradation size based on expected detection sensitivity (detection threshold) will lead to a more realistic growth rate estimate. However, since detection sensitivity is the issue, the assigned starting degradation size is an arbitrary assignment. If this approach is used a simulation of the growth rate should be performed to ensure that the combination of noise, POD, initiation function and growth rate would be expected to produce depths at the prior inspection consistent with the assumed detection threshold. Multi-cycle benchmarking can help to support this practice. It is more reliable to deal only with data where sizing results are available for both inspection intervals and/or to use default growth rate data discussed in later sections.

Growth rate is a key input parameter to the OA. When evaluating growth rate for SCC indications, when the most recent inspection data suggests the presence of a precursor flaw, it is recommended to continue this backward-looking process to develop growth characteristics over as many inspections as possible. This process may support the presence of a depth-dependent growth rate in the early stages of crack initiation. That is, extending this process backwards may suggest that the growth rate slows after the crack depth has achieved some level, where the crack initiation and initial growth (which may be stress driven) dramatically slows and continued crack growth is then a function of the material and microstructure. This condition could be present if the influence of residual stress is significant with regard to initiation and influence on growth rate upon initiation. If the significant residual stress has a limited depth of penetration, the ability for the indication to experience accelerated growth rates is minimized once the SCC depth reaches the point where the residual tensile stress is diminished. This behavior appears to describe the majority of the A600TT SCC indications reported to date.

<u>Wear Considerations:</u>

Note that experience has shown that for replacement SGs (A690TT tubing), the second ISI results may not be bounded by a linear projection of the first ISI results, both with regard to number of indications and depth/growth of indications where both cycles have approximate equal length. Thus, it is important to consider the effects of a small growth rate population size at the first ISI to ensure that the second ISI results are adequately projected and evaluated.

Empirical data suggests that very shallow (<10 to 15%TW) support structure wear indications may be systematically underestimated with regard to depth. Thus, application of the indicated depth in early inspections without validation of the indication depth could lead to a non-conservative OA result if multi-cycle operation is implemented after a limited number of inspections. Consequently, for the early inspections of new SGs experiencing wear, if extended length operating periods between inspections are planned for the subsequent period, it is recommended to validate (using an alternate probe) the reported depth from bobbin coil analysis for shallow depth (<15%TW) indications to confirm that a systematic under-reporting has not occurred for these shallow, low amplitude signals.

For paired growth data (i.e., reported during two successive inspections), there is no need for NDE sizing adjustment since systematic and random error is built into each measurement, and, for a large growth population, the systematic error will cancel out. For situations in which an adequate number of paired wear indications is not available to establish a reliable growth distribution, newly reported indications with no precursor signal may be used to augment the growth rate dataset. In this case, it is recommended to adjust the reported depth of these indications using the mean sizing regression; a necessary step since the systematic NDE error is only applied for one inspection.

For large depth new indications, tools are available for estimating postulated indication depths at the prior inspection if no precursor indication is present. These can include depth estimation based on prior inspection noise, the POD curve, and benchmarking of prior results. It is recommended that if large depth new indications which exceed the maximum depth for repeat growth are observed, these indications should be considered for inclusion in the growth function.
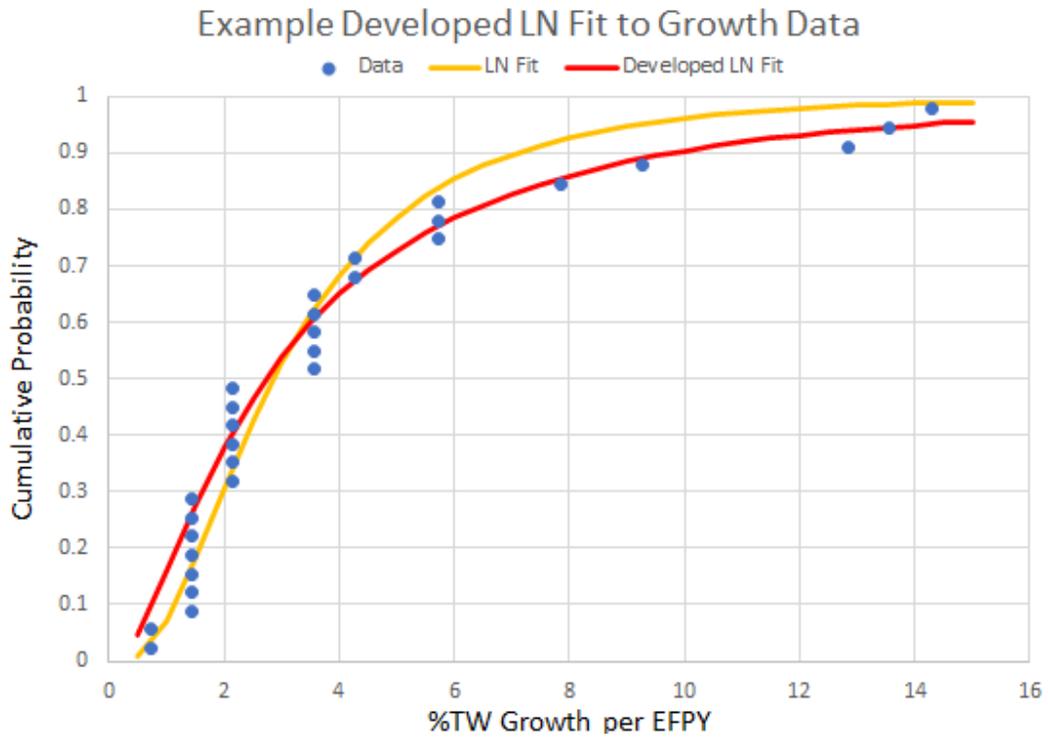
Figure 5-1-
Example of the Developed LN Fit Growth Distribution Which Represents the Upper Tail of the Growth Rate Data

6
DEGRADATION ASSESSMENT

6.1   Introduction

Degradation assessment (DA) 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 SG.

- Existing degradation is defined as indications of degradation previously and/or currently observed in a SG.

- Potential degradation is a mechanical or corrosive process that has not been discovered in prior inspections in the SGs but is judged to have a potential to occur in the current inspection interval based on industry experience and/or laboratory data.

All tubing locations associated with existing and potential degradation mechanisms shall be inspected during each technical specification inspection period. Foreign object wear would never be considered existing degradation but could be considered potential if the plant has a history of foreign object intrusion.

The DA focuses on integrity of the SG tubing. Based on past SG tube inspection results, the tubing can be subjected to a variety of degradation mechanisms. The DA along with the OA and operating experience (OE) provides the supporting basis for the inspection interval.

6.2   Purpose

The overall purpose of the DA is to ensure that appropriate inspections are performed during the upcoming outage, and that the requisite information for integrity assessment is provided. In conjunction with the SG program, it is recommended that the DA address the following objectives as a minimum:

1. Identify existing and potential degradation mechanisms.

2. Identify the limiting SIPC and the appropriate loading conditions for existing and potential degradation mechanisms. If using actual secondary pressures to establish the SIPC for the OA vs design specification values, these predictions should be monitored. A change in plant operation may require a recalculation of the OA. (Sections 2 and 3)

3. Identify CM limit for all existing and potential degradation mechanisms and the appropriate measurement parameter for each degradation mechanism. (Section 3)

4. Select appropriate techniques for detection and sizing and document the NDE measurement uncertainties for each degradation mechanism. (Section 4)

5. Document inspection locations, sampling sizes, and expansion criteria.

6. Plan for monitoring degradation in tube hardware such as plugs and sleeves.

7. Identify relevant industry OE.

8. Identify planned secondary side activities, including those for monitoring the condition of secondary side structures, such as tube supports, anti-vibration bars, and top support plate blockage; and those for investigating and dispositioning of foreign objects. (Section 10).

Additionally, the DA may be utilized to capture proactive inspections that are performed by the utility that are not required by Technical Specifications. These inspections can provide useful information to both the utility and the industry.

6.4   Identification of Steam Generator Degradation Mechanisms

A general plant description pertinent to the operation of the SG should be included or referenced in the DA. The description includes details of the SG design, material, and manufacturing processes variability. This includes the tubing dimensions, tube sheet and support plate designs, as well as details of the anti-vibration bars and support structures. Other design, as built configuration, and plant system information that can affect SG tube integrity are also included in the DA. A listing of similarly designed and/or operated SGs could prove to be useful in evaluating both existing and potential degradation mechanisms.

To provide appropriate outage planning, prior to an outage during which SGs will be inspected, previously identified degradation mechanisms on both the secondary and primary sides of the SG that affect tubing, support structures, or pressure and leak boundaries should be characterized in the DA as to location and possible extent. Growth rate information for the existing degradation mechanisms should also be reviewed. It is also useful to include preventive measures that have been taken such as heat treatment, chemical cleaning, or sludge lancing. If tube sections have been removed for destructive examination, then results of the examinations should be discussed.

The DA and inspection planning process includes an assessment of potential degradation mechanisms with identification of their likelihood of occurrence. Anticipating newly developing degradation mechanisms is necessary for preparation of initial inspection and expansion plans, and identification of applicable NDE equipment, techniques, personnel, and disposition requirements.

