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PWR Steam Generator Tube Repair Limits: Technical Support Document for Outside Diameter Stress Corrosion Cracking at Tube Support Plates

Nonproprietary Version

Prepared by
Electric Power Research Institute
Palo Alto, California

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Final Report, August 1992
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Prepared by
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for ODSCC at TSPs

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ABSTRACT

Stress corrosion cracking initiating on the outer diameter (ODSCC) of alloy 600 steam generator tubes has been diagnosed in the tube support plate (TSP) region of many PWR steam generators. When existing tube plugging limits based on crack depth are applied, many tubes may require repair that is unnecessary from either a safety or reliability standpoint. Allowing tubes with axial ODSCC to remain in service can be justified based on a combination of enhanced in-service inspection, a repair limit based on eddy-current testing (ECT) voltage, a limit on the number of cracked tubes remaining in service (determined by leakage limits for faulted loads), and a reduced primary-to-secondary allowable leak rate at normal operation. This report provides the technical support for a repair limit for tubes where axial ODSCC is the dominant degradation mechanism in the TSP region of steam generators in U.S. PWR power plants. In this approach, ECT voltage is used as a measure of tube integrity and tube leakage potential, and operation with cracks that may be through-wall is permitted. This document has been prepared by a committee of U.S. and foreign industry participants who are experts on the technical and licensing issues associated with development and implementation of steam generator tube repair limits. The document represents the committee's recommended approach, and presents information for use by utilities as a reference or supplement to site-specific analyses for developing revised tube repair limits associated with axial ODSCC in the TSP region of steam generators.

Application of the tube repair limit criterion documented in this report requires, as a prerequisite, unit-specific qualification which establishes the tube damage mechanism for which this criterion is applicable.

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EXECUTIVE SUMMARY

Stress corrosion cracking initiating at the outer diameter (ODSCC) of alloy 600 steam generator tubes has been diagnosed in the tube support plate (TSP) region of many PWR steam generators. When existing tube plugging limits based on crack depth alone are applied, many tubes may require repair that is unnecessary from either a safety or reliability standpoint. Allowing tubes with ODSCC to remain in service can be justified based on a combination of enhanced in-service inspection, a repair limit based on eddy-current testing (ECT) voltage, a limit on the number of cracked tubes remaining in service (determined by leakage limits for faulted loads), and a reduced primary-to-secondary allowable leak rate at normal operation.

The combination of remedial measures, inspection, an acceptable repair limit, and a reduced allowable leak rate, along with several repair options for cracked tubes, provides a series of plant-specific alternatives that can be used to develop the most cost-effective means to maintain safety and acceptable reliability for steam generators experiencing ODSCC at TSPs. The criteria described in this report are in addition to previous work that established degradation specific evaluation criteria (e.g., P*, F*, wastage, etc.) and provided significant operational benefits while maintaining adequate safety margins.

This document has been prepared by a committee of U.S. and foreign industry participants who are experts on the technical and licensing issues associated with development and implementation of steam generator tube repair limits. This document represents the committee's recommended approach, and presents information for use by utilities as a reference or supplement to site-specific analyses for developing revised tube repair limits associated with ODSCC in the TSP region of steam generators. In this approach, ECT voltage is used as a measure of tube integrity and tube leakage potential, and operation with cracks that may be through-wall is permitted.

Field experience indicates that ODSCC is generally axial, occurs either singularly or in networks of multiple cracks, and is located within the TSP. While circumferential cracks generally do not occur in combination with axial cracks, some circumferential branching of axial cracks has been observed in pulled tubes. Shallow intergranular attack (IGA) has also been observed in combination with ODSCC. Tubes with these degradation characteristics were burst tested to develop the ODSCC repair limit. Consequently, the repair limit recommended for ODSCC provides adequate margin against tube rupture for ODSCC degradation typically found in service.

This document is applicable for tubes where axial ODSCC is the dominant degradation mechanism. The repair limits described in the document are not applicable to dented tubes or tubes having nondestructive examination (NDE) indications evaluated to be distinct circumferential cracks. Currently, the ODSCC repair limit is applicable to tubing and degradation lengths of up to ; ongoing work is directed toward extending application of the repair limit to other tubing sizes and larger degradation lengths.

Distinguishing between different degradation mechanisms at tube support plates is difficult using presently available NDE techniques. Consequently, it is incumbent on the user who chooses to apply the repair limits documented in this report to demonstrate that axial ODSCC is the dominant degradation mechanism for their unit.

The repair limit has been developed based on an uncovered tube span. This approach is appropriate for drilled hole TSP designs, if the cracked tube section becomes uncovered during postulated faulted loads, and for egg crate and quatrefoil TSP designs.

While the repair limits developed in this report can be applied for axial ODSCC that remains confined within the TSP for drilled hole designs, the repair limit will be unnecessarily conservative . Less restrictive repair limits can be used provided it can be demonstrated that the ODSCC will remain covered during faulted loads. Demonstration that ODSCC will remain confined within a drilled hole TSP should incorporate detailed analysis of TSP motion during postulated faulted loads; the analysis should include phenomena that may limit TSP motion (e.g., denting). If it can be shown that ODSCC will be covered by the TSP under all loading conditions, it is likely that tube rupture need not be considered, and repair limits can be based on leakage limits for faulted loads.

In addition to application of remedies to limit ODSCC degradation, the elements of this approach include:

- At each scheduled inspection outage, perform eddy-current inspections of 100% of the TSP regions where ODSCC has been detected.

- Perform selected inspections using enhanced eddy-current methods to confirm the ODSCC damage mechanism.

- Repair of tubes with ODSCC using a conservatively established repair limit which includes the following elements:

  --Use of a conservative correlation between tube rupture and ECT voltage.

--Application of USNRC Regulatory Guide 1.121 safety factors.

--Use of lower bound material properties.

--Allowance for ODSCC growth between inspections.

--Allowance for ECT voltage measurement error.

--A limit on leakage during postulated faulted loads so that the dose rate is a small fraction of 10CFR100 limits.

Implementation of this U.S. approach is expected to require the following utility actions:

- Application of the ECT voltage criteria to plant-specific inspection results using the information in this report supplemented by available plant-specific data on material properties, normal and faulted tube pressure differentials, ODSCC growth rates, and NDE measurement error.

- Implementation of an allowable leak rate limit of   during normal plant operation.

- Calculation of the potential leak rate expected during postulated accident loads from the cracked tubes that remain in service.

- Calculation of maximum allowable site specific leak rate during postulated accident loads to ensure that the dose rate due to leakage is a small fraction of 10CFR100 limits.

Implementation of these elements constitutes a defense-in-depth approach that was developed to ensure adequate levels of safety and compliance with applicable General Design Criteria in 10CFR50. The inspection scope and procedures, tube ECT voltage repair limits, and the leak rate limits developed for tubes with ODSCC in the TSP region ensure adequate margins against failure and excessive leakage and meet the requirements specified in the applicable General Design Criteria.

Section 1 of this document summarizes the overall approach, need, and justification for a degradation-specific repair limit for ODSCC. Section 2 describes the NDE capability and develops the approach for dealing with inspection error and ODSCC growth. Section 3 provides a discussion of data and criteria used to develop the relationship between margin against tube rupture and allowable ECT voltage for ODSCC degraded tubes. Section 4 provides a discussion of the calculation of the leak rate during postulated accident loads from cracked tubes that remain in-service following an inspection (i.e., tubes with ECT voltages below the repair limit).

Section 5 integrates the information in sections 2 through 4 to define the repair limit for tubes with ODSCC in the TSP region. Appendices A through D provide additional background and supporting material, and are appropriately referenced in the body of the document.

Section 1

INTRODUCTION AND BACKGROUND

1.1 OVERVIEW

This report documents the development and justification for a repair limit for alloy 600 steam generator tubes having axial stress corrosion cracks that initiate at the tube outer diameter in the tube support plate (TSP) region. The repair limit was developed for PWR power plants in the United States and is applicable to drilled hole, egg crate and quatrefoil TSP designs.

The outer diameter stress corrosion cracks (ODSCC) are illustrated in figure 1-1 for a drilled hole TSP design. The cracks are axial, occur either singularly or in networks of multiple cracks, and are located within the TSP. While circumferential cracks generally do not occur in combination with axial cracks, some circumferential branching of axial cracks has been observed in pulled tubes.

In addition to axial ODSCC, intergranular attack (IGA) has been observed in some pulled tubes. IGA is a corrosion degradation of tube grain boundaries, the depth of which is generally uniform. IGA can occur in isolated two-dimensional patches or finger-shaped areas. IGA can also occur as a network of patches or fingers which may encompass the entire tube circumference within the tube support plate.

This document is applicable for tubes where axial ODSCC is the dominant degradation mechanism. Axial ODSCC may be accompanied by shallow IGA. To be classified as shallow IGA, its depth should be less than   of the tube wall thickness and its contribution to the indicated bobbin coil ECT voltage associated with the axial ODSCC should be small. The repair limits described in this document are not applicable to dented tubes or tubes having NDE indications evaluated to be distinct circumferential cracks. Currently, the ODSCC repair limit is applicable to   tubing and degradation lengths of up to approximately   ; ongoing work is directed toward extending application of the repair limit to other tubing sizes and longer degradation lengths.

Distinguishing between different degradation mechanisms at tube support plates is difficult using presently available NDE techniques. Consequently, it is incumbent on the user who chooses to apply the repair limits documented in this report to demonstrate that axial ODSCC is the dominant degradation mechanism for their unit.

Figure 1-1. Illustration of ODSCC in Steam Generator Tubes in the TSP Region

Implementation of this document satisfies the following general requirements:

- Compliance with the General Design Criteria.

- Avoid conditions that lead to exceeding a conservative leakage limit of during normal operation.

- Provide adequate margin against tube rupture under normal operating and postulated accident loads (e.g., steam line break).

- Avoid excessive leakage under postulated accident loads.

The remainder of paragraph 1.1 summarizes the approach used to meet these general requirements.

Eddy-current testing (ECT) voltage is used to define the repair limit for axial ODSCC in the TSP region. This approach employs laboratory and field degraded tubes to correlate bobbin coil (BC) ECT voltage with leak rate and burst pressure. The correlations are developed from and are applicable to tubes with axial ODSCC having depths up to wall thickness.

When axial ODSCC is located entirely within the TSP for drilled hole designs, the TSP limits tube radial deformation and tube burst is precluded. However, cracks have occasionally been detected outside the TSP, and analyses indicate that a TSP may, in certain instances, move during postulated faulted loads and reduce the constraint effects. Consequently, the repair criteria for the drilled hole TSP design and egg crate and quatrefoil designs are based conservatively on burst of an uncovered tube span, and include margins against burst that are consistent with U.S regulatory guidelines for normal and postulated faulted loads.

Field application of this approach includes inspection of the TSP region by BC for 100% of the tubes in regions of the steam generator where the tubes are susceptible to ODSCC. These affected regions include the hot leg, and the cold leg down to the lowest TSP where ODSCC has been diagnosed. Those tubes where the BC voltage is greater than that established for ensuring adequate margin against rupture will be repaired.