Assessment of potential degradation mechanisms should consider, but not be limited to:

- Experience of SGs with similar design and materials

- Susceptibility of the tubing material to SCC (Microstructure), including localized tube deformations and total stress (residual plus operating), residual stresses associated with tube bending and expansion processes during fabrication or operation

- Operating temperature and pressure

- Differences in as-built vs design of the SG (i.e., AVB positioning)

- Secondary side water chemistry, including the potential for contaminants such as lead, chlorides, sulfates, and copper

- Secondary side deposit management

- Previous experience with foreign objects or relevant experience during the previous operating cycle (i.e., damaged gaskets in the feedwater system)

Foreign object induced tube wear is not directly related to SG design, or SG manufacture. Instead, foreign object wear is typically dependent upon ingress of material from the balance of plant. Some SG designs include a straining or trapping systems. Some designs include elements which effectively reduce foreign material introduction to the tube bundle (feedring spray cans). Since no such system is 100% effective, it is recommended that foreign object wear be identified as a potential mechanism for all SG types and designs. The licensee is responsible for selecting the foreign object/wear detection methods and the FOSAR inspection interval. Some plants have experienced tube wear due to manufacturing remnants left in the SGs; with additional accrued operating time the likelihood that manufacturing remnants will be encountered is reduced.

6.4.1   Plug Inspections

Steam generator plugs can be classified into two basic categories. Plugs in the first category are installed prior to operation and commonly referred to as 'shop' plugs. Plugs in the second category are installed following final shop fabrication or are field installed plugs. SG plugs are most often installed either mechanically or through a welding process and can be installed with or without a tube present within the tubesheet. All SG plugs shall be inspected while in-service regardless of the plug type, material, and installation method. Visual inspections are adequate to verity acceptance.

Attributes to consider when preparing the DA and evaluating inspection results for a field or shop installed plugs:

- **Plug Design** – Certain plug designs may be readily apparent based on unique features visually observable from the primary side while others may appear no different from an open tube. It is recommended that plug installation records be reviewed to corroborate visual inspection information when verifying the installation of a specific plug design.

- **Plug Material** – The plug material is a key input in the determination of the inspection interval.

- **Prior Inspection Results** – A side-by-side comparison of results over several inspections could provide early identification of a change in plug condition and promote early identification of a potential impending failure.

A key objective of the DA is to ensure that the performance criteria for operating SG structural and leakage integrity are satisfied and consideration of SG tube and tubesheet plugs is an essential part of achieving this objective.

6.4.2   Guidance for Plugged Tubes

Since tubes removed from service are no longer subjected to inspection, the following guidance is provided:

1. Review the potential effects of chemistry excursions and intrusions, foreign material, and other contributors to tube degradation, on the degradation of all tubes whether plugged or in-service.

2. Unless the results of a stabilization analysis indicate otherwise, it is recommended that all tubes with circumferential cracks within the expansion transition region or within a minimum of 0.5 inch of the bottom of the transition be stabilized. Analysis should include the effects of

the tube being locked at the first tube support plate when appropriate and the potential for continued growth of degradation.

3. When plugging for structure wear, analysis should consider post-plugging growth to determine the need to stabilize. For tubes plugged early in life for significant structure wear and not stabilized, an analysis should be performed to determine if adjacent in-service tubes should be plugged, or if NDE monitoring of adjacent in-service tubes is sufficient.

4. Tubes plugged for preheater wear that have been evaluated as part of the preheater wear issue resolution do not have a potential for tube severance and do not require stabilization. However, if an analysis to determine the need for stabilization has not been done, the tube should be stabilized.

6.4.3   Sleeves and Other Tube Repairs

Consistent with the SG tubing and tube plugs, any existing or potential degradation mechanisms in tube sleeves or other tube repairs should be identified and discussed in the DA along with the planned NDE inspection scope and techniques.

6.4.4   Channel Head Degradation

In-service, primary side visual inspections of SGs have identified visually apparent defects in the SG channel head. The most significant observations included indications of degradation in the cladding and/or divider plate-to-channel head weld with exposure and wastage of the channel head base material. A breach of the SG channel head bowl cladding is necessary for wastage or erosion of the channel head base metal to occur. A failure modes and effects analysis conducted by EPRI SGMP concludes that visual inspections will likely ensure that there are no gross defects that would permit degradation similar to that described in Westinghouse Nuclear Safety Advisory Letter (NSAL)-12-1. Assuming only visual inspections, it is shown that the maximum extent of low-alloy steel wastage without visible evidence of degradation is limited by the amount of under-clad volume that can be accommodated by the cladding before it fails. Specifically, corrosion deposits would form under the cladding and force it to expand until it failed and produced visible damage. Given the small amount of under-clad deposits that can be accommodated by the cladding without visible damage, it is not likely that structurally unacceptable (i.e., exceeding Code stress margins) wastage can occur without being visually detectable. Other areas of the SG channel head are also potentially susceptible, including the tubesheet cladding.

Primary water stress corrosion cracking has been identified in the heat affected zones of the divider plate-to-stub runner and stub runner-to-tubesheet welds in some international Westinghouse-licensed model SGs with thin (1.3") divider plates and welds made of Alloy 600 material. SGMP conducted research over period of approximately 8 years and published several reports. SGMP research concludes that this operating experience is not capable of causing the divider plate to fail under the worst-case conditions; however, it is possible that cracks in the divider plate could grow over time. This led to further research that concluded for the Westinghouse fleet, there is no impact on accident analyses, stress reports, and mechanical plugs and sleeves of a fully degraded divider plate. It was believed at the time, that this work would bound all US steam generator models.

With plant license extension, the US NRC questioned whether cracking in the channel head weldments might propagate through the low alloy steel channel head or to the tube-to-tubesheet welds. Another concern was with Alloy 600 material in tubesheet cladding and its vulnerability to PWSCC. This led to additional investigation which concluded that the only mechanism to propagate a crack through the low alloy steel channel head is fatigue, propagation from the divider plate to the tubesheet welds is unlikely, and there is sufficient chromium in the autogenous tube-to-tubesheet welds to resist PWSCC. Follow-up finite element stress analyses concluded that assumed axial and circumferential flaws in the steam generator channel head material remained well below the allowable flaw depths after 40 years of operation.

The NRC accepted the conclusions of the industry analyses and issued Interim Staff Guidance for License Renewal, Letter LR-ISG-2016-01: "Changes to Aging Management Guidance for Various Steam Generator Components". The LR-ISG revises the GALL Report aging management program (AMP) for Steam Generators and provides an acceptable approach for managing the associated aging effects for SG components within the scope of License Renewal. Specifically, it addresses the changes to aging management guidance on: 1) cracking due to PWSCC of divider plate assemblies and tube-to-tubesheet welds, and 2) loss of material due to boric acid corrosion of SG channel heads and tubesheets.

Plants with materials susceptible to PWSCC shall perform SG channel head visual inspections of the primary side cladding, divider plate, stub runner, if applicable and associated welds using a visual scan by remote video camera or naked eye each time the SG primary manway is removed for tube inspections. The DA should document the SG inspection requirements and frequency.

6.5   Identification of NDE Techniques

NDE techniques selected for detection and/or sizing of degradation in tubing, including tube repairs shall be selected. Information required for integrity assessment such as POD and sizing uncertainties should be identified.

6.6   Identification of Inspection Plan

The objective of the initial plan (6.6.1) and the expansion plan (6.6.2) is to ensure the detection of flaws of any type (e.g., volumetric flaws, axial and circumferential cracks) that may be present along the length of the tube, from the tube-to-tubesheet weld at the tube inlet to the tube-to-tubesheet weld at the tube outlet. The tube-to-tubesheet weld is not part of the tube.

6.6.1   Initial Plan

An appropriate tube bundle sampling strategy and expansion plan shall be defined in the DA for each existing and potential degradation mechanism identified. Minimum sampling is typically established in Plant Technical Specifications.

If a less than 100% inspection is being performed and degradation is detected, one cannot assume that the worst case flaw has been identified. This statement applies to both overall tube bundle and discrete sample plans.

The examination scope may include several discrete pre-defined sample plans based on the degradation mechanisms, examination techniques to be used and the regions of the tube to be inspected. For example, a full-length bobbin coil inspection may be one sample plan. Rotating

coil examinations may include three discrete sample plans; (a) hot leg expansion transitions, (b) low row u-bends and (c) dents and dings. The same tube(s) may be selected for multiple sample plans. Sampling serves to monitor the general condition of the SG by detecting the onset of new degradation or the recurrence of previously experienced degradation. The guidance for performing expansion will be provided in Section 6.6.2.

Inspections performed to provide baseline data, informational data, data to challenge DA assumptions, etc., should not be labeled as inspections for potential mechanisms.

6.6.2   Expansion of Examination Scope

Based on the results of the initial inspection, expansion of the eddy current program may be required. Expansion can be due to the detection of SCC, due to wear at structures, or wear due to foreign object interaction.