In some instances, inspections using rotating pancake coil (RPC) eddy current technology will also be used either to confirm that detected degradation is axial ODSCC or to establish a basis for leak rate predictions. The inspection results from the tubes not requiring repair will be used to determine the ECT voltage distribution in the steam generator, and a leak rate analysis will be performed for the accident loads to determine if the dose rate from the leakage will remain a small fraction of 10CFR100 limits. If results from the accident leak analysis indicate an excessive leak rate, tubes will be selectively repaired so that the dose rate is a small fraction of

10CFR100 limits. Figure 1-2 presents a graphic overview of the evaluation procedure developed to implement the alternative repair limits for tubes with axial ODSCC at TSPs.

The repair limit includes adjustments for inspection error and ODSCC growth to ensure with a high level of confidence that adequate margins against burst and unacceptable leakage are maintained throughout the subsequent operating interval. To provide additional assurance against abnormal leakage and tube rupture at normal and faulted loads, a leak rate of has been established as the allowable primary to secondary leak rate limit during normal operation.

1.2 COMPLIANCE WITH GENERAL DESIGN CRITERIA

The repair limit for tubes with axial ODSCC in the TSP region has been developed to ensure compliance with the applicable General Design Criteria (GDC) in Part 50 of Title 10 of the Code of Federal Regulations (10CFR50). The GDC were reviewed and it was concluded that GDC 14, 15, 30, 31, and 32 are applicable to the development of repair limits for axial ODSCC occurring in steam generator tubes. The remainder of paragraph 1.2 summarizes the bases for compliance with the applicable GDC.

1.2.1 GDC 14

GDC 14 requires the reactor coolant pressure boundary to be designed, fabricated, erected and tested so as to have an extremely low probability of abnormal leakage, of rapidly propagating failure, and of gross rupture.

R.G. 1.121, "Bases for Removing Degraded PWR Tubes From Service" provides explicit and implied safety margins for tube loading. R.G. 1.121 explicitly states that tube loading should have a safety factor of 3.0 under normal operating conditions. The regulatory guide further states that the margins of safety against tube rupture under postulated accident conditions should be consistent with the margin of safety determined by the stress code limits specified in Section III of the ASME Boiler and Pressure Vessel code. The repair limit discussed in this report is shown to meet all of the above acceptance criteria.

Following implementation of the TSP ODSCC tube repair limit, steam generator tube integrity is maintained both by eddy-current inspection and by measuring steam generator primary-to-secondary leakage. To further ensure that adequate safety margins are maintained during service, in-service inspections are performed for 100% of the affected regions during each refueling outage. Any tubes found to have flaws larger than those necessary to maintain acceptable margins against tube rupture and abnormal leakage (including consideration of additional flaw growth during service) will be repaired. Service experience indicates normal operating leakage levels at plants having ODSCC in the TSP region can be expected to remain at very low levels (see paragraph 4.1).

Figure 1-2. Evaluation Procedure for Implementation of an Alternative Repair Criterion for Tubes with ODSCC at TSPs

A maximum leak rate of has been established for normal operation. This leakage level provides added assurance against tube rupture at normal and faulted conditions, and, together with limiting the number of degraded tubes that can remain in service, helps to ensure that the dosage contribution from tube leakage will be limited to a small fraction of 10CFR100 dose limits for postulated faulted events.

1.2.2 GDC 15

GDC 15 requires the reactor coolant system and associated auxiliary, control and protection systems to be designed with sufficient margin to assure the design margins of the reactor coolant pressure boundary are not exceeded during any condition of normal operation, including anticipated operating occurrences.

Because the steam generator tubing represents a large portion of the total primary system pressure boundary, factors of safety of three on normal pressure loads and 1.4 on accident loads are used in the ODSCC repair limit to define the maximum ODSCC degradation allowed to remain in service and to ensure that the steam generator tube integrity is maintained during normal operation, including anticipated operational occurrences. In addition, a maximum leak rate of at normal operation has been established to enhance the likelihood of leak-before-break.

1.2.3 GDC 30

GDC 30 requires that components which are part of the reactor coolant pressure boundary shall be designed, fabricated, and erected, and tested to the highest quality standards practical. Also, means shall be provided for detecting and, to the extent practical, identifying the location of the source of reactor coolant leakage.

With implementation of the TSP ODSCC tube repair limit developed in this document, 100% of the affected area will be inspected. Those tubes where degradation is indicated will be evaluated to assess compliance with the repair limit. Tubes that are not in compliance with the repair limit will be repaired.

During reactor operation the secondary side of the steam generator will be monitored for radioactivity to detect leaks from cracks in steam generator tubes. If leakage exceeding is detected during normal operation, the unit will be shutdown and the steam generator tubes will be inspected to determine the source of the leakage. Tubes that have been identified as having leaks will be repaired.

1.2.4 GDC 31

GDC 31 requires that the reactor coolant pressure boundary will be designed with sufficient margin to ensure that when stressed under operating, maintenance, testing and postulated accident conditions: (1) the boundary behaves in a nonbrittle manner, and (2) the probability of rapidly propagating fracture is minimized.

The design shall reflect consideration of service temperatures and other conditions of the boundary material under operating, testing and postulated accident conditions and the uncertainties in determining: (1) material properties, (2) irradiation effects on material properties, (3) residual, steady state and transient stresses, and (4) the size of flaws.

To ensure that the tubes behave in a nonbrittle manner and the probability of rapidly propagating fracture is minimized during operating, maintenance, testing and postulated accident conditions, the tubes are manufactured from ductile materials and conservative margins are applied to normal operation, maintenance, testing and postulated accident loads. These margins have been confirmed from experiments with tubes experiencing TSP ODSCC. This testing has been used as the basis for development of the repair criterion.

The margins have been determined considering the temperatures and pressures at normal and postulated accident loads, and the uncertainties associated with material properties, stresses, degradation measurement error, and in-service crack growth. Again, as noted above, the margins are in compliance with those specified in Regulatory Guide 1.121, the ASME Code, and where the measured values for these variables are unavailable, conservative values have been used.

1.2.5 GDC 32

GDC 32 requires that components which are part of the reactor coolant pressure boundary should be designed to permit inspection and testing of important areas and features to assess their structural and leaktight integrity.

Eddy-current inspections can be performed for 100% of the tube to TSP intersections in regions of the steam generator where the tubes are susceptible to ODSCC. Degradation in the TSP region does not adversely affect the ability to inspect the tubes, to interpret the eddy-current signal, locate the degradation, and categorize the condition of the tube. Performing these inspections will provide assurance that the ODSCC is within limits such that the safety margins used in the structural integrity evaluation are maintained during service conditions, and steam generator primary-to-secondary leak rates during normal and postulated accident condition loads remain within required limits.

1.2.6 GDC Summary

Section 2 of this report describes the examination methods, including provision for measurement error, that will be used to detect and evaluate tubes having ODSCC in the TSP region. Implementing the methods described in section 2 provides bases for compliance with various requirements in GDC 14, 15, 30, 31, and 32.

Section 3 of this report defines the burst pressure for tubes having ODSCC in the TSP region, while section 4 describes the expected leakage during normal and postulated accident conditions. Section 5 defines the repair limit, including consideration of NDE measurement error and in-service crack growth, that will ensure adequate margins against rapidly propagating failure, and excessive leak rate for postulated faulted events.

The information in sections 3 and 5 provide the bases for compliance with GDC 14, 15 and 31, while implementing the leak rate limits as described in section 4 will ensure compliance with GDC 14, 15, 30, and 32.

1.3 BACKGROUND

1.3.1 Steam Generator Tube Degradation

Experience shows that steam generator tubes may be susceptible to degradation from a variety of mechanisms. As degradation progresses, the affected tubes (or tube segments) are repaired based on in-service inspection (ISI) results, or when primary-to-secondary leakage exceeds a preestablished limit during power operation. Defective segments are repaired either by taking the entire tube out of service, or by installing internal sleeves in the area of local degradation. If degradation progresses and a large number of segments are removed from service, core cooling requirements ultimately may dictate that either the plant be derated or the steam generator be replaced.

Guidelines for evaluating steam generator tube integrity are contained in Regulatory Guide 1.83 (Revision 1, July 1975), "Inservice Inspection of Pressurized Water Reactor Steam Generator Tubes" (1) and Regulatory Guide 1.121, (Draft for Review and Comment, July 1976), "Bases for Plugging Degraded PWR Steam Generator Tube," (2).

In the United States, the application of the current depth-based guidelines for steam generator tube degradation management can be broadly characterized as follows:

- Assume each degradation form is of equal concern.

- Determine the allowable degradation size based on part through-wall depth regardless of defect length, volume of material loss, or cause of the degradation.

- Establish a shutdown leak rate to help ensure that a degradation that progresses through-wall during an operating cycle will leak rather than break.

- Assume that the combined application of known remedial measures, the inherent leak-before-break nature of alloy 600 for many degradation-types, and the mandated inspection protocol provide assurance that the consequences of tubing damage will be acceptable.

While the depth-based approach has proved acceptable (experience shows that there have been few tube ruptures, and that the consequences of those ruptures are acceptable (3)), in certain cases it has led to excessive and unnecessary tube repair (specifically in the case of small volume degradation such as isolated pits and primary-water-initiated stress corrosion cracks). In such cases, a more degradation-specific approach has been developed to provide significant benefit to affected plants while still maintaining acceptable safety margins. Several examples of these degradation-specific criteria include:

- P* and F* Criteria - permit through-wall cracks to remain in service within the steam generator tubesheet region (4-7).

- Tube Support Plate Primary Water Stress Corrosion Cracking - proposed a justification for through-wall axially oriented cracks to remain in service at the support plate elevation with denting present (8).

- Pitting Degradation - justifies a 64% of wall thickness repair limit for tubes experiencing pitting (9, 10).

- Tube Support Plate Outside Diameter (OD) IGA/SCC - justifies an allowable wall loss of 82%; implementing Reg. Guide 1.121 considerations, the corresponding tube repair limit was conservatively limited to 51% of wall thickness (11, 12).

- Wastage - justifies a 47% of wall thickness repair limit for steam generator tube thinning (13, 14).

- Expansion Zone Primary Water Stress Corrosion Cracking - justifies through-wall axially oriented cracks to remain in service in the tube expansion zone roll transition at the top of the tubesheet (15).

In each of these examples, a degradation-specific limit has been developed that satisfied the intent of Reg. Guide 1.121. The justification for degradation-specific criteria integrates concern for structural capability and leakage of the degraded tubing with nondestructive examination accuracy, in-service degradation growth and leak detection capability.

1.3.2. TSP ODSCC

Plants that have experienced TSP ODSCC are listed in table 1-1 (16, 17). Appendix A provides a detailed summary of TSP ODSCC plant experience .

ODSCC has been observed in steam generators with mill-annealed alloy 600 tubing. It can be caused by concentration of alkaline solution within the crevice between the tube and TSP. Application of boric acid has been used in a number of plants to control ODSCC.

Experience shows that TSP ODSCC cracks are generally short, axially oriented and sometimes may be through-wall. The cracks generally have been found in tubes in the steam generator hot-leg; fewer ODSCC incidents have been observed in the cold leg. Intergranular attack (IGA) alone or in combination with SCC has also been observed to occur in the TSP region. IGA can occur in either networks over a significant portion of the tube circumference, or isolated patches. Circumferential branching of axial cracks has been observed in pulled tubes in some instances.

With few exceptions, ODSCC has been confined to the region within the TSP. Cracks have been found outside the TSP at one plant. At another plant, an ODSCC indication outside the TSP was found by BC in a dented area at the top of the TSP; however, this indication could not be confirmed by RPC. The other known occurrence of an ODSCC crack extending outside the area of constraint provided by the drilled hole was in a flow distribution baffle where sludge was present on top of the baffle.

1.4 CURRENT INTERNATIONAL PRACTICES

1.4.1 EdF Practices for TS ODSCC

In France, inspections are performed in the TSP region using BC. Inspection results indicate ODSCC in the TSP region at approximately eleven plants. All ODSCC detected to date has been contained within the TSP. Repair of tubes with ODSCC is not required when the cracking remains within the TSP.

1.4.2 Belgian Practices for TSP ODSCC

The Belgian utility (Electrabel) performs inspection of the tubes in the TSP region using BC. ODSCC at TSPs has been found in Belgian plants, and a repair limit is now being implemented for tubes with degradation within the TSP.

Table 1-1

PLANTS WITH EITHER CONFIRMED OR DIAGNOSED ODSCC AT TSPs[a]
(Refs. 16 and 17)

1.4.3 Spanish Practices for TSP ODSCC

Inspection procedures include inspection with BC; tubes with BC indications also are inspected using RPC technology. The current repair limit is based on a maximum through-wall depth. ODSCC has been found in the TSP region for four plants in Spain. An interim repair limit has been proposed but not yet accepted by licensing authorities. The interim limit includes repairing tubes having crack depths greater than through-wall. This repair limit is based on experimental results that indicate tubes with through-wall cracks the length of the TSP will not burst. A crack growth per year adjustment and a allowance for NDE uncertainty are used to minimize the potential for tube leakage.

1.4.4 Swedish Practices for TSP ODSCC

Inspection procedures include inspection with BC; tubes with BC indications are inspected using RPC technology. Current repair criteria are based on a maximum through-wall depth. ODSCC has been found in the TSP region at a Swedish plant. An alternative repair limit for ODSCC has been proposed but not yet accepted by the licensing authorities. The alternative limit includes repairing tubes having crack depths greater than through-wall. This repair limit is based on experimental results that indicate tubes with through-wall cracks the length of the TSP will not burst. A crack growth per year adjustment and a allowance for NDE uncertainty are used to minimize the potential for tube leakage.

1.5 REFERENCES

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Section 2

NDE CONSIDERATIONS

2.1 OVERVIEW

This document defines a tube repair limit based on eddy-current testing (ECT) bobbin coil (BC) signal amplitude (voltage) for tubes with axial ODSCC at tube support plates. Test data from model boiler specimens and tubes removed from operating steam generators are used to define the tube voltage repair limit. Application of the repair methodology assumes the user implements field eddy-current data acquisition and analysis procedures similar to those used during laboratory testing. This section provides an overview of the applicable eddy-current test conditions and discusses allowances for measurement error and degradation growth rate. Estimates of these factors are incorporated into the calculation of the tube voltage repair limit described in section 3.

2.2 APPLICABLE TEST CONDITIONS - OVERVIEW

The tube voltage repair limit has been determined empirically using laboratory and field BC ECT data acquired under specific test conditions, including:

- . Alloy 600 tubing with a nominal wall thickness.
- . Nonmagnetic bias BC operated in a differential mode. Conventional coil dimensions, i.e., coil winding width and spacing, are required as discussed in appendix B.
- Eddy current primary and secondary test frequencies of . These frequency combinations are mixed linearly, with the mix channel used to determine signal amplitude.
- No significant denting or copper deposits, which may alter the bobbin coil mix channel signal amplitudes, present at tube support plates.

In addition, special calibration requirements are imposed to ensure consistency with laboratory test data. Detailed data acquisition and analysis requirements are discussed in appendix B.

2.3 EDDY-CURRENT DATA

BC eddy-current data used in the tube repair limit are shown in figure 2-1. The upper part of the figure shows the eddy-current graphic - primary analysis channel, i.e., b differential - for a support plate signal and a signal diagnosed as ODSCC centered within the support plate. These same data are shown in the lower part of the figure using the mix analysis channel. In this case, the support plate signal is suppressed as a result of the mixing process leaving only the indication diagnosed as ODSCC. The eddy-current analysis software is then used to measure the peak-to-peak voltage of the ODSCC indication in the mix channel. This measured voltage is compared with the tube voltage repair limit (see section 5).

Application of the BC tube voltage repair limit assumes that ODSCC is the dominant damage mechanism at tube support plates. Damage mechanism confirmation can be accomplished by inspecting some tubes with BC indications below the repair limit but above a threshold value using rotating pancake coil (RPC) technology. ODSCC diagnosis is accomplished by viewing the RPC isometric and observing the presence of linear indications directed along the tube longitudinal axis. As the RPC is translated and rotated through the tube, it describes a helical path, as shown in figure 2-2(a). A linear discontinuity within the tube wall, i.e., a crack, will be scanned once during each rotation of the probe. The RPC coil output voltage from a given rotation is used to generate a line scan which represents signal amplitude as a function of coil position around the tube circumference (see figure 2-2(b)). A similar display can be developed with ultrasonic (UT) examination. Pseudo-image formation (in a two-dimensional cylindrical coordinate system) is accomplished by plotting a series of consecutive line scans with line scan generation synchronized with probe rotation. This allows for the reconstruction of an image in perspective format as shown in figure 2-2(c). Crack presence is determined by recognizing the existence of linear features in the reconstructed image; orientation is inferred by noting the direction of the major axis of the image.

Figure 2-1. Bobbin Coil Signal Amplitude Analysis

Figure 2-2. RPC Confirmation of ODSCC at the TSP Intersection

2.4 VOLTAGE MEASUREMENT ERROR

Various sources contribute to the uncertainty in measuring bobbin coil signal amplitude. Two of the more significant contributors include: (1) measurement repeatability, which is strongly influenced by wear of the probe centering device, and (2) calibration standard hole diameter and wall thickness. Estimated error values (in percent), along with the total RMS error, are summarized in table 2-1. The basis for each of the errors and estimates of their magnitude is discussed below.

Table 2-1

VOLTAGE MEASUREMENT ERROR ESTIMATES

2.4.1 Measurement Repeatability

A significant contributor to measurement repeatability error is poor probe centering which can be introduced as the result of wear on the probe centering mechanism. Signal amplitude variation due to probe wear occurs as the result of probe tilt caused by unequal wear of the probe centering mechanism during tube examination. For localized tube wall degradation, the measured signal amplitude will vary depending on the proximity of the probe to the degraded tube section, e.g., the probe can lean or tilt towards or away from one side of the tube.

Probe wear measurement error effects were evaluated by making repetitive scans of an eddy-current calibration standard containing diameter through-wall holes. The holes were spaced apart circumferentially, and separated axially. A drawing of this standard is shown in appendix B. Numerous test runs were made with the calibration standard mounted in a vertical condition simulating in-generator data acquisition conditions. For a given amount of probe wear, the tube was rotated after each run to provide for variation in probe-to-tube orientation; a total of runs for the holes (data points) were completed for a given amount of probe wear.

The probe centering mechanism evaluated during this study consisted of sets of spring-loaded plastic buttons apart protruding approximately from the probe body. Probe wear was introduced by repeatedly running the probe through the tube with an abrasive tape on the tube ID. The amount of wear was varied in steps from , e.g., no wear, to a maximum value of approximately .

Test results are summarized in figure 2-3, which shows clustered sets of voltage readings (plotted along the ordinate) that were obtained for the ranges of probe wear that were tested (grouped along the abscissa). Notice that for the case of no probe wear, there is some scatter in the measured voltages; the sample standard deviation is . This scatter represents a lower bound test repeatability limit and is the smallest error that can be achieved in measuring signal voltage. For increasing degrees of probe wear, the variation in signal amplitude increases significantly as evidenced by the larger scatter in the measured voltages. At , the standard deviation is , while at , the sample standard deviation is .

Measurement repeatability due to probe wear can be limited or controlled by using a wear monitoring standard. This is accomplished by utilizing a standard for in-service testing of a probe during steam generator inspection. In this manner, the overall repeatability of BC voltage measurements can be directly controlled. For calculational purposes, it is assumed that probe wear will be limited to . For this case, a voltage variation of has been used in table 2-1 for the probe wear contribution to the total voltage measurement error.

2.4.2 Calibration Standard Variations

Voltage calibration is typically accomplished using an ASME standard with drilled holes; the eddy-current signal amplitude from these holes is set to some pre-established voltage using eddy-current analysis software. The voltage error due to calibration standard variations results from using a standard in the field different from the one used in the laboratory to establish the initial voltage repair limit database.

Figure 2-3. Eddy-Current Signal Degradation Due to Probe Wear

2-7

An eddy-current standard with drilled holes is recommended for system calibration. through-wall holes, apart in a single plane around the tube circumference, are used to reduce probe centering effects. Through-wall holes are specified in order to eliminate variations in individual hole depth.

The eddy-current signal amplitude or voltage V from a single through-wall holes is proportional to the total hole volume where:

Hole Volume = (2-1)

where d is hole diameter and t is tube wall thickness. The change in voltage dV due to variations in both d and t can be obtained from Eq. 2-1 by taking the total derivative of the right side of the equation with respect to d and t. After differentiation, the fractional voltage change is obtained by dividing the total differential dV by Eq. 2-1. Multiplying by 100 gives the percentage voltage change, V(%), where:

$\Delta V(\%)$ = (2-2)

As can be seen from Eq. 2-2, the contribution to the total voltage caused by variations in hole diameter is twice that of wall thickness variations. This equation predicts how the voltage changes as either the hole diameter or wall thickness or both are varied. If the variation in hole diameter and wall thickness is uncorrelated, then the voltage percentage error is given by the RMS combination of the two individual error sources, e.g., by taking the square root of the sum of their squares. Thus,

$\delta V(\%)$ = (2-3)

Assuming that dimensional variations in calibration standard hole diameter and wall thickness are controlled within and with a hole diameter of and tube wall thickness of , the percentage error in these dimensions are and , respectively. Substituting into Eq. 2-3 yields a bobbin coil voltage percentage error of .

The error contribution due to field calibration secondary standard dimensional tolerances could be effectively eliminated by direct comparison or calibration with the laboratory primary standard using a transfer standard concept. In doing this, the calibration error described in the previous paragraph can be eliminated.

2.4.3 Total Measurement Error

The two error sources due to measurement repeatability and calibration standard differences are RMS combined to give the total voltage measurement error. The total RMS error assuming no calibration against the laboratory standard is versus if a direct comparison is done using the transfer standard concept. This term is designated as %NDE and is used in section 5, table 5-1, for calculating the voltage repair limit.

2.5 ODSCC GROWTH RATE

Because the tube repair limit utilizes signal voltage as a measure of structural integrity, BC voltages from consecutive operating cycles must be examined to infer an allowance for ODSCC growth rate.

An important source of growth rate data are French units which have operated with ODSCC at tube support plates for several years (1). An example of typical growth rate data is shown in figure 2-4 which illustrates BC voltage histograms for the same population of tubes over four consecutive inspection cycles from Fessenheim 1. As seen from the figure, the histograms shift systematically towards larger voltages with time which is indicative of ODSCC growth in the population of tubes.