Detection of SCC requires expansion to 100% of the region of interest (ROI) in the affected SG(s) and a sample of each unscheduled SG. Multi-cycle modeling can be used to benchmark the number and observed depth of SCC indications for purposes of estimating the number of potential indications in unaffected, sampled SGs for the affected ROI.

Expansion of the inspection plan due to structure wear indications should consider observed growth rates and the inspection period of those tubes not included in the inspection plan for the current outage. The selected expansion scope must support preparation of the OA to the next scheduled inspection, for both the population inspected at the current outage and any tube not inspected at the current outage. If the growth rate is found to be accelerating, it should be assumed that the non-inspected tubes could also be subject to this growth rate. For SGs with mature wear mechanisms (predictable decreasing growth rate), it is unlikely that expansion would be required unless a change in historic growth rate and/or depth distribution and number of newly reported indications is observed. Thus, inspection plan expansion is most likely to be considered for SGs with a limited inspection history.

Guidance for expansion of the inspection plan due to detection of foreign object wear and foreign objects is provided in section 10.3.4.

When cracking and volumetric indications occur in the same region, it is recognized that the bobbin coil technique is not capable of distinguishing between the two mechanisms. Therefore, upon initial detection of cracking, the licensee shall inspect 100% of the current bobbin indications using a technique capable of characterization in that region to correctly characterize cracking and volumetric indications. During subsequent examinations, inspect all new indications and sample historical indications with a technique capable of characterization.

6.7   Integrity Assessment Limits

Pre-outage preparations begin with identifying SG existing and potential degradation mechanisms as discussed above. Other important information should be included as discussed below.

6.7.1 Structural Integrity Limit

The limiting SIPC and the appropriate loading conditions for the degradation of interest shall be determined. In general, based on currently applicable SIPC, this will usually be an applied differential pressure, ΔP, equal to three times the NOPD, i.e., $3 \times$ NOPD to demonstrate adequate resistance to burst. Bending loads should also be considered. There may be circumstances where the combination of degradation mechanism, geometry and material properties leads to other applicable criteria (see Section 3).

For the case of $3 \times$NOPD, proper determination of the operating conditions at normal steady-state full power (>99%) is important when defining the limiting SIPC margin requirement. There are effectively two ways that NOPD can be established.

The first approach is to use actual operating pressures at normal steady-state full power conditions from the current operating cycle. In this approach, it is recommended that the secondary side pressure be monitored. Such pressure information is typically readily available in the plant computer. The recorded steam pressure at normal steady state full power is used to calculate NOPD = P_{Pri} - P_{Sec} for each SG. Primary-side pressure (P_{Pri}) is relatively constant with little fluctuation during steady-state conditions. Measurement readings from multiple pressure sensors representative of the outlet steam pressure at normal steady-state full power conditions for each SG may be averaged over a suitable period of time to define P_{Sec} in the calculation of NOPD, provided that these sensors are in the same location (e.g., main steam line). If line loss values between the sensing location and the SG outlet are available, this information can be used to calculate NOPD more accurately. This calculation is performed for each SG and the limiting (highest) value of NOPD should be used in determining the CM and OA structural limits. If the NOPD is based on actual operating pressures, it is recommended that the NOPD be increased by a small incremental value, or neglect any steam line losses, to provide additional margin on pressure differential for the operating period.

If steam conditions show variation during operation, the steam pressure should be trended over time to determine if there is a systematic decrease in secondary-side pressure that will lead to a potential increase in NOPD between inspections. The potential increase in NOPD should be projected until the next inspection and included in the calculation of the NOPD limit for the operating period.

The second way to determine NOPD which would be conservative for future operating cycles is to use a lower bound estimate for secondary-side steady-state pressure based on thermal performance for the steam system design. The NSSS vendor can provide this information for the SG design. The advantage of using a lower bound steam pressure for NOPD is that there will be high confidence the NOPD will not be exceeded in the operating period before the next inspection.

Regardless of the approach used to define NOPD, any change in design parameters or plant operation shall be assessed. Examples of operational changes include power uprates, flex-power operations, or permanent changes in design parameters (plugging or sleeving levels, primary or secondary side modifications, change in THot, etc.). Operational changes shall be evaluated for the potential impact on NOPD and accident pressure and non-pressure loadings that can lead to redefining the SIPC margin requirement, because the change may result in primary-to-secondary pressure differences or non-pressure loading conditions that are greater than the values used in

the evaluation of SIPC. For flex-power operation, it is recommended that the value of secondary-side pressure at the lower power level under steady-state conditions should be evaluated to confirm that NOPD at full power will be bounding.

6.7.2 Accident Leakage Limit

The appropriate accident-induced leakage limit shall also be determined. Establishment of the accident induced leakage limit requires a review of all design basis accidents to determine which assume primary-to-secondary leakage. Current Tech Spec Bases and current FSAR chapter 15 analysis define the accident-induced leakage limit. The steam generator engineer should confirm the DA/CM/OA applies the appropriate AILPC value. NRC Regulatory Information Summary (RIS) 2007-20 provides the NRC staff's position related to the implementation of the leakage performance criteria.

Accidents that assume leakage will have a leakage amount as an input to the accident analysis. The leakage assumed in the design basis accidents defines the accident-induced leakage limit for that event. For example: If the locked rotor accident analysis assumes 0.5 gpm primary to secondary leakage, the accident-induced leakage limit for that accident is 0.5 gpm.

The limiting accident may depend on the type of tubing degradation of interest, for example, high axial loads are significant for circumferential degradation but not for axial degradation. The limiting accident is defined by the combination of accident specific loads and the accident specific leakage limit leading to the smallest allowable flaw size. It is this flaw size that must meet CM and OA requirements.

Typically, the limiting accident for leakage is simply the accident producing the largest tube loads. However, this may not always be the case. There may be accidents with a low allowable leakage limit combined with loads that, while less than the maximum, lead to the smallest allowable flaw size for leakage. Accident specific loads and accident specific leakage limits must be evaluated to identify the limiting leakage accident. This can be a difficult exercise since leakage limits based on dose assessments must be combined with accident loads that may be grouped under umbrella transients for convenience and economy. In the absence of more detailed information, it is conservative to construct a bounding case by combining the lowest allowable accident leakage with the largest accident tube loads. For plants with accident analyses that assume the same accident leakage for all design basis accidents, other than SG tube rupture, the limiting accident for leakage is not necessarily the accident producing the largest tube loads.

Several plants have made commitments to the NRC Regulatory Guide 1.183 which provides an alternate source term approach for the parameters and assumptions to be met for accident analysis. This could enable plants to increase accident-induced leakage limits. These limits require approval by the NRC prior to implementation.

For plants that assume the same leak rate in each design basis accident, one AILPC limit shall be established using the assumed leak rate combined with the highest accident loading condition on the tubing.

For plants that do not assume the same leak rate in each design-based accident, utilities shall use one of the two options below:

1. The loading condition on the tubing for each accident can be evaluated along with the assumed leak rate to define an AILPC limit for each accident, or

2. The lowest leak rate assumption can be combined with the highest tube loading condition to define one bounding AILPC limit.

6.8 Plugging Limits

The Technical Specification plugging limit is typically 40% TW when adequate sizing capability exists for the indications. Through review of plant specific, or industry typical defect growth rates, the appropriate tubing plugging limits can also be calculated or identified. This will identify which degradation mechanisms are adequately covered by the plant's Technical Specification plugging limit. Preventive plugging may be required based on OA considerations. Depending on the growth rate of the degradation mechanisms that are identified from the inspection, the length of time between planned inspections (multi-cycle inspection intervals), and the number of flaws identified, it may be necessary to establish a lower through-wall limit for plugging to ensure tube integrity at the time of the next inspection. Plug on detection is the strategy employed for all cracks and volumetric indications where no acceptable sizing capability is available.

When a tube that is plugged has the potential to sever, stabilization criteria are used to decide whether or not to stabilize the plugged tube (see Section 6.4.3). In this situation, each plant should establish appropriate criteria.

6.9 Secondary Side Considerations

The chemistry environment in contact with the tube surfaces can affect crack initiation and growth. Locally aggressive environments are possible within concentrating crevices formed by deposit accumulations or SG design characteristics. Chemistry excursions during operation and the presence of certain impurities within the deposits could exacerbate tube corrosion. These factors should be considered when evaluating acceptable inspection scope, interval, and/or mitigating actions. The DA shall include secondary side considerations. The SG secondary side integrity assessment can be incorporated either by directly integrating the assessment into the DA or by reference (see Section 10).

7
CONDITION MONITORING

7.1 Introduction

Condition monitoring involves the evaluation of inspection results at the end of the inspection interval to determine the state of the SG tubing relative to the SIPC and AILPC. This section provides guidance on performing structural assessments. A discussion of leakage assessments is given in Section 9. Condition monitoring can be accomplished by analytical methods or by in situ pressure testing.

Condition monitoring provides a means of verifying EOC tube integrity and previous OA predictions. Assessments can be performed deterministically or probabilistically. In order to decide on the appropriate evaluation methodology, information provided in the following discussion specifies the essential elements of the different assessment strategies.