The signal amplitude data shown in figure 2-4 cannot be used directly as an estimator of growth rate in measured volts/cycle because of differences between U.S. and French eddy-current calibration and analysis procedures. However, it has been determined that the relative voltage growth (percent change) is independent of calibration procedures and can be used directly.

A detailed discussion of U.S. and European eddy-current calibration differences and an overview of ODSCC growth rate data for European and U.S. units is given in appendix C. Based on the analysis of the data discussed in appendix C, an average value of per cycle (typically 18 months at 80% capacity) expressed as a percentage of the measured signal voltage--is used to characterize the ODSCC growth rate until plant specific data is developed. This term is designated as $\%V_{CG}$ and is used in section 5.

2.6 REFERENCES

1. J. P. Hutin. "EDF Steam Generator Operating Experience - 1990." EPRI SGRP Technical Advisory Group Meeting, February 26, 1990, Palo Alto, California.

Figure 2-4. ODSCC Bobbin Coil Signal Amplitude Histograms - Fessenheim-1

Section 3

TUBE BURST CONSIDERATION

3.1 OVERVIEW

Tube rupture and burst are used interchangeably in this document and describe the condition of a tube segment with a crack at the maximum pressure it can support under actual steam generator conditions. Rupture or burst occurs by significant tube deformation followed by crack tip extension.

As pointed out in section 1, one of the requirements of a tube repair limit is to provide margin against tube rupture under normal operation and postulated accident loads (e.g., steam line break).

For drilled hole TSP designs, if it can be shown under all postulated loading conditions that the ODSCC will remain covered by the TSP, the TSP will limit tube deformation and tube rupture is precluded. However, for other TSP designs and when TSP-to-tube relative movement can not be precluded, the confinement effect can not be guaranteed. In these cases, it is conservative to ignore the confining effect of the TSP for tube rupture considerations, and assume that the ODSCC occurs in the tube free span uncovered by the TSP. This conservative assumption is used in this document.

In this section the relationship between burst pressure and bobbin coil voltage is developed for uncovered tubes with ODSCC. This relationship is based on tube rupture experiments performed for EPRI and reported in (1). The results from these experiments are summarized here, and mean and statistical regression curves are developed to correlate burst pressure with bobbin coil (BC) voltage. A BC voltage below which tube integrity is assured is defined from these correlations using appropriate margins on pressure. This relationship is used in section 5 in the development of tube voltage repair limits. Other factors used in the repair limit development are adjustments for NDE measurement error and ODSCC growth between inspections (see section 2).

3.2 TUBE RUPTURE EXPERIMENTS

Tube rupture experiments were conducted by Westinghouse for EPRI as part of a program to develop interim repair limits for ODSCC at TSPs (1). These experiments utilized alloy 600 , tubing with ODSCC. Tubes were either pulled from operating steam generators, in which the ODSCC developed in service, or were cracked under model boiler conditions in the laboratory.

Burst tests were conducted by pressurizing the cracked tubes at room temperature until pressure could no longer be maintained. A crack sealing system utilizing a flexible bladder without local metal reinforcement was used. In some experiments, the ability to maintain pressure was lost before there was significant tube deformation or crack tip extension. In these cases, the maximum pressure achieved in the test was reported and used here as the burst pressure. Burst tests were conducted without the presence of a TSP. That is, ODSCC was in the free span of the tube.

In addition to the tests with tubes with ODSCC in the tube free span, a limited number of tests were conducted with EDM notches confined by either an egg crate or quatrefoil TSP. These tests showed that the presence of the TSP reduces deformation and the resulting leakage area, but with these TSP designs, the maximum pressure the tube can sustain is not significantly increased (1), relative to the free span burst pressure.

3.3 DATA INTERPRETATION

A broad interpretation of the physical significance of the eddy-current BC voltage indication is that the voltage reflects the volume of material which is cracked. For a particular pattern of cracking, the BC voltage is related to the extent of cracking. As burst pressure also depends on extent of cracking, it is reasonable to expect a correlation between burst pressure and BC voltage.

A summary of the pulled tube and model boiler burst pressure and BC voltage test results are provided in table 3-1 and are plotted in figure 3-1. A second order polynomial fit to the burst pressure versus log BC voltage has been made and a curve derived. The curve is the mean curve reduced by a factor of times the standard deviation where the standard deviation was calculated with the assumption that the test data is normally distributed about the mean curve. The curve has been further adjusted downward by a factor equal to a lower bound estimate (2) divided by the mechanical properties of the tubes tested at room temperature. The mean and the curves are shown in figure 3-1 and are described in reference 3-1.

Table 3-1

EXPERIMENTAL DATA (BOBBIN COIL VOLTAGE AND BURST PRESSURE) FOR TUBES WITH ODSCC IN THE TUBE FREE SPAN (1)

Figure 3-1. Burst Pressure Versus Bobbin Coil Voltage Experimental Data with Mean and Corrected Curves

A simple linear relationship which bounds the curve is shown in figure 3-1 for bobbin coil voltages between has been derived. Using this equation to define the voltage structural limit, V_{SL}, in terms of tube burst pressure, BP

$$BP =$$

(3-1)

$$V_{SL} =$$

Eq. 3-1 is valid for V_{SL} from and is used in section 5.2 to calculate tube repair voltage limits. It should be noted that as additional tube burst data are developed, the curve will likely change as will the voltage structural limit equation that bounds this curve.

3.4 APPLICATION OF SAFETY MARGINS

USNRC Regulatory Guide 1.121 (3) recommends that when establishing tube repair limits, safety factors be applied to tube load. Recommended safety factors are:

- 3 under normal service conditions;
- A value consistent with the limits set by ASME Code, Section III, paragraph NB-3225 for accident conditions. In compliance with NB-3225, this factor is taken as 1.4 for postulated accident conditions.

Consequently, in establishing an allowable bobbin coil voltage that assures tube integrity, it is recommended that safety factors of three be applied to normal operating differential pressure and that a factor of 1.4 be applied to accident differential pressures. The smaller of the bobbin coil voltages calculated in this manner will be the voltage structural limit for tube burst considerations (V_{SL}).

It should be pointed out that applying a safety factor of three to the normal operating pressure differential and assuming that TSP has moved such that ODSCC is no longer covered by the TSP is extremely conservative for drilled hole TSP designs. This is because no TSP movement will occur during normal operation. On the other hand, it is possible in some cases that the TSP will move under accident loading conditions (1). At this time, it is assumed that tube ODSCC is not confined by the TSP at either 3 x normal operating pressure differential or 1.4 x accident pressure differential. Assuming an uncovered tube during normal operation is appropriate (and may be slightly conservative) for quatrefoil and egg crate TSP designs.

Less restrictive repair limits can be used provided it can be demonstrated that the ODSCC will remain covered for all loading conditions. If one can show that under all loading conditions ODSCC will be covered by the TSP, it is likely that tube rupture need not be considered and repair limits can be based on leakage limits alone.

Steam generator maximum normal operating differential pressures range from 1300 psi to 1550 psi, while maximum accident differential pressures are on the order of 2650 psi. Three times maximum normal operating differential pressure would range from 3900 to 4600 psi, while 1.4 times accident differential pressure of 2650 psi is 3710 psi. Consequently, 3 times normal operating pressure is the most limiting case.

Voltage structural repair limits of which correspond to pressures of 3900 and 4650 psi, respectively, are shown schematically in figure 3-1. Sample calculations of the tube voltage repair limits based on these structural voltage limits are included in section 5.

3.5 REFERENCES

1. T. A. Pitterle et al. Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates - Data Base for Alternate Repair Limits - Volume 1: 7/8 Inch Diameter Tubing. Palo Alto, Calif.: Electric Power Research Institute. NP-7480-L, vol. 1. (to be issued in March 1992).

2. J. A. Begley and J. L. Houtman. "Inconel Alloy 600 Tubing - Material Burst and Strength Properties." WCAP12522, January 1990.

3. U.S. Nuclear Regulatory Commission Regulatory Guide 1.121. "Bases for Plugging Degraded PWR Steam Generator Tubes." Draft for Comment, August 1976.

Section 4

TUBE LEAKAGE CONSIDERATIONS

4.1 LEAKAGE UNDER NORMAL LOADS

The actual in-service leakage from ODSCC at TSP intersections has been very limited on a world wide level. This experience is consistent with a 40% depth repair policy, even if deeper degradations can not be precluded and may exist. Other countries following a policy similar to that currently used in the United States have reported only one leakage event. This event occurred at a Spanish plant and resulted from a pluggable indication that was missed during the previous outage.

In European countries with no repair criteria to prevent through-wall defects at TSP intersections, reported leakage events are low. In Belgium, no leakage has been observed at Tihange 1 (where all 3 steam generators are known to have been affected by ODSCC for a number of years). A 1990 leakage event reported for the Doel 4 plant cannot be qualitatively correlated with the two detected leakers at the TSP level because of three leaking tubes attributed to primary water stress corrosion cracking (PWSCC) in the expansion zones (EZ) of roll transitions . In France, 11 units with ODSCC at TSP intersections have been operating for a significant period (more than five years for at least two units) without detectable leakage.

This insignificant in-service leakage from TSP ODSCC, even when no criteria are set to prevent through-wall defects, is likely to result from a combination of the following factors:

- Crack morphology is such that wall penetration is not readily achieved (relatively long cracks are prevented from leaking by a thin ligament on the ID side and, even after penetration, the ID length remains substantially less then the OD length). Also, unbroken ligaments between the crack faces often tend to restrict the leakage path.

- The small opening areas of through-wall cracks can get clogged easily by circulating corrosion products, impurities, or precipitates.

- The crevice chemistry may block the leak path, either by corrosion product accumulation (leading to "packed crevices"), or by tube denting from the corroded TSP.

While this experience indicates that leakage from TSP-ODSCC is not an operational concern, some consideration should be given to tube leak-before-break (LBB) to deal with possible unanticipated leaks or cracks that might grow at a greater than expected rate and thus challenge the adequacy of the structural repair limit. Using the LBB methodology to reduce the probability of tube break to a negligible level also addresses the issue of a single large leaker (outside the predicated range) during postulated faulted loads.

Because a specific leak rate database cannot be established from service experience with ODSCC, the database and LBB assessment available for axial EZ-PWSCC (1) has been used here. This procedure is considered acceptable because stress corrosion is the mechanism for both ODSCC and PWSCC and leads to the recommendation to reduce the allowable leak rate at normal operation from 0.35 gpm to . While it is not feasible to have a leak rate limit that ensures LBB for all tubes (1), the recommended limit will improve the detectability of degradations with lower than anticipated margins against tube rupture.

To provide a high level of confidence that tubes that may not exhibit LBB behavior at faulted load are removed from service, BC inspection will be performed for 100% of the TSP intersections where ODSCC has been diagnosed. Tubes with signal amplitude greater than a conservative allowable value (defined in section 5 as the tube voltage repair limit) will be repaired.

4.2 LEAKAGE AT POSTULATED ACCIDENT LOADS

4.2.1 Background

Standard Technical Specifications and many plant Technical Specifications limit the allowable primary-to-secondary leakage during normal operation through all steam generators not isolated from the reactor coolant system (RCS). The allowable limits are based on the following considerations:

- The total steam generator tube leakage limit of for all steam generators not isolated from RCS ensures that the dosage contribution from the tube leakage will be limited to a small fraction of 10CFR100 limits in the event of either a steam generator tube rupture or steam line break event. The limit is consistent with the assumptions used in the analysis of these accidents.