7.2 Data Exploration

During the course of a SG examination and concurrent with the CM process, intermediate inspection results should be explored in order to extract useful information that may otherwise be missed, such as tube-to-tube wear or foreign object wear. A comprehensive review of the locations and characteristics of all detected eddy current indications may be an effective diagnostic tool for evaluating inspection data. This comprehensive review may include:

- Plotting all locations where indications have been detected both radially within the SG tube bundle and axially along the tube length

- Reviewing all indications together or looking at subsets of various types of indications

- Determining an eddy current indication's angular position in the tube can be accomplished by, but not limited to, placing a magnet or energized probe in an adjacent tube. For example, positioning a magnet probe into an adjacent tube near the area of interest, while scanning the signal with a rotating coil in the tube of interest, allows a determination of the angular position of the signal. This can also be accomplished by placing an energized array probe in an adjacent tube while scanning the signal with another array probe in the tube of interest, as the energized array probe creates crosstalk in the tube of interest.

- Plotting changes in signal amplitudes to determine if the indications are changing with time

Performance of the comprehensive review may, for example, reveal a clustering of eddy current indications or another pattern that may warrant additional attention (e.g., migration of a foreign object left in a SG or the tube-to-tube wear phenomenon).

This review could also look at changes in indication patterns in the current inspection relative to previous inspections to ascertain if discrete areas are changing or expanding relative to history. Also, for indications assessed as possible corrosion degradation on tube OD surface, this review

could look at patterns of indications relative to historical OD sludge maps to assess if change/increase in secondary side deposits may be contributing to new/changed degradation

7.3 Condition Monitoring Evaluation

The objective of a CM is that the observed worst case degraded tube for each mechanism will exhibit, via NDE sizing and analysis or in situ testing, a minimum burst pressure that meets the SIPC at a probability of 0.95 at 50% confidence. Since the set of observed degradation encompasses the worst case degraded tube, then determining the minimum burst pressure by CM procedures provides a direct confirmation that the worst case degraded tube meets the SIPC.

A CM evaluation is carried out using the following general steps,

1. Determine the dimensions of the tubing being analyzed. The nominal dimensions of the tubing are sufficient for the analysis.

2. Characterize the geometry, i.e., morphology, of the degradation and its location on the tube. For example, for an AVB wear scar the depth and length of the degradation are important parameters. Also identify any tube geometry features that are of specific interest to the type of degradation being considered.

3. Determine the material properties of the degraded tube or tubes.

4. Identify the limiting SIPC and the appropriate loading conditions for the degradation of interest. In general, based on currently applicable SIPC, this will usually be an applied differential pressure, ΔP, equal to three times the NOPD, i.e., $3 \cdot \Delta P_{NOp}$ to demonstrate adequate resistance to burst. Bending loads may also be important. There may be circumstances where the combination of degradation mechanism, geometry and material properties leads to other applicable criteria (see Section 3).

5. Select the appropriate equation, or equations, to be used for the analysis of the degradation.

6. Identify applicable uncertainties to be considered in the analysis. These will be associated with the material properties, the relationship between the burst pressure and the characterizing parameter(s) of the degradation, and NDE sizing when the size of the indication is determined by NDE measurement.

7. When meeting the performance criteria cannot be demonstrated based on the results of qualified inspection techniques, an engineering analysis, augmented inspection method(s) (e.g., ET diagnostic techniques, PT, video probe), or in situ pressure testing are acceptable alternatives. CM by engineering analysis or augmented inspection methods shall include a rational basis for concluding the performance criteria have been met.

7.4 Structural Integrity Evaluation Using Inspection Results

For verification of structural integrity during the preceding cycle of operation, each indication of a degradation mechanism is shown to meet the appropriate limiting structural integrity performance parameter with probability of 0.95 at 50% confidence, including consideration of all relevant uncertainties. Either estimate actual physical degradation dimensions, or relate a strength characteristic to an NDE characteristic, e.g., relating burst pressure, tensile strength, probability of leak, or leak rate to signal amplitude. When physical degradation dimensions are calculated from NDE values, the relevant CM uncertainties are NDE sizing errors, material

strength variations and burst equation errors (relating burst pressure to a geometric dimension or dimensions of interest). When a relational approach is used with NDE values, the relevant uncertainties are the NDE measurement process errors, material property variations, and relating-equation errors.

The relational error refers to the uncertainty in the relationship between the burst pressure and the structural variable. In most cases, this relationship is developed empirically, i.e., from experimental data obtained from test programs. As expected, there is always scatter of the data. Statistical analysis is performed to determine the form and parameters of the mean relationship along with the standard deviation of prediction errors and to calculate confidence limits for the relating curve. The relational uncertainty can be calculated from these results.

The important material properties that are used in the evaluation are the yield and ultimate tensile strength. These properties are also determined from test programs. Again, there is scatter in the data and analysis is performed to obtain the statistical parameters describing the variation of the properties. The material property variation is calculated using the results of the analysis. There are situations where the actual material properties of the affected tubes can be estimated from the fabrication records for the SG, e.g., from the tubing logs and the CMTRs (certified material test reports). Current practice is to ignore the within heat variation of material properties.

The NDE measurement errors are those associated with the characterization of the degradation morphology or magnitude. There are two sources of measurement error: 1) the error associated with the technique used and 2) the error associated with the analyst performing the examination or interpretation of results. Measurement error associated with the destructive examination of degraded tubes is judged to be non-significant and omitted from consideration.

Treating the uncertainties assures that a flaw measured to be at the CM limit satisfies the SIPC with at least 0.95 probability at 50% confidence.

7.4.1 Probabilities and Percentiles

A discussion of the use of term 95th percentile is provided herein for clarification. Statements are commonly made regarding the 95th percentile worst burst pressure when what is really being discussed is the 5th percentile of the burst pressure population when considered in ascending order. A probabilistic lower bound value of the burst resistance of the degraded tube is of interest relative to the performance criteria. The 5th percentile value is also commonly referred to as the lower 95th percentile of the burst pressure population. The aim of the analysis is to assure that the probability of burst of the worst case degraded tube at a specified value, say $3 \cdot \Delta P$, is less than or equal to 0.05; the probability that a burst does not occur being greater than or equal to 0.95 is equivalently discussed. The basis for using the arithmetic combination of the relational, material, and measurement errors each at a 5th percentile level is that it assures that the resulting value has a probability of occurrence of no greater than 0.05.

7.4.2 Arithmetic Strategy for Combining Uncertainties

The arithmetic strategy is the simplest described here, however, it is also the most conservative. In this method the NDE sizing, material strength and burst equation uncertainties are taken at their 95th percentile worst case values. The distributions of the uncertainties or errors are assumed to be normally distributed, and the 95th percentile sizes are 1.645σ greater than the

mean value, while the material strength and burst relation predictions are at 1.645σ below their respective mean values. The worst case value of a parameter may be either the lower value or the higher value. The lower value case uses the lower 95th percentile, and the higher case uses the upper 95th percentile. For example: material strength is taken at the lower 95th percentile.

7.4.3   Monte Carlo Strategy for Combining Uncertainties

The Monte Carlo strategy can be easily performed using Microsoft Excel™ or any of several other available computer codes. An accurate assessment of SG tube integrity is possible by combining the uncertainties through repeated Monte Carlo simulations. The uncertainties do not have to be normally distributed. The individual input and uncertainty distributions are needed. However, this almost always reduces to specifying mean and standard deviation values. The regression and material uncertainty distribution are needed as well as the NDE technique uncertainties.

7.5   Verification

A comparison of the current outage CM results to the previous outage OA predictions shall be performed.

The most important elements of the comparison are:

- Projected versus observed degradation growth rates.

- Projected versus observed dimensions of the worst case degradation.

- Projected versus observed leak rates for normal operation and projected versus CM calculation of accident induced leakage.

- Projected effective full power days versus actual effective full power days

- If using actual steam pressure for the SIPC, projected pressure differential versus actual pressure differential

There are four typical factors leading to OA projections that are non-conservative:

- Probability of detection worse than anticipated

- NDE sizing relationship and uncertainty issues

- Degradation growth rates worse than anticipated

- Large flaw population leading to worse case flaw sizes not captured by simplified analysis methods.

8
OPERATIONAL ASSESSMENT

8.1   Introduction

Operational Assessment 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. All existing degradation shall be evaluated in the OA, and if operating more than one cycle, it may be necessary to evaluate potential mechanisms in the OA.

Results of secondary side inspections (foreign object search and retrieval, steam drum inspections) should be evaluated if tube integrity can be impacted. Forms of degradation that have been found at prior inspections but have not been observed at the current inspection shall also be evaluated.

The purpose of this section is to provide guidance for performing an OA and evaluating the results. The focus of this section is structural integrity. Leakage integrity is covered in Section 9. The OA determines the appropriate inspection interval between inspections of the SGs to ensure tube integrity. If the plant operates longer than was projected in the OA, a recalculation of the OA may be necessary.

For new or replacement SGs with no operational time and hence no in-service degradation, the interval between the baseline inspection and the first in-service inspection can be based upon the existing design and installation documentation for the SGs. This documentation should provide reasonable assurance that tube integrity issues experienced by other new or replacement SGs within the industry will not occur during the first cycle of operation. In addition, utilities should consider the potential of foreign object wear during the first cycle of operation.