- The limitations on the specific activity of the primary coolant in the plant technical specifications ensure that the resulting two hour doses at the site boundary will not exceed an appropriately small fraction of 10 CFR 100 limits following a steam generator tube rupture in conjunction with an assumed steady state primary-to-secondary leakage rate .

- The leakage limit per steam generator is intended to ensure that steam generator tube integrity is maintained in the event of a main stream line rupture or under LOCA conditions. Permitting operation with leakage in excess of this limit increases the potential that steam generators may be vulnerable to tube rupture during a postulated steam line break event.

As indicated above, service experience with ODSCC at TSP intersections indicates that leakage during normal operation will be small. Further, inspection and repair limits developed in this document will result in limited ODSCC remaining in service. To provide additional assurance that cracks that might grow at a much greater rate than expected are detected, an operational leakage limit of is established. Consequently, ODSCC at TSP intersections will not challenge current Technical Specification leak rate limits. However, because the objective of this work is to justify the presence of through-wall and/or deep part through-wall cracks, it is recommended that the leakage at faulted load be assessed. The assessment would identify the leak rate that assures that the site boundary dose remains an acceptably small fraction of the 10CFR100 limits during postulated accidents. This leak rate is site-specific and, among other factors, will define the number and morphology of the cracks allowed to remain in the steam generator tubes subsequent to inspection.

The accidents that should be considered in calculation of accident leak rates are those that assume that primary-to-secondary leakage is combined with secondary steam release to the environment (e.g., steam line break (SLB), locked reactor coolant pump rotor, control rod ejection, loss of load/loss of off-site power). For many plants, the limiting event with regard to primary to secondary leakage will be SLB. For some plants, the locked rotor event may be more limiting depending upon the number of assumed fuel failures and the assumed iodine partition coefficient. To ensure that the most limiting condition is addressed relative to primary-to-secondary leakage, all accidents which combine leakage with steam release should be considered.*

This section outlines a method that can be used to assess the leak rate during a postulated SLB for any specified crack distribution of tubes with BC voltages above a threshold value.

4.2.2 Leak Rate Model

With simple through-wall crack geometries, the leak rate of a degraded tube can be correlated with the length of the axial through-wall crack. Even when the ODSCC is characterized by randomly distributed patterns of short axial cracks, the leakage

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*For the combined SSE + LOCA loading condition, the potential exists for yielding of the TSP in the vicinity of the wedge groups followed by deformation of some tubes. Tube deformation alone, although it may impact the steam generator cooling capability following a LOCA, does not affect the tube repair limits. On the other hand, this deformation may lead to opening of preexisting tight through-wall cracks, resulting in some primary-to-secondary leakage during the LOCA + SSE event.

behavior remains dominated by a single larger crack network. This has been confirmed by the leak rate measurements on model boiler test specimens (2).

However, it is not feasible to develop a correlation model between leak rate and crack length for ODSCC due to the crack morphology. This includes: (1) the shape factor (ratio of ID to OD lengths) of ODSCC is highly variable, (2) the crack faces are often constrained by unbroken thin ligaments, which prevent ODSCC from opening, and (3) the dominant leaking crack may result from linking of separate aligned components. Consequently, a correlation between leak rates (as measured on representative test specimens under SLB conditions) and the BC signal amplitude (voltage level, under well-defined calibration procedure) was developed.

Eddy-current signal amplitude is an indicator of the volume of "material loss" (or rather "material interaction" with EC flow) in that it reacts to crack depth, crack length, and crack width (or, more precisely, the extent of conductive contact between the mating faces of the crack). Because the signal and leak rate amplitudes basically react to the same factors, some correlation is to be expected and is observed from experimental data. When using the BC signal, a large scatter is observed (see appendix D) which is attributed mainly to the relatively large number of cracks in one TSP intersection, while the leak rate is usually governed by a single large crack.

The scatter between leak rate and EC voltage can be reduced by using an RPC probe because of the reduced integration effect of the RPC probe magnetic field. The drawback is the need for RPC inspection of the TSP intersections, although the number of RPC inspections can be kept within reasonable limits by use of a prior BC screening process (based on an amplitude threshold).

The proposed leak rate model is

$$Q = \qquad (4\text{-}1)$$

where
- Q = tube leak rate under faulted loads (l/hr),
- A = signal amplitude (V), and
- K and n = constants to be defined.

The model constants (K and n) are conservatively associated with an open crevice TSP condition. This also envelopes the case of a packed crevice if the relative tube to TSP displacement uncovers the crack(s) during an SLB accident. Preliminary values of K and n are given in appendix D.

4.2.3 Leak Rate Calculation - Probabilistic Approach

While in-service leakage can be expected to be negligible, the primary-to-secondary leak rate could be considerably increased under accident loads (such as an SLB accident) because of crack widening, washout of crud/impurities clogging the cracks, failure of the ligaments at the crack ID front or between the crack faces, and tube to TSP relative displacement.

The generic method proposed to predict the steam generator leak rate under postulated accident loads uses a probabilistic approach based on the leak rate model presented in paragraph 4.2.2. The probabilistic methodology is a Monte Carlo type evaluation, with repeated calculation of the base formula for every possible combination of values for the relevant parameters; for instance it assumes appropriate statistical distribution for: (1) NDE uncertainty on ECT signal amplitude, (2) signal amplitude growth until next scheduled inspection, and (3) coefficients in the leak rate model. Thus, an end-of-cycle amplitude population is assessed (accounting for uncertainties) for leakage potential. If the dose rate associated with the calculated leakage value exceeds an acceptably small percentage of the site-specific 10CFR100 dose limit, the repair limit needs to be reduced (i.e., more tubes are repaired) until compliance can be demonstrated. This methodology is further detailed in appendix D.

Alternatively, a conservative deterministic approach, which assumes that each crack leaks at a bounding limit, can be used as noted in paragraph 4.2.4, below.

4.2.4 Leak Rate Calculation - Alternative Deterministic Approach

An alternative deterministic approach can be used to provide a simplified and conservative evaluation of leak rate at faulted loads. This approach uses a conservative representation of the eddy-current voltage versus leak rate at SLB pressures experimental data. When RPC inspection data are to be used, the leak rate data is bound by the relationship (see appendix D):

$$Q = \qquad (4\text{-}2)$$

where

Q = total leak rate at SLB pressure, l/hr, and

V_{RPC} = expected RPC voltage for each tube that is to remain in service and has a BC voltage above the leakage threshold voltage.

If BC voltage is used in the leak rate assessment, the total leak rate at SLB pressure can be predicted from the relationship (see Appendix D)

$$Q = \qquad (4\text{-}3)$$

where

Q = total leak rate at SLB pressures, l/hr, and

V_{BC} = expected BC voltage for each tube that is to remain in service and has a BC voltage above the leakage threshold voltage.

For both cases, the expected voltage (V_{RPC} or V_{BC}) is the measured value increased by the NDE measurement error and the voltage growth rate per inspection interval, as defined in section 2. The dose rate associated with the total leak rate calculated from either Eq. 4-2 or 4-3 must be a small fraction of the site-specific 10CFR100 dose limits. If the leak rate is greater than the required value, tubes would be repaired selectively until the dose rate associated with the leakage determined from Eq. 4-2 or 4-3 is an acceptably small fraction of the site-specific 10CFR100 limits.

4.2.5 BC Voltage Leak Rate Threshold

Leak rate tests with tubes containing ODSCC suggest that there is a BC voltage below which leakage will be negligible under accident conditions. Further, available data show that this threshold is about (no leakage was observed for tubes where the BC voltage was less than (2)). Using the procedure presented in paragraph 5.2 this voltage is reduced to approximately after adjustment for NDE measurement error and possible ODSCC growth.

In the calculation of leak rates under accident loading conditions, it is reasonable to include a threshold below which no leak rate contribution need be considered. This simplifies the calculation and eliminates the need to include in the calculation BC signals below a certain value. Based on available data, it is suggested, at this time, that a BC voltage leak rate threshold of be used.

4.3 REFERENCES

1. PWR Steam Generator Tube Repair Limits - Technical Support Document for Expansion Zone PWSCC in Roll Transitions, Revision 1. Palo Alto, Calif.: Electric Power Research Institute, December 1991. NP-6864-L, Revision 1.

2. T. A. Pitterle et al. Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates - Data Base for Alternate Repair Limits - Volume 1: 7/8 Inch Diameter Tubing. Palo Alto, Calif.: Electric Power Research Institute. NP-7480-L, vol. 1. (to be issued in March 1992).

Section 5

TUBE REPAIR LIMITS

This section integrates the results from the prior three sections to develop the technical basis for tube repair limits for ODSCC at TSP intersections.

The tube repair limits are based on burst data for which axial ODSCC was the dominant degradation mechanism. The database includes pulled tube and laboratory degraded tubes with limited presence of IGA and circumferential branching of axial cracks. These repair limits are not applicable to dented tubes or tubes having NDE indications evaluated to be distinct circumferential cracks.

Currently, the tube repair criteria are applicable to tubing and degradation lengths up to approximately . Definition of acceptable voltage normalizations for tubing other than are planned but have not yet been determined. The degradation length restriction is imposed because all supporting test data are based on ODSCC generated within . It is expected, but not yet demonstrated, that the voltage limits will be acceptable for crack network lengths exceeding .

5.1 GENERAL APPROACH

The general approach taken to develop the tube repair limits included:

- Specifying a requirement to perform 100% BC inspection for all hot leg TSP intersections, and all cold leg intersections down to the lowest cold leg TSP where ODSCC indications have been diagnosed.
- Conservatively assuming open crevice conditions to maximize leakage potential.
- Specifying conservative burst correlations based on an uncovered tube span.
- Satisfying the R.G. 1.121 structural guidelines for tube burst margins by establishing a conservative structural limit on BC voltage amplitude that ensures three times normal operating pressure and 1.4 times faulted pressure differential for tube burst capability.
- Satisfying the final safety evaluation report requirements for allowable leakage under accident conditions by demonstrating that the dose rate

associated with potential leakage from tubes remaining in service is a small fraction of 10CFR100 limits.

- Including degradation growth and NDE measurement error in both the structural assessment and leakage analysis.

5.2 TUBE REPAIR CRITERION FOR MARGINS AGAINST TUBE BURST

The tube repair limits are developed conservatively to preclude free span tube burst. Tube repair criteria and example limits to provide R.G. 1.121 tube burst margins are developed in this section.

The combined field and laboratory burst test results are evaluated in section 3 to define a conservative correlation between BC voltage and burst pressure. This correlation was adjusted to account for operating temperature and minimum material properties. To establish the structural voltage limit (V_{SL}) that satisfies the R.G. 1.121 guidelines for margin against tube burst, the burst correlation must be evaluated at the higher of 1.4 faulted pressure and three times the normal operating pressure differential. The structural voltage limit then must be reduced to allow for NDE measurement error and ODSCC growth between inspections. These parameters are developed in section 2.

The NDE measurement errors described in section 2 generally can be applied consistent with the voltage normalization, frequency mix and probe wear limits presented in section 2. Information in appendix C and section 2 indicate that voltage growth rates expressed as a percent change in voltage amplitude per EFPY are essentially independent of voltage level. Due to plant variability in secondary chemistry and operating temperatures, percentage voltage growth rates for developing tube repair limits should be based on plant-specific operating experience as it becomes available.

The tube voltage repair limit that will provide margins against tube rupture consistent with R.G. 1.121 guidelines, including allowances for NDE measurement error and defect growth, can be expressed as follows:

$$= V_{SL} \qquad (5\text{-}1)$$

where:

V_{RL} = voltage limit for tube repair,

V_{NDE} = NDE voltage measurement error,

V_{CG} = voltage growth anticipated between inspections, and

V_{SL} = voltage structural limit from the burst pressure versus BC voltage correlation.

In section 2, the NDE voltage measurement error and voltage growth rate terms are presented as a percentage of measured BC voltage ($\%V_{NDE}$ and $\%V_{CG}$). Using V_{RL} as the maximum measured BC voltage to be left in service, V_{NDE} and V_{CG} in Eq. 5-1 are:

V_{NDE} =

V_{CG} =

Using these expressions for V_{NDE} and V_{CG}, Eq. (5-1) can be rewritten as

V_{RL} = (5-2)

Values for $\%V_{NDE}$ and $\%V_{CG}$ have been determined from available data (see section 2 and appendix C), and are $\%V_{NDE}$ = and $\%V_{CG}$ = . Substituting these values into Eq. 5-2 gives

V_{RL} = (5-3)

The BC voltage structural limit, V_{SL}, is found by utilizing the tube primary-to-secondary differential pressure times a safety factor as the burst pressure and the curve from figure 3.1 or from Eq. 3-1 which bounds the curve. V_{SL} is voltage associated with the larger of 3 times normal operating differential pressure and 1.4 times accident differential pressure. The BC voltage repair limit, V_{RL}, is found by substituting V_{SL} into Eq. 5-3.

Table 5-1 shows V_{RL} based on 3 times normal operating differential pressures of 1300, 1450 and 1550 psi. These pressures span the range operating differential pressures for steam generators now in service and when multiplied by 3 are all greater than 1.4 times a typical accident peak differential pressure of 2650 psi.

Table 5-1

EXAMPLE OF TUBE REPAIR VOLTAGE LIMITS TO SATISFY STRUCTURAL REQUIREMENTS

5.3 ACCIDENT LEAKAGE EVALUATION

It is required that a leakage analysis be performed following each inspection to demonstrate that the dose rate from potential leakage during postulated accidents for tubes left in service is a small fraction of 10CFR100 limits. The leakage models described in paragraph 4.2 can be applied for this assessment.

If it is found that the potential accident leakage for degraded intersection planned to be left in service exceeds acceptable levels, then additional tubes would be repaired to reduce predicted accident leakage to acceptable levels.

5.4 OPERATING LEAKAGE LIMIT

The operating leak rate of as discussed in paragraph 4.1 will be implemented in conjunction with application of the tube repair limit. The tube repair limit coupled with 100% inspection at affected TSP locations provide the principal protection against the potential for tube rupture. In addition, the limit provides the capability for detecting ODSCC that might grow at a much greater rate than expected and thus provides additional protection against exceeding accident leakage limits.

5.5 SUPPLEMENTAL INSPECTIONS

An RPC inspection of some tubes with BC voltage less than the tube repair limit but greater than a BC voltage leak rate threshold (see paragraph 4.2.5) should be performed to establish that the principal indications can be characterized as ODSCC. If an RPC voltage versus leak rate correlation is to be used for predicting accident leak rates, then all tubes with BC voltage less than the tube repair limit but above a threshold voltage value should be RPC inspected. A leak rate threshold value is currently recommended as accident leakage is expected to be negligible below this value (see paragraph 4.2.5).

5.6 SUMMARY OF TUBE REPAIR LIMITS

As developed in the sections above, the repair criteria for ODSCC at TSPs can be summarized as follows:

5.6.1 Inspection Requirements

A 100% BC inspection shall be performed for all hot leg TSP intersections, and all cold leg intersection down to the lowest cold leg TSP where ODSCC indications have been detected. Supplemental RPC inspections shall be performed to the extent required for either ODSCC confirmation or leak rate correlation.

5.6.2 Tube Repair Criterion

The plant-specific voltage limit for tube repair, V_{RL}, shall be determined from Eq. 5-3. Tubes with BC voltages greater than V_{RL} should be repaired.

5.6.3 Accident Leakage Control

Predicted accident leak rates from tubes left in service must be less than the plant specific allowable value for each steam generator. Leak rates may be based on correlations with either RPC or BC voltages (see paragraph 4.2.4).

5.6.4 Operating Leakage Limits

Plant shutdown will be implemented if normal operating leakage exceeds per steam generator.

Appendix A

PLANT EXPERIENCES WITH CORROSION DEGRADATION ON THE TUBE OUTER DIAMETER AT TUBE SUPPORTS

A.1 NATURE OF CRACKING

Examination of tubes removed from service indicates corrosion degradation initiating on the tube outer surface at tube supports can be placed into one of three categories (1):

1. Stress corrosion cracking (SCC), where a distinct axial or circumferential crack front first initiates on the tube outer surface and subsequently grows radially through the tube thickness by intergranular degradation. Typically, SCC is short, axially oriented, and can be through-wall. Circumferential branching of axial cracks also has been observed.

2. Intergranular attack (IGA), where a network of intergranular degradation forms over an area on the tube outer surface and subsequently propagates radially through the tube thickness by intergranular degradation. Recent experience indicates that extensive IGA can occur at tube/TSP intersections.

3. Combinations of SCC and IGA.

The discussion in this appendix is applicable for tubes where axial ODSCC is the dominant degradation mechanism. The repair limits described in the document are not applicable to dented tubes, tubes having extensive IGA (e.g., greater than about of the wall thickness), or tubes having nondestructive examination (NDE) indications evaluated to be distinct circumferential cracks.

A.2 OVERVIEW OF U.S. PLANT CONDITIONS AND ODSCC EXPERIENCE

ODSCC was first diagnosed in a U.S. plant about 1972 (2). The number of plants reporting ODSCC degradation has increased significantly in the last several years, and as of December 1991, 26 U.S. plants have reported ODSCC at tube/TSP intersections. The number of repaired tubes in these plants range from a few tubes to more than a thousand tubes. No leakage or tube rupture has resulted from only ODSCC at tube supports in U.S. plants. However, one tube leak has occurred and has been attributed to ODSCC in combination with denting. With one exception, ODSCC has been confined to the region within the TSP.

There are a variety of tube/tube support intersection designs in U.S. PWRs. B&W-designed units have carbon steel support plates with broached trefoil shape tube supports and high-temperature, mill-annealed alloy 600 tubes. Tubes in B&W generators are sensitized from stress relief of the steam generator.

CE-designed units have either egg crate or a combination of egg crate and drilled hole tube supports and high-temperature, mill-annealed alloy 600 tubes. Early CE units have carbon steel tube supports while later designs used stainless steel.

Most Westinghouse-designed plants have carbon steel TSPs with drilled holes and low-temperature, mill-annealed alloy 600 tubes. Recent Westinghouse designs used alloy 600 thermally treated tubes (in a few cases, alloy 690 has been used), and stainless steel tube supports with broached quatrefoil shape designs.

Currently, U.S. experience indicates that all reported ODSCC incidents have occurred in plants with mill-annealed alloy 600 tubes and carbon steel tube supports. Thermally treated alloy 600 tubing has been used recently to reduce the susceptibility to corrosion attack, and trefoil or quatrefoil tube support designs are used to mitigate crevice conditions that may lead to ODSCC.

Because ODSCC often has been attributed to alkaline concentrations in crevices, secondary side on-line boric acid treatment has been implemented to help reduce the potential for ODSCC, although some researchers have suggested that acid concentrations within the crevices can produce corrosion degradation (1). Currently, 21 U.S. plants have boric acid treatment; many of these plants instituted boric acid treatment prior to reporting ODSCC to reduce the incidence of denting.

Table A-1 provides a summary of the time when ODSCC was first reported, and the cumulative number of tubes repaired due to ODSCC degradation. The table also identifies the tube/tube support intersection design and, where applicable, the date boric acid treatment was implemented (2-4).

A.3 OVERVIEW OF INTERNATIONAL PLANT CONDITIONS AND ODSCC EXPERIENCE

Currently, various ODSCC repair criteria are being used or are under development internationally (5). In France, current repair criteria (as of September 1990) do not require degradation of any depth at TSPs to be repaired. The main bases for these criteria are that tests have shown that tubes with severe simulated secondary side degradations at TSPs do not have reduced tube burst strength, and that the tubes burst in free span areas.

Table A

SUMMARY (,UBE/TSP CONDITIONS AND EXPERIENCE WITH ODSCC AT TSPs

Table A-1
(Continued)

Table A-1
(Continued)

Table A-1
(Continued)

In Spain and Sweden, current repair criteria (as of September 1990) for degradation at TSPs are the same as for free span defects, i.e., of tube wall in Spain and in Sweden. However, in both of these countries, alternative repair criteria have been developed and proposed to safety authorities. These alternative repair criteria justify leaving degradations up to depth (in Sweden and Spain, respectively) at TSPs without repair. The values provide a margin against leakage and include allowances for degradation growth and inspection error. In Belgium, a repair limit for tubes with ODSCC at tube supports has recently been developed and implemented.

The severity of occurrence of ODSCC at tube supports in international plants varies. However, the numbers of units affected, the numbers of tubes affected, and the degradation size in individual tubes are increasing generally. As of December 1991, ODSCC at tube supports has been reported at 25 plants.

In some countries, ODSCC at tube supports has been a factor in recent decisions regarding steam generator strategic planning (5, 6). In Spain, ODSCC at tube supports was a factor in a recent decision to initiate replacements of steam generators at four units starting in 1994 (5). In addition, ODSCC has resulted in over of the total number of tubes being affected at three Japanese units (6). Boric acid treatment has been introduced at several plants in Spain and Japan to reduce the rate of ODSCC (4). In Sweden, the operating temperature of one unit has been reduced to decrease the rate of ODSCC and primary water stress corrosion cracking (5).

Examination of pulled tubes has shown that ODSCC at tube supports mainly consists of axial cracks. The ODSCC have almost always been located within the edges of the tube supports. The one known exception occurred at a flow distribution baffle, not a tube support, where sludge was present on top of the baffle (5).

Early international plant designs have mill-annealed (either high- or low-temperature) alloy 600 tubes and (generally carbon steel) support plates with drilled holes. Recent designs used alloy 600 thermally treated tubes (in some cases, alloy 690 has been used) and stainless steel tube support plates with (in some cases) broached quatrefoil shape designs. Current international experience indicates that all reported ODSCC incidents have occurred in plants with mill-annealed (either high- or low-temperature) alloy 600 tubes and support plates with drilled holes. Generally, the support plates have been carbon steel; however, in one case, the support plate was stainless steel.

Table A-2 provides a summary of the international experience, including the time when ODSCC was first reported, and the cumulative number of tubes repaired due to ODSCC degradation. The table also identifies the tube/tube support intersection design and, where applicable, the date boric acid treatment was implemented (2-4, 7).