The fundamental objective of an OA is to ensure that the SIPC and AILPC will be met over the length of the upcoming inspection interval. The OA demonstrates that the degradation detection sensitivity and/ or NDE sizing uncertainty combined with degradation growth rates leads to the expectation that structural and leakage integrity criteria will be met at the end of the next inspection interval. In terms of structural integrity, the fundamental OA requirement is that the projected worst case degraded tube for each existing degradation mechanism meets the limiting structural performance parameter with a 0.95 probability at 50% confidence.

During actual operation of a given SG in a given cycle, for the degradation mechanism of interest, one tube has the lowest structural performance parameter associated with it. However, this is one of many possible outcomes for the given starting condition. A probabilistic analysis leads to a distribution of possible outcomes of SG operation for all degradation sites both detected and undetected for a given degradation mechanism (or sub mechanism). An illustration of a probabilistic treatment of the tube bundle for a given mechanism is shown in Figure 8-1. In this illustration, a Monte Carlo analysis for the tube bundle is used to establish the distribution of the tubes that produce the lowest burst pressure for the given degradation mechanism (or sub

mechanism). As shown in Figure 8-1, the "projected worst case degraded tube" is defined as follows:

> For a given degradation mechanism "projected worst case degraded tube" is defined as the degraded tube with the 5th percentile structural performance parameter at 50% confidence of the distribution of lower extreme values of structural performance parameters representative of all degraded tubes in the bundle.

This parameter is, almost exclusively, the burst pressure or axial tensile strength. Plastic collapse in bending is not relevant for current operating steam generator designs.

The term degradation mechanism as used for tube integrity assessments is based on the flaw morphology and its associated causes or characteristics. Once the degradation mechanisms are defined, the determination of the minimum burst pressure for the worst case tube for each mechanism can be calculated and compared against the SIPC margin requirements.

The flaw types identified within the Degradation Assessment existing or potential are typically defined by the appropriate NDE techniques used for flaw detection and sizing. The attributes for each flaw type include the flaw orientation, characteristic flaw shape and length, whether the flaw initiates from the primary side or secondary side of the tube, and the flaw location within the tube (i.e., in straight freespan, in u-bends, at tube support plates, at expansion transitions, or within the tubesheet). These attributes are evaluated collectively to establish the individual degradation mechanisms for integrity assessment purposes. Under certain circumstances, a degradation mechanism for integrity assessment may include more than one of the flaw types identified in the Degradation Assessment.

In general, tube degradation can be categorized as being caused by either mechanical means or by environmental/stress factors. Examples of degradation mechanisms that are typically used in integrity assessments for Alloy 690TT tubing and evaluated on an individual basis to the SIPC performance standards are listed below:

Mechanical:

- Wear at adjacent upper-bundle support structures such as AVBs, vertical straps, diagonal bars, or fan bars
- Wear in straight tube sections at tube support plate intersections (both OTSGs and U-tube SGs)
- High cycle fatigue cracking due to flow induced vibration of the tube
- Tube-to-tube wear due to flow-induced instabilities or loss of tube support effectiveness
- Foreign object wear due to loose parts

Using the definition of the projected worst case degraded tube to perform the OA is mathematically equivalent to demonstrating that the probability of violating the SIPC is no greater than 0.05 at 50% confidence. Conversely, the probability of meeting the performance criteria is at least 0.95 at 50% confidence.
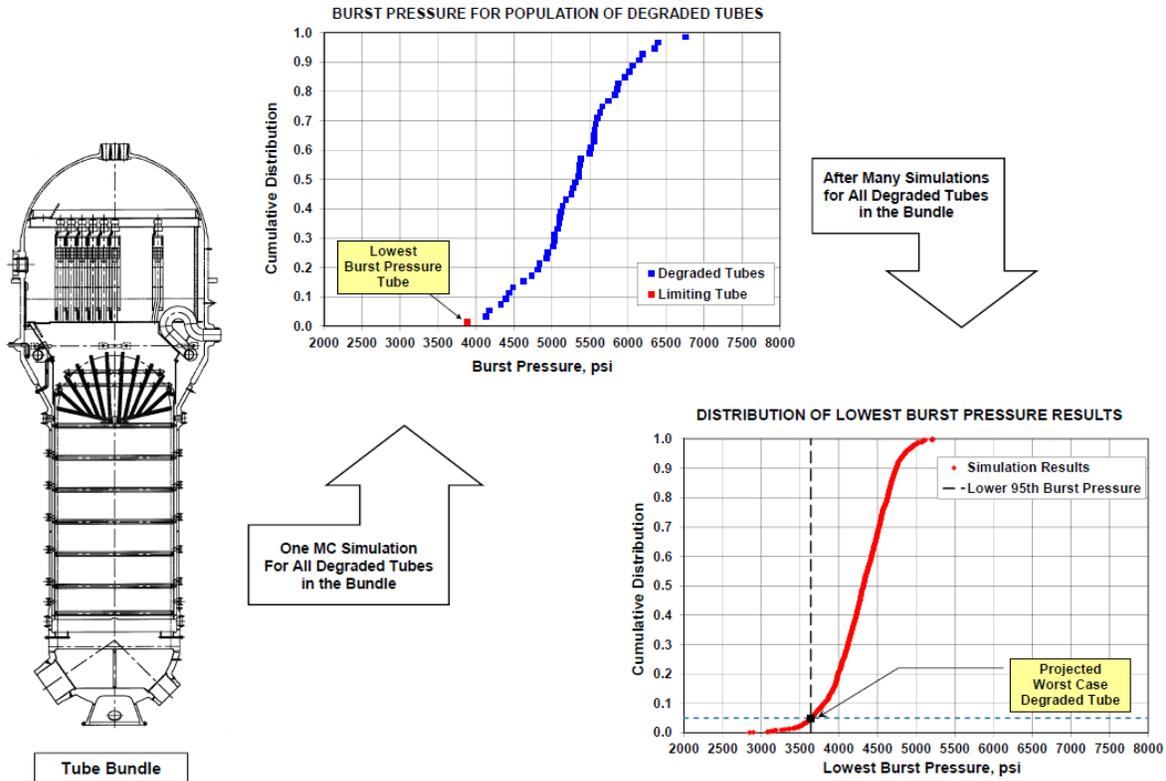
Figure 8-1
Fully Probabilistic Monte Carlo Simulation to Establish Worst-Case Degraded Tube – Full Bundle Analysis

8.2 Projection of Worst-Case Degraded Tube

The main objective of an OA is to demonstrate that tube degradation will not challenge tube integrity as defined by the SIPC for tube burst and accident induced leakage. Therefore, the determination of the worst-case degraded tube until next inspection is an important aspect of the OA.

8.2.1 General Methods and Strategies

There are two general approaches to the projection of the worst-case degraded tube: 1) probabilistic calculation, and 2) simplified techniques. The probabilistic approach considers the entire flaw population for a given degradation mechanism. It uses Monte Carlo simulation to predict the distribution of EOC structural integrity parameters so that the lower 95th percentile of the worst case burst pressure values may be obtained. By accounting for all of the at-risk tubes in the bundle and modeling all flaws (both detected and non-detected), the probabilistic method, with appropriate statistical distributions for each important input variable, produces the different sets of possible outcomes to establish the probability of burst. In performing this calculation, independence between the probabilistic variables is typically assumed.

Simplified methods of projecting the worst-case degraded tube are designed to provide conservative approximations of probabilistic calculations that consider the entire projected flaw population and the variety of possible outcomes for a given cycle of operation. In the simplified

techniques, the worst case flaw is projected using conservative assumptions coupled with uncertainties that are combined using the Arithmetic strategies.

It is important to note that there are two basic plugging strategies or options for detected degradation, Plug on Detection and Plug on NDE Sizing. Plug on Detection means that no detected degradation is intentionally left in service; hence, the basic issue for performing the OA is to account for the undetected flaw population. Estimating the BOC flaw does not include NDE sizing uncertainties because postulated degradation is not returned to service via a sizing process.

For a Plug on NDE Sizing scenario, detected degradation is intentionally left in service if the size determined by NDE is below a certain level, which may be the technical specification repair plugging limit of 40%TW NDE maximum depth or some lower value. The most important considerations in this scenario are accounting for the NDE sizing uncertainties associated with the flaws left in service and a conservative growth allowance.

If a less than 100% inspection is being performed and degradation is detected, the OA shall evaluate the uninspected population. When degradation is identified in a less than 100% inspection, one cannot assume that the worst case flaw has been identified.

The 40% TW NDE maximum depth plugging limit is usually only applied to tube wear at supports and foreign object wear if the object is no longer present.

While CM deals with observed NDE measurements of degradation and whether the structural and leakage resistances of the tubes meet the desired performance criteria for the previous period of operation, OA deals with the projected physical dimensions of the degradation and is typically performed by:

- Determining degradation dimensions at BOC,

- Adding a growth allowance to determine the EOC degradation dimensions, and,

- Evaluating the projected EOC dimensions versus the limiting structural and leakage integrity performance criteria, including uncertainties in burst/strength equations and material properties.