Table A-2

SUMMARY OF INTERNATIONAL TUBE/TSP CONDITIONS AND EXPERIENCE WITH ODSCC AT TSPs

Table A-2
(Continued)

Table A-2
(Continued)

A.4 DEGRADATION TRENDS INDCIATED BY U.S. AND INTERNATIONAL EXPERIENCE

Evaluations of the service experience presented in tables A-1 and A-2 indicate that while there is significant scatter, there appears to be a distinct trend toward an increasing number of degraded tubes with increasing temperature and time at temperature.

Generally, the overall trends indicate long times to ODSCC degradation at hot leg temperatures less than about . Between , significant numbers of degraded tubes can occur from ODSCC after about of operation. At temperatures at or above about , significant ODSCC can occur within relatively few years of operation. These general trends can be affected on a plant-specific basis by factors other than time and temperature, such as secondary side chemistry and materials.

Evaluations of laboratory data and service trends indicate that boric acid treatment can be effective in mitigating ODSCC at tube supports in areas easily accessible to the inhibitor (4, 6). Limited service data are available, however, and more service experience seems to be required before the effect of boric acid treatment can be thoroughly assessed.

A.5 REFERENCES

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Appendix B

BOBBY COIL EDDY-CURRENT DATA ACQUISITION AND ANALYSIS GUIDELINES

B.1 SCOPE

These guidelines provide the direction in applying the ODSCC alternate repair limit as described in the main document. Utility/owners using these guidelines should ensure that the methods and techniques detailed in this appendix are incorporated in the applicable inspection/analysis procedures.

B.2 APPLICABILITY

These guidelines define specific acquisition and analysis parameters and methods to be used for the inspection of steam generator tubing. The use of these guidelines alone does not imply that the voltage repair limit for ODSCC at tube support plates can be used. It is the responsibility of the utility/owner to ensure that the specific design and operating parameters of the steam generators to be inspected are supported by the main document.

B.2.1 Tubing

These guidelines apply to alloy 600 mill-annealed or thermally treated tubing with

B.2.2 Probes

To ensure consistency with laboratory data, probes with the following parameters shall be used:

1. Differential bobbin type.

2. Outer diameter.

3. coil grooves with spacing between adjacent edges.

4. Nonmagnetic bias.

5. The design shall incorporate centering features that provide for minimum probe wobble and offset.

B.2.3 Conditions

Tube support plate intersections shall be free of significant copper deposits, denting and other anomalies that influence the signal to be used for amplitude and phase (if applicable) measurements.

B.3 ACQUISITION PARAMETERS

The following parameters apply to data acquisition and should be incorporated in the applicable inspection procedures to supplement, not necessarily replace, those parameters normally used.

B.3.1 Test Frequencies

This technique requires the use of test frequencies using the differential mode. It is recommended that the absolute mode also be used and the data recorded. Additionally, a low-frequency channel should be recorded to provide a positive means to verify tube support plate edge detection for flaw locating purposes.

B.3.2 Digitizing Rate

A minimum digitizing rate on should be used. Combinations of probe speeds and instrument sample rates should be chosen such that:

$$\frac{\text{Sample Rate (Samples/Sec.)}}{\text{Probe Speed (in/sec)}} \geq$$

B.3.3 Spans and Rotations

Spans and rotations can be set at the discretion of the user and/or in accordance with applicable procedures

B.3.4 Mixes

A differential mix should be established with as the primary frequency and as the secondary frequency and suppression of the tube support plate simulation performed. If probe wear assessment is to be performed during acquisition, this channel should be used to assess changes in signal amplitude.

B.4 TUBE STANDARDS

The following calibration standards shall be used. In most cases, the requirements for the ASME standard will have been established through procedures developed to support required in-service inspections.

B.4.1 ASME Standard

Through-Wall Hole

Flat Bottom Hole, through from O.D.

Flat Bottom Hole, through from O.D.

Flat Bottom Holes, through from O.D. spaced 90 degrees apart in a single plane around the tube circumference.

B.4.2 A Simulated Tube Support Plate Standard Manufactured From A-285-Grade C Carbon Steel or Equivalent

B.4.3 An Optional Probe Wear Standard for Monitoring the Degradation of Probe Centering Devices Leading to Off-Center Coil Positioning and Potentially, Variations in Flaw Amplitude Responses

This standard shall be built from tubing of the same material specification and same nominal size as to be inspected in the steam generator. This standard shall include through-wall holes, , spaced apart circumferentially around the tube with an axial spacing such that signals can be clearly distinguished from one another (see paragraph B.8)

B.5 ANALYSIS PARAMETERS

This section discusses methodology for establishing data analysis variables such as spans, rotations, mixes, voltage scales, and calibration curves. Although indicated depth measurement is not required to support this alternative repair criteria, the methodology for establishing the calibration curves is presented. The use of these curves is recommended for consistency in reporting and to provide compatibility of results with subsequent inspections of the same steam generator and for comparison with other steam generators and/or plants.

Should these techniques differ substantially from established procedures for required in-service inspections and the user wishes to perform these simultaneously, then it is recommended that additional differential mix channels be established to provide voltage scales and calibration curves as required herein.

B.5.1 400 kHz Differential Channel

5.1.1 Rotation. The signal from the through-wall hole should be set to with the initial signal excursion down and to the right during probe withdrawal.

B.5.1.2 <u>Voltage Scale</u>. The peak-to-peak signal amplitude of the signal from the O.D. flaws should be set to

B.5.1.3 <u>Calibration Curve</u>. Use the established 4.1 curve that fits phase angle values to indicated depth values, respectively.

B.5.2 Differential Mix Channel

B.5.2.1 <u>Rotation</u>. Set the signal from probe motion to be horizontal with the initial excursion of the through-wall hole signal going down and to the right during probe withdrawal.

B.5.2.2 <u>Voltage Scale</u>. The peak to peak signal amplitude of the signal from the O.D. flaws shall be set to

B.5.2.3 <u>Calibration Curve</u>. Establish a curve using measured signal phase angles in combination with the "as-built" flaw depths for the flaws on the calibration standard.

B.6 REPORTING REQUIREMENTS

The reporting requirements recommended herein are in addition to any other reporting requirements specified by the user.

B.6.1 Minimum Requirements

At a minimum, mix signals at the tube support plate intersections that are both free of influence of denting, significant copper deposits or other anomalies and whose peak to peak signal amplitude exceeds , or revised leakage threshold, must be reported. Smaller amplitude signals should also be reported for historical purposes and to provide an assessment of the overall condition of the steam generator(s). This minimum amplitude can be set at the discretion of the user and is suggested to be between

B.6.2 For each reported indication, the following information should be recorded.

Tube Identification	(Row, Col)
Signal Amplitude	(Volts)
Signal Phase Angle	(Deg)
Indicated Depth	(%)*
Test Channel	(CH#)
Axial Position in Tube	(Location)
Extent of Test	(Extent)

*It is recommended that an indicated depth be reported rather than some letter code. While these measurements are not currently required to meet the alternative repair criteria, this information may be found useful in the future.

B.7 ANALYSIS METHODOLOGY

Bobbin coil indications at support plates attributable to ODSCC are quantified using the Mix 1 data channel. This is illustrated with the example shown in figure B-1. The (Channel 1) primary analysis channel can be used to locate the indication of interest within the support plate signal. The peak-to-peak voltage extreme for the ODSCC indications are initially identified using Channel 1 as shown in the upper portion of the figure; one then switches to Mix 1 (shown in the lower part of the figure) and records the Mix 1 channel signal amplitude. This voltage is then entered as the analysis of record for comparison with the repair limit voltage.

B.8 PROBE WEAR STANDARD

A calibration standard has been designed to monitor for probe wear. This standard is shown in figure B-2 and consists of through-wall hole of consistent diameter staggered axially at intervals around the tube circumference. During steam generator examination, the bobbin coil probe is inserted into the wear monitoring standard; the amplitude response from each of the four holes is initially determined and compared on an individual basis with subsequent measurements. Individual signal amplitudes or voltages from the individual holes—compared with their previous amplitudes—must remain within of each other for an acceptable probe wear condition. If this condition is not satisfied, then the probe must be replaced.

Figure B-1. ODSCC at TSP-Bobbin Coil Amplitude Analysis

Figure B-2. Probe Wear Calibration Standard

Appendix C

ODSCC GROWTH RATE

This section discusses the growth rate of ODSCC indications at tube support plates. Data from one European and three domestic units were reviewed to assess amplitude growth from cycle to cycle. The French data suggest that the percent growth in amplitude is independent of the initial amplitudes. However, the domestic plants clearly show decreasing percent growth with increasing initial amplitude. The data are discussed below in further detail.

C.1 FARLEY UNIT 1

The scheduled program of EC inspections performed at Farley Unit 1 in the 9th refueling outage (October 1989) included full-length bobbin probing of 100% of the tubes in service. Bobbin EC indications observed at the TSPs were distributed in a random manner across the tube bundle. Approximately equal numbers were found in each steam generator— in A, B, and C, respectively. Of these signals, almost all were reported as distorted indications, were retested with RPC probes. Histograms depicting the distribution of signal amplitudes for each S/G are given in Figure C-1; Figure C-2 illustrates the axial distribution of the indications. It should be noted that cold leg indications found on peripheral tubes at lower TSP elevations many result from a wastage phenomenon.

Reevaluation of the 1988 inspection records indicated very little progression—less than through-wall depth increase and amplitude increase during Cycle 9 operation; in fact, review of 1986 inspection tapes for these indications shows that very little change is evident over the two operating cycles (3 years). By examining the voltage levels (amplitudes) of such signals reported in both years, i.e., 4/88 and 10/89, the average change in amplitude can be determined: this result, as indicated above, was . The dependence of voltage change on observed amplitude is displayed in Figure C-3 for the data recorded in both the 1988 and 1989 inspections.

Figure C-1. Distorted Indication Signal Amplitudes in Farley-1 S/Gs (October 1989)

Figure C-2. Axial Distribution of Distorted Indication Signals in Farley-1 (October 1989)

Figure C-3. Support Plate Indication Progression in Farley-1 S/Gs

C.2 FARLEY UNIT 2

During the Cycle 7 refueling outage of Farley Unit 2 in Octo in probe EC testing was performed full length on 100% of the tubes ir dications depth at TSP locations as well as almost all the dist s are reported on the hot leg side of the tube bundle. 1 jected to RPC testing to assist in characterizing the extent and nature of t adation. Though lot leg indications reprobed with the RPC were verified to exhibit signs of degradation, the bobbin amplitude of these signals was below for at least of them. Figure C-4 summarizes the axial distribution of the TSP indications.

A reevaluation of the prior EC tape records has been performed beginning with each indication reported in the 10/90 inspection, working back in time for these indications while adding in the previously plugged tubes. All these records were analyzed using the EC interpretation guidelines employed in the field in 10/90, so that a normalized or rationalized data base could be constructed. Growth rates were developed over four operating cycles from 1985 to 1990. The phase angle changes for the four cycles are displayed in Figure C-5, from which it can be seen that only a light negative shift in average phase angle has occurred since 1985. For conservatism, summing only the negative average phase shifts since 1985 yields over four cycles, or approximately total growth in equivalent depth of tube wall penetration over that 4-cycle, 5-year time period.