Benchmarking

Benchmarking the OA analysis involves comparing OA results for prior and current outages with actual outage results to develop confidence that the process will accurately and conservatively predict future SG conditions.

Benchmarking of previous inspection results, whether the mechanism is wear related or corrosion related, is essential for assuring accuracy. An acceptable benchmark is generally achieved when the following comparisons between model predictions and observed NDE inspection results are obtained:

1. Number of detected indications is well characterized by OA predictions.

2. The CDF of measured NDE sizes (i.e. PDA, length, and depth) is reasonably represented by the CDF of predicted measured sizes, especially in the upper tail.

3. Worst maximum (peak) sizes detected in the SG is reasonably represented by the distribution of predicted worst simulated flaw size. Note that the comparison needs to be performed on a

consistent size basis (i.e., both values must be expressed either as an NDE size or as an actual physical size).

8.2.2   Plug on NDE Sizing

Both single and multiple cycle probabilistic models can be applied using a Plug on NDE Sizing strategy. It is both convenient and realistic to only include detected and NDE sized flaws that are left in service in single cycle models. However, undetected flaws in a Plug on NDE Sizing strategy can and should be reflected in the analysis if the POD is poor, or if the initiation rate and/or growth rate of newly initiated flaws is expected to be aggressive going forward. The effect of NDE sizing uncertainty is included in the analysis to ensure that the results are appropriately realistic and/or conservative. Multiple cycle models include NDE sizing uncertainties to allow comparison of actual NDE results with projected NDE results. In this case, the Plug on NDE Sizing strategy is implemented within the simulation by including the plugging decision-making process.

The ability of deposits to affect wear growth rates is unique to each SG design and OE should be considered to assess the impact on growth in multi-cycle, plug on sizing OAs.

8.2.3   Plug on Detection

Both single and multiple cycle probabilistic models can be applied using a Plug on detection strategy. Both models are used to estimate undetected flaw populations using POD curves, and for both models, the end result is a probabilistic, quantitative evaluation of the projected EOC degradation population. Extreme value EOC burst pressure distributions and leakage rate distributions can be calculated along with the probability of meeting required SIPC and AILPC. This level of sophistication may be required in special circumstances, for example, if the simplified worst case degraded tube projection methods in the following sections prove to be unsuccessful against the performance criteria.

9
PRIMARY-TO-SECONDARY LEAKAGE ASSESSMENT

9.1   Introduction

This section provides a discussion on primary-to-secondary leakage assessments. For CM, degradation detected during an inspection shall be evaluated against the AILPC. Degradation length or depth measured for CM purposes is adjusted for NDE measurement uncertainties. Leakage at normal operating conditions is monitored during plant operation and compared to the operational leakage performance criterion. Operational assessment shall be performed to provide assurance that the AILPC will be met until the next scheduled SG inspection. OA projected degradation length or depth at the EOC are not measured parameters and therefore no NDE measurement uncertainties need to be applied.

9.2   Accident Induced Leakage

The allowable tube leakage limit is defined by the AILPC in Section 2. Leakage limits shall be met for all design-based accidents, other than a SG tube rupture, and not exceed the leakage assumed in the plant accident analysis in terms of the total leakage for all SGs and the leakage rate for an individual SG.

9.3   Operational Leakage

The allowable operational leakage limit is defined in plant Technical Specifications and Section 2.

The following information generalizes the relationship between operational and accident-induced leakage limits and is provided by the NRC in Regulatory Issue Summary 2007-20:

> The loading conditions on the tubes during an accident may be different than the loading conditions on the tubes during normal operation. As a result, the primary-to-secondary leak rate observed during normal operation may change under accident conditions. In some cases, the primary-to-secondary leak rate may increase as a result of the accident, while in other cases it may decrease. If the loading conditions during an accident result in an increase in the primary-to-secondary leak rate (when compared to the normal operating leak rate), it may be necessary to restrict the normal operating leak rate to less than the normal operating leakage rate limit. This applies not only to units that assume the primary-to-secondary leak rate observed during the accident is the same as the normal operating primary-to-secondary leak rate limit, an assumption that is permitted by the NRC's Standard Review Plan; but also to other units since the increase in primary-to-secondary leak rate going from normal operating conditions to accident conditions can result in significant increases in the leak rate (depending on the accident). The actual amount that the leak rate may increase is

a function of several factors including the type of flaw that is leaking. For example, the leak rate from a crack may increase significantly (e.g., by an order of magnitude depending on through-wall crack length) under accident conditions.

If operational leakage causes a forced outage, a root cause evaluation shall be performed. A forced outage can result from incorrect assumptions or errors in past analyses.

If operational leakage is less than shut-down levels and is consistent with that predicted by the OA, no adjustments to OA methodologies are required; however, in situ pressure tests may be required. If operational leakage is not predicted by the OA, it is recommended that the assessment strategies be modified accordingly.

During an inspection outage following operational leakage, the steps presented below are recommended to establish information about the leak.

1. Determine which SG(s) are leaking: Monitor all SGs to determine which SG(s) are leaking.

2. If possible, determine the source of the leakage: This is typically performed by a hydrostatic test, bubble test, or helium leak test to identify suspect tube(s) locations on the tubesheet. Quantify the rate (for example, drops per minute or gallons per minute [liters per minute]) of leakage. Correlate the calculated leakage (pressure/temperature adjusted leakage) versus the operational leakage. Determine if results have accounted for the observed operational leakage, while recognizing that an accurate comparison of operating and shutdown leakage measurements is difficult. If the source of the leakage cannot be identified using the methods described above, 100% eddy current examination should be considered. If the eddy current examination locates the potential leakage, proceed with Step 4. If the leakage has not been identified, an evaluation of the actions within Step 6 should be considered.

3. Examine leaking location(s): This inspection is typically performed by bobbin coil eddy current examination to establish axial location within the SG.

4. Examine to determine extent, orientation, and morphology: This is typically performed by rotating coil or array coil technology.

5. Review prior inspection history: Review the information contained in the database and the actual historical bobbin and rotating data to establish factual information about the data. If the leakage is originating from a plug or sleeve, review the installation records for that location. Evaluate if installation parameters were met and identify any inconsistencies or nonconforming conditions.

6. Perform a root cause evaluation that includes all SG program elements in accordance with the utility's program(s). This evaluation should address the need to perform eddy current and/or secondary-side visual inspections. Also consider supplementing the root cause team with industry peers. The root cause team should identify immediate, short-term, and long-term actions to correct any process deficiencies.

7. Execute root cause corrective actions

8. Update and revise the DA, CM, and OA as necessary to address the unexpected leakage.

9. Perform required plugging or repairs.

Leakage at normal operating conditions in the previous cycle is monitored during plant operation. Hence, determination of CM operational leakage integrity is performed directly.

9.4 Operational Assessment Evaluation for Leakage Integrity

The potential primary to secondary leakage rate for the most limiting postulated design basis accident, other than a SGTR, shall be assessed. For leakage integrity the fundamental OA requirement is that projected total leak rate from all degradation within a SG is less than the AILPC with 0.95 probability at 50% confidence. Leakage from all sources is considered including degraded tubes, plugs, sleeves, rerolls and any other repair process. Upper 95th percentile projected leak rates for each degradation mechanism can be added arithmetically to bound the total SG leak rate. If projected leak rate distributions available for several mechanisms are developed, their contribution to the total projected leak may be combined using probabilistic methods as described in previous sections. If the probability of zero leakage is known for each degradation mechanism, then the probability of zero leakage for the entire bundle can be computed. If this value is greater than or equal to 0.95 then the OA leakage integrity requirement is met. If simplified OA leakage integrity analyses methods are used and the worst case degradation does not leak at a probability of 0.95 or greater, the probability of zero leakage can be taken as equal to 1.0.

With the bounding worst case degraded tube approach to OA the expectation is that no accident induced leakage will be projected at 0.95 probability with 50% confidence. This is the common circumstance. If leakage is projected for the worst-case degraded tube for a given degradation mechanism, then the number of projected leakers and the level of leakage is needed for a total leak rate projection. Typically, this then requires use of analytical methods which project the population and severity of leakage sites.

If projected degradation is not calculated to penetrate the tubing wall and projected worst case EOC degradation is not calculated to tear through the remaining wall thickness at accident loading conditions, there is no projected OA accident induced leakage. This is a common circumstance. For circumferential cracking and the circumferential extents of volumetric degradation leakage integrity depends on maximum degradation depth and total length. For axial cracking and predominantly axial volumetric degradation under pressure loading flaw shape effects may be included.

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10
MAINTAINING THE SECONDARY SIDE INTEGRITY

10.1 Introduction

The SG integrity assessment process considers the potential for foreign objects or degradation of secondary side components to affect structural and leakage integrity of the primary pressure boundary. This section discusses actions to address impacts on SG tube integrity

The SG program shall include measures to assess the SG secondary-side integrity. An assessment of SG secondary side integrity involves the review of chemistry trends, operational parameters, and inspection data. Inputs considered in the SG secondary side integrity assessment may include, but are not limited to the following:

1. Steam Generator Design

    a. Materials of Construction

    b. General Design and Configuration

    c. Thermal Hydraulic Information (High Flow Regions, etc.)

2. Secondary Side Chemistry History/Trends

    a. Chemistry Excursions (Operating and Shutdown)

    b. Chemical Analysis and Characterization of Scale and Other Deposits

    c. Deposit Distribution Assessment utilizing ECT data (Scale Profiling/Deposit Mapping)

    d. Corrosion Product Transport and Mass Balance

    e. Hideout Return

3. Secondary Side Maintenance History/Trends

    a. Deposit Removal (sludge lancing, chemical cleaning, etc.)

    b. Tubesheet Deposit Condition

    c. Tube Support Plate / Upper Bundle Fouling

    d. Foreign Objects Identified, Removed, and Remaining in the SGs

    e. Foreign Objects Identified that Caused Tube Wear

    f. Upper Internal Condition (moisture separator, steam dryer, feedring, etc.)

4. Site Specific and Industry OE

    a. Foreign material exclusion (FME) or Equipment Degradation Events (SG Foreign Objects Concern)

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b. NDE Detectability Issues (Foreign Objects Detection)

c. Secondary Side Visual Inspection Results

d. Secondary Side Component Integrity (Including NRC GL 97-06)

10.2   Secondary Side Assessments and the DA, CM, and OA

Degradation assessments shall include the SG secondary side integrity assessment either by directly integrating the assessment into the DA or by reference. It is recommended that foreign object wear be included as a potential degradation mechanism in the Degradation Assessment, even if the plant's design includes foreign object part strainers.

Condition Monitoring applies specifically to the as-found condition of the tubing within the SGs. Consequently, the condition of secondary side components will rarely impact the conclusions of the CM assessment. An example scenario in which secondary side component condition could impact the CM conclusion is one that could have initiated or exacerbated primary to secondary leakage had an accident occurred during the prior operating cycle (e.g., gross loss of tube bundle support). Unless such conditions are identified or relevant tube degradation is visually detected, outages during which only secondary side activities are performed require no CM assessment. Secondary side component degradation shall, as a minimum, be documented and evaluated within the licensee's corrective action program.

Operational Assessment applies specifically to the projected condition of the tubing throughout the next inspection interval. The OA shall include aspects of secondary side conditions that could affect tube integrity such as foreign material remaining in the SGs, material degradation that could generate foreign objects during operation, and degraded SG secondary side components and support structures. The OA shall establish the acceptable inspection interval for degraded secondary side components that could impact tube integrity during future operation. Other SG secondary side component degradation shall, as a minimum, be documented and evaluated within the licensee's corrective action program.

10.3   Foreign Object Search and Retrieval

Foreign object search and retrieval is an important part of maintaining RCS pressure boundary integrity. The following sections discuss details of planning for this outage activity. The inspection guidance is primarily for secondary side visual inspections; however, eddy current can provide useful information.

NRC Information Notice 2004-17 documents operating experience with challenges associated with detection of foreign object and related tube damage in steam generators and computerized data screening algorithms used in the evaluation of steam generator tube eddy current data.

10.3.1   Inspection Interval

The SG secondary side integrity assessment shall determine an appropriate foreign object search and retrieval (FOSAR) inspection interval. For RSGs, it is recommended that FOSAR be performed each time sludge lancing is performed and/or when foreign objects are identified or there is reason to expect that foreign material was introduced into the SG secondary side. Likewise, sludge lancing should be performed each time FOSAR is performed. The design of

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some SGs limits the occurrence of foreign objects. For example, small diameter nozzles in OTSGs and RSG feedwater spray cans, and downcomer screens prevent the intrusion of most foreign material to the tube bundle. Also, OTSGs do not have a steam drum, which appears to be the source of many foreign objects that originate during fabrication of RSGs. Despite these design features, it is possible for small diameter objects to enter the secondary side of OTSGs and RSGs and cause tube wear.

The FOSAR interval is determined based on the plant's historical foreign objects, foreign object wear indications, maintenance activities, and the planned SG primary side inspection intervals. The evaluation should consider the following elements:

- Location and description of historical foreign objects (including those found on sludge lance grit screens)

- Description of foreign objects with associated wear indications

- High secondary side fluid flow, or other susceptible areas

- Secondary side inspection limitations

- The type of material entering the SGs and potential for tube degradation

- Plant-specific and industry trends for foreign object wear

- Foreign material collection or trapping system

- Review contractual / warranty requirements before making significant changes to your inspection/maintenance frequencies.

It is recommended to perform the FOSAR during the same outage that eddy current testing is performed. It should be recognized that performance of the FOSAR at an outage when eddy current testing is not performed could involve exigent mobilization of eddy current testing if foreign object SG tube wear is observed.

10.3.2 Inspection Scope

When performing FOSAR, it is recommended that the minimum regions to be examined include the shell-to-tube bundle annulus region (including periphery tubes) and the no tube lane. FOSAR of the tube lane in the central region may not be required based on local flow velocities and SG design details. Visual inspection of the periphery tubes may be achieved by articulating the camera angle to view several tube rows and/or columns into the tube bundle from the annulus region. Visual inspections conducted in this manner provide reasonable assurance that foreign objects with potential to degrade tubes located on the secondary face of the tubesheet will be identified. This inspection may not apply to SGs with unique design features such as a preheater. In all cases, the SG design should be taken into consideration in defining the inspection scope.

When scheduling sludge lancing and FOSAR, the following should be considered:

- Sludge lancing tends to sweep foreign material toward the annulus, where the material is typically removed by the suction lines back to the lance trailer, or if not removed by lancing, may allow for easier retrieval via FOSAR.

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- Foreign object visibility is often increased when the sludge pile is minimized or removed prior to FOSAR.

- If it is desired to visually determine the location and character of a potential foreign object as it relates to a reported wear indication, it may be easier to do so prior to sludge lancing, as cleaning processes have the potential to move the foreign object(s) away from the wear scar.

Several plants have experienced problems with foreign objects after SG replacement. During assembly and shipment, SGs are typically kept horizontal. When the SGs are set in place during installation, foreign material could fall to the tubesheet and become accessible. Therefore, FOSAR should be performed during the SG replacement outage prior to operation after the SGs are installed in their final orientation. In addition, many replacement SGs have incorporated design features to mitigate against foreign object intrusion, such as strainers and weirs, to minimize foreign object entry into the SG tube bundle during operation. These design features should be routinely inspected since their effectiveness should be considered when planning for inspections.

Depending on the SG design and foreign object properties (mass, size, etc.), foreign objects entering the secondary side of the SG may locate on the tubesheet within the shell-to-tube bundle annulus region or the blowdown lane (tube lane). SG tubes are typically susceptible to foreign object degradation in regions of high secondary feedwater velocity. Therefore, the tubes near the shell-to-tube bundle annulus region and the tube lane (the periphery tubes) are typically most susceptible to flow induced foreign object tube wear/degradation.

10.3.3 Foreign Material Evaluations

All foreign material that has the potential to challenge tube integrity shall be removed from the SGs, given the limitations of the equipment and personnel dose. SGMP has provided prioritization strategies for foreign object removal, and these reports are publicly available. Foreign material removed from the SGs, either by lancing or by FOSAR, shall be documented and evaluated for potential impact to tube integrity, and also considered when planning for future inspections. Irretrievable foreign material with the potential to cause tube damage shall be evaluated for continued operation or remediated by stabilizing and plugging the affected or potentially affected tubes. It is recommended that any tubes with wear attributed to foreign material which is still present next to the tube be removed from service unless continued operation is justified by the operational assessment. Important details to consider in any foreign object evaluation (both for objects removed and for objects not removed) include the following, as applicable:

1. An estimation of the material and size of the object (diameter, length, and weight)

2. Location of the object (tube row/column, hot leg or cold leg, top of tubesheet, TSP, etc.)

3. The estimated axial location of contact between the object and the tube

4. Whether or not the object is firmly lodged or able to move

5. Whether or not tube wear is present as a result of the object

6. Evaluation of potential wear rate if the object moves and contacts tubes during the planned inspection interval. This evaluation should include conservative assumptions regarding the

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object's size, the material of the object, tube vibration amplitudes and cross flow fluid velocities.

7. Whether historical eddy current data shows the presence of the object or tube degradation.

Tubes adjacent to irretrievable foreign material that has caused tube wear or is considered to have the potential to cause tube wear shall be inspected on the primary and secondary side during future SG inspections. The required secondary side inspection interval is determined in accordance with Section 10.3.1, and the required primary side inspection interval (i.e., for non-plugged tubes) is established in accordance with OA requirements.

It is necessary to consider the potential for a foreign object to migrate during future operation. This scenario may require an inspection from either or both the primary and secondary side when a tube has been plugged in order to address an adjacent irretrievable foreign object. This may be accomplished by performing an eddy current examination of the in-service tubes surrounding the plugged tube(s) or by performing a thorough secondary side visual examination of the potentially affected area. The examinations should consider the secondary side fluid flow conditions when identifying the most likely pattern of foreign object migration. All tubes in the vicinity that are subject to wear in the upcoming interval should be plugged. If subsequent inspections reveal that the foreign object has shifted position such that the integrity of neighboring in-service tubes could be affected, or if the object is no longer present in the same location, the potential for degradation of the neighboring tubes shall be evaluated.