Figure C-6 displays the frequency distribution of voltage levels for all TSP indications in Farley-2. Figure C-7 presents the observed amplitude changes from 4/89 to 10/90 as a function of the 1989 signal amplitude. It is apparent that the largest voltage increases during Cycle 7 are associated with the lower amplitude signals present at the start of the cycle. Figure C-8 shows the distribution of voltage changes per EFPY for the last four operating cycles. Estimation of the growth in signal amplitudes in the three S/Gs (A, B, and C) were found to have changed by , respectively. The composite changes for the 3 S/Gs combined was in amplitude, based on evaluation of the signals.

C.3 KEWAUNEE

A review of the past eddy-current results from Kewaunee steam generator tubes was conducted to assess the progression of ODSCC in the Kewaunee S/Gs. The tubes plugged during the 1990 outage formed the sample for this reevaluation which was performed in the lab using data from eddy-current tests conducted in the field. For these tubes, eddy-current test results for outages in 1987 through 1990 were evaluated, unless the data was not available. The OD indications were present both in the hot leg (most tubes) and in the cold leg. Figure C-9 shows a frequency distribution of the TSP location of indications in S/G-A and S/G-B.

Figure C-4. Axial Distribution of TSP Indications in Farley-2 S/Gs (October 1990)

Figure C-5. TSP Indication (Phase Angle) Evolution in Farley-2

Figure C-6. Signal Amplitudes in Farley-2 S/Gs

Figure C-7. Support Plate Indication Progression in Farley-2 S/Gs

Figure C-8. TSP Indication (Voltage) in Farley-2

Figure C-9. Kewaunee S/G-A, B Locatio.ı (TSP) of Indications

A frequency distribution of bobbin amplitudes from the 1990 inspection is displayed in figure C-10. It may be noted that over of the indications in each S/G had amplitudes below . The indications ranged from . Growth in amplitude for each year from 1987 through 1990 were calculated only for the cases where data were available for at least two years; i.e., no assumption about the depth or signal voltage for prior years was made if such data was not available.

Figure C-11 shows a plot of the growth in amplitude from 1989 to 1990 as a function of the 1989 amplitude for the indications. The growth in S/G-A ranged from and in S/G-B from . The negative growths (and possibly some of the high positive growth values) result from the uncertainties in the eddy current inspection and data evaluation. Overall, the distribution of amplitudes and their growths are similar in the two S/Gs. A frequency distribution of the voltage growth between 1989 and 1990 in both S/Gs is shown in figure C-12. Please note that the mode (interval of highest frequency) is near .

The average growth in amplitude for all indications was calculated for each of the three cycles for both S/Gs. This is plotted as a trend curve for each S/G in figure C-13. The number of indications used in the calculation of the average is also shown in the figure, next to each point. In S/G-A, the average growth in amplitude from 1989 to 1990 was only . The growths during the prior two cycles in that generator were . The average growth rates in S/G-B during the last three cycles were , respectively.

The standard deviation associated with the growths in amplitude during the last cycle was for each of the two S/Gs. As discussed before, part of the scatter results from the uncertainty in the eddy current tests and the data evaluation and the remaining from the variability in growth between indications. Note that the average growth from 1987 to 1988 in S/G-B was calculated from only four (4) data points. The accuracy of the data is not high enough to pay attention to the small differences in the averages between cycles and between S/Gs; nor to the slopes of the trend lines. These differences may be attributable to randomness of the data. Overall, it may be noted that the average amplitude growths in each S/G is low, being in the range of per cycle.

C-4 EUROPEAN DATA

The above field inspection results obtained from domestic plants apply essentially the same voltage calibration standards and comparable frequency mixes for indications at TSPs. The operating experience data base can be increased substantially by including plant data from European plants that utilize different voltage calibrations and absolute frequencies for TSP indications.

Figure C-10. Kewaunee S/G-A, B Bobbin Voltage Distribution

Figure C-11. Kewaunee Bobbin Amplitude Growth Rate

Figure C-12. Kewaunee Bobbin Voltage Growth Distribution

Figure C-13. Kewaunee Bobbin Amplitude Growth Trend

To compare the domestic plant data with these European data, an order of magnitude voltage adjustment is necessary to make the European data roughly comparable to the other data in this report. However, any conversion factor is disputable because it depends on the varying probe and crack responses to different frequencies as well as procedural/environmental conditions and thus may vary from case to case. Recognizing the uncertainties in the voltage conversion factors, comparisons with the European data are particularly valuable for the following comparisons:

- Trends in indications and growth with time for equivalent voltages much higher than available in domestic plants which have applied 40% depth criteria for tube plugging. None of the European data at higher equivalent voltages have had identifiable operating leakage for ODSCC at TSPs.

- Percentage growth in voltage from European plants can be used to estimate growth rates for equivalent voltages much higher than that available in domestic plants.

In France and Belgium, a differential inspection is most commonly applied. Voltage renormalization was evaluated by fabricating the French and Belgian standards and comparing their procedure with that of this report. Results of this study are given in table C-1. The U.S.-to-French voltage ratio was further evaluated using an Intercontrole probe commonly used by EdF (Electricité de France) and applying this probe, as well as a domestic probe to the calibration standard and to several model boiler specimens with ODSCC. The results of this evaluation are given in figure C-14, where the voltage ratio between the European and U.S. procedures are plotted as a function of phase angle determined at (French procedure). These results show a consistent ratio (within) at any given phase angle for both probes and between calibration standards and ODSCC specimens. In figure C-14, phase angles of and correspond to ASME hole depths, respectively. Voltage renormalization was performed using the phase angle (related to depth of tube wall penetration) dependent normalization factor shown in figure C-14 so that the European data can be compared with the eddy-current data from the domestic plants.

Data for ODSCC at TSPs for French unit Fessenheim-1, S/G-1 is available for four successive inspections with no tube plugging as shown in figure C-15. The upper figure shows the number of indications versus voltage amplitude (French voltage normalization process) while the lower figure shows the percentage distribution of indications within each outage. Without tube plugging to eliminate the larger indications, the distribution becomes more heavily weighted at the larger indications with increasing operating time. It can be estimated that the largest indications in figure C-15 would be about if adjusted to the U.S. voltage normalization of this report.

Table C-1

COMPARISONS of VOLTAGE AMPLITUDES BETWEEN
U.S.-ASME AND EUROPEAN STANDARDS

Figure C-14. Voltage Ratios Between U.S. and French Calibration Procedures Using U.S and French Bobbin Coil Probes

Figure C-15. Distribution of TSP Indications for Fessenheim-1 (1986-1990)

Figure C-16 shows growth rate data for Fessenheim Unit-1 both as voltage amplitude and percentage growth as a function of voltage amplitude. The data of figure C-16 tend to indicate percentage growth rates are not a significant function of absolute voltage amplitude. As generally expected, the spread in the data at low amplitudes is greater than for larger voltages due to the greater influence of voltage uncertainties and measurement repeatability at low amplitudes. Figures C-17 and C-18 compare the percentage growth rates per year between domestic plants Farley and Kewaunee with that for Fessenheim. Figure C-17 shows the individual data points; the bottom figure is a magnification of the range, up to voltage growth from the upper figure. Figure C-18 compares the average growth rates and standard deviations between domestic and French plants. The averages are displayed for different ranges of the initial amplitude. The first range is , the second range is , and the third is for initial amplitudes greater than . In the case of the U.S. plants, there is very little data above initial amplitude; hence, such data is included in the second range. The French data (Fessenheim-1) indicate percent growth rates nearly independent of initial amplitude, whereas the domestic units display percent growth rates decreasing with increasing amplitude.

C.5 CONCLUSION

The domestic plants dominate the growth rate data of figures C-17 and C-18 for low amplitudes, whereas the data for larger amplitudes is from the European plant. The average percent growth rate for all data in figure C-17 is about with a standard deviation of . In this calculation, the negative growth rates (see figure C-17) were conservatively treated as zero growth rates. Ignoring the negative growth rates biases the average growth by ignoring negative random fluctuations. Part of the apparently larger number of negative voltage growth rates for the domestic data may result from variations in calibration standards for the depth normalization which may be more sensitive to fabrication tolerances than the depth normalization standards employed for the European data.

The results indicate that percentage growth rates are comparable between domestic and European plants. The average growth rate of amplitude per fuel cycle is about and appears to be essentially independent of prior cycle voltage amplitude.

Figure C-16. TSP Indication Voltage Growth Rates for Fessenheim-1

Figure C-17. Percent Voltage Growth Rates for Kewaunee, Farley-1, and Fessenheim-1

Figure C-18. Average Percent Voltage Growth Rates for Kewaunee, Farley-1, Farley-2, and Fessenheim-1

Appendix D

ANALYSIS METHOD FOR LEAK RATE CALCULATION

D.1 INTRODUCTION

This appendix describes a methodology for predicting the primary-to-secondary leakage during postulated faulted loads in a steam generator with axial through-wall ODSCC at the tube support plates intersections. The approach uses probabilistic (Monte Carlo) methods combined with a simple leak rate model (correlation with ECT signal amplitude). An alternate deterministic approach is also presented.

D.2 BASE LEAK RATE MODEL

The leak rate model proposed for axial ODSCC at tube support plate intersections is

Q =

where

Q is the leak rate (volumetric) under accident conditions such as steam line break (SLB)

A is the signal amplitude from a bobbin coil (BC) or rotating pancake coil (RPC) eddy-current probe (as used by a well defined inspection procedure)

K and n are coefficients the value of which may depend on both deterministic or stochastic factors.

Examples of factors affecting the coefficient K are:

- Deterministic: The calibration procedure used for the ECT probe; for instance a different calibration standard will result in an offset of the straight line correlating Q to A in a log-log diagram.
- Stochastic: The specific morphology of the cracked section, the make and wear of the probe, the fabrication tolerance in the calibration setup; also the basic uncertainty in the correlation (deviation from the power law).

  Some of those factors are in fact deterministic but appear stochastic because they are out of reasonable human control. The stochastic factors generate the scatter band of actual data across the average trend defined by the model.

D.3 LEAK RATE MODEL

The present structure of the model is essentially derived from the leak rate measurements performed under representative SLB conditions on pulled tubes and test specimens with ODSCC at simulated TSPs obtained by operation in "model boilers" (1).

The model boiler database is conservatively restricted to open crevice conditions; however to increase the number of data points, consideration is also given to results produced under normal operating (NOP) leakage conditions.

All data are summarized in table D-1, along with additional relevant information on cracking morphology.

Four subsets of data points have been statistically analyzed for correlation between leak rate (under either NOP or SLB conditions) and ECT signal amplitude (either by BC or RPC).

For each of these subsets, the input data points are listed in tables D-2 through D-5 and plotted in a log-log diagram as shown in figures D-1 through D-4.

Data points with zero leakage have been located arbitrarily at an insignificant level of ; these data points include cracks demonstrated to be through-wall or very deep ( ) by destructive examination, but also some cracks assumed to have a similar depth range while no verification is (yet) available. It is conservative to include these data points as equivalent to small leakers; however, to avoid an overconservative bias of the database, it is recommended that any such data points (as produced by future testing programs) be limited to crack depths in excess of .

For each of the four subsets of data points, a statistical analysis has been performed to provide a straight line least square fit.

This corresponds to a power law correlation defined by

$Q =$

when

Q = leak rate (in l/hr)
A = signal