10.3.4   Coordination with Primary Side Inspections

When potential loose parts (PLPs) are identified during the ECT inspection, they shall be further dispositioned. The following actions can be applied to aid in the disposition of the PLP:

- Performing bounding inspections of the affected and adjacent tubes with a technique capable of detecting foreign objects induced tube wear.

- Performing a visual inspection in the area where the PLP was identified.

- Reviewing historical and current ECT data for PLP signals and wear.

- Reviewing past visual recordings in the area.

- Performing an engineering analysis concluding that there will be no tube integrity impact if left as-is."

All actions, findings, and decisions related to foreign objects and foreign object wear should be recorded in a suitable vendor or site-specific database.

Tube integrity shall be evaluated with technique(s) with quantified sizing uncertainties. Those techniques could include visual, optical, replicate mold or other type of NDE inspection. Superficial surface marks or deposit removal patterns on the tube outer diameter are not considered tube degradation.

When a foreign object is reported, it is possible that either primary or secondary side inspections are not available. For example, the secondary side integrity assessment could prescribe performing FOSAR when primary side inspections are not planned. Similarly, primary side inspections could be performed with no secondary side inspections planned. In either case, planning should include consideration for the potential identification of foreign objects. When

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both primary and secondary inspections are performed, these activities should be coordinated to ensure that potential foreign objects identified by eddy current are able to be investigated visually on the secondary side. Similarly, foreign objects identified during the secondary side examination should be brought to the attention of the eddy current leads to evaluate eddy current data for wear. If secondary side inspection of PLPs confirms the presence of foreign objects which can cause tube wear, it is recommended that the description and location of the objects be documented for consideration during future eddy current examination. If primary side eddy current inspections are scheduled, the tubes in the area of the foreign objects shall be examined with techniques capable of detecting tube wear. If primary side eddy current inspections are not scheduled, emergent ECT mobilization may be considered to disposition potential tube wear. As an alternative to ECT mobilization, visual inspections may be considered adequate if the visual quality and coverage is sufficient to convincingly demonstrate that tube degradation is not present in the areas that could have been affected by the object(s). In this case, if an object is small enough to enter the tube bundle, visual inspection coverage should include the entire circumference of the tubes in areas potentially affected by the part.

With regard to scope expansion requirements for when foreign object wear or a foreign object is detected, the scenarios are numerous and specific expansion scope cannot be prescribed for each potential scenario. The inspection scope shall support the proposed inspection interval. Some considerations for scope expansion logic for foreign objects and foreign object wear are provided below.

- Examine tubes surrounding any eddy current potential loose part (PLP) indication at the same elevation using techniques capable of detecting foreign objects and foreign object wear. Continue these bounding tube examinations until at least one contiguous "ring" of adjacent tubes has been examined in which no PLP or wear indications are detected.

- Bound new tube wear indications which could have been caused by a foreign object in the same manner as above, whether or not a PLP indication is present.

- If the wear is located near the periphery, but not on the outer most tube, examine those tubes along the most likely migration path to ensure that all wear is observed.

- Observations of severe foreign object wear growth rates indicate that at least one object capable of causing significant wear rates is present in the SG. All practical steps should be taken to identify and retrieve the object responsible. A larger inspection sample of the affected region and other susceptible regions (e.g., high flow regions) should be considered to confirm that there are no other similar parts capable of generating significant wear.

- If identified wear exceeds the plugging (or repair) limit, confirm that the inspection sample for the technique that identified the wear is adequate in the affected region, and expand the scope as necessary.

- For foreign objects which cannot be retrieved, with or without tube wear, consider examining tubes in the most likely migration path using the technique that initially detected the object or wear. This may be necessary in order to determine if the object damaged any additional tubes while migrating into the bundle.

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- When devising scope expansion plans, consider the potential for the same condition to occur in the opposite leg. Foreign object migration has no known tendency to prefer one SG leg over the other.

10.4   Internal Structures

The frequency of secondary side internals examinations shall be established to ensure that SG safety functions will not be jeopardized by degraded secondary side subcomponents.

For RSGs, it is recommended that the upper steam drum internals be periodically examined. The areas of inspection and focus of the inspection may vary based on SG design and materials but should typically include:

- Drain pipes and seal buckets for blockage

- Instrumentation taps (level transmitters, etc.) for blockage

- Demister banks for blockage

- Deck plates for foreign material

- Downcomer barrels for erosion/corrosion

- Wrapper transition to swirl vanes for erosion/corrosion

- Primary separators including swirl vanes for erosion/corrosion

- Feedwater ring, feed ring components, and support straps for erosion/corrosion

- Orifice rings for erosion/corrosion

- Applicable welds for pitting, cracking

- Nozzles for erosion/corrosion, cracking

When degradation is identified within the upper steam drum internals, the preferred short-term option may be to perform engineering analyses to determine the amount of component degradation that can be reasonably justified. The assessment should include thermal-hydraulic, structural, and plant safety parameters. When the degradation exceeds this acceptance criteria, either a temporary or permanent repair should be implemented.

10.5   Deposit Accumulation

Sludge and scale deposits in contact with the tubes have the potential to impact tube integrity, since they can accelerate the initiation of corrosion and potentially impact the ECT data. It is recommended that accumulation of material be periodically documented, either deposit mapping and/or iron transport, as part of the trending activities. Primary side eddy current examination data may be used to determine the extent and distribution of deposition on the secondary side of SG tubes. It is important to monitor the top of tubesheet for deposit accumulations in low flow velocity regions as well as broached support plate regions. In extreme cases, off normal chemistry conditions can cause denting at the top of the tubesheet. Effective sludge lancing can mitigate deposit at the top-of-tubesheet and sometimes the flow distribution baffle.

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In RSG's, heavy deposit accumulation at tube support intersections and freespan regions can modify local flow conditions potentially resulting in the following observations:

- SG liquid water level instability. The reduction in flow area associated with accumulating deposits in the broached holes increases the pressure drop through the tube bundle and reduces the recirculation ratio. This higher pressure drop can cause density-wave-driven instabilities during otherwise steady full-power operation that are manifested as level and flow oscillations which, as they increase in size, make plant control difficult.

- Broached-hole blockage. Changes in flow patterns induced by broached-hole blockage can result in increased velocities in certain regions of the SG that lead to increased tube wear and an increased risk of tube fatigue failure caused by flow-induced vibration.

- Reduced SG heat-transfer efficiency. As noted above, increased pressure drops across the TSPs lead to a reduction in the recirculation ratio. This decrease results in lower two-phase velocities through the tube bundle and a consequent reduction in the secondary-side heat-transfer coefficient, lowering the SG steam pressure.

- Increase in SG tube wear growth rate at structures or initiation of wear at regions historically unaffected by wear.

Lobe blockage generally tends to be most severe toward the top of the SG. Even a moderately affected unit tends to exhibit blockage only at the top of 3 or 4 support elevations. Usually, the hot leg side is more severely affected. Therefore, it is recommended to monitor the uppermost tube supports for blockage via periodic visual inspection and/or blockage assessments utilizing ECT data.

In OTSGs, deposit-induced blockage of the TSP broached holes causes an increase in the pressure drop as water and steam flow up through the tube bundle. The resulting increase in pressure drop across the TSPs is compensated by an increase in the water level in the downcomer because the downcomer and tube bundle are connected at the aspiration port just above the feedwater nozzles in the OTSG designs.

Note that iron concentrations within the SG can be highly elevated following outages and during power escalation. If adequate secondary side cleanup during restart is not performed, this material should be considered when determining the total SG deposit inventory.

10.6   Secondary Side Cleaning Strategies

Steam generator cleaning strategies are either preventive or reactive. A preventive approach helps prevent potential operational issues that have been associated with sludge and scale accumulation such as tubing corrosion, heat transfer limitation, and water level instability. Some examples of preventive strategies are:

- Controlling SG sludge deposit accumulation through chemistry optimization, sludge lancing/upper bundle flush supplemented by more aggressive cleaning methodologies at appropriate intervals

- Trending of total iron transport and comparison with applicable OE

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- Monitoring of SG performance parameters

- Future outage planning of cleaning activities based on plant and chemistry conditions

- Scheduling chemical cleaning based on Steam Generator assessments and economics

The objective of the reactive approach is to restore SG secondary-side condition when water level instability, heat transfer limitations or other operation issues have occurred. It is essential that SG deposit conditions and chemistry are well understood prior to implementing a reactive approach.

The secondary side integrity assessment considers the risks and benefits of both strategies and suggests an approach for the next refueling outage(s). As sludge and scale deposits form regions where corrosive impurities can concentrate, care must be taken to minimize their buildup on and around tube surfaces. Due to the different corrosion susceptibilities of the different tubing materials, the more resistant tubing (i.e., Alloy 690TT) can tolerate sludge deposition to a greater degree. These differences should be considered when developing an SG secondary side cleaning strategy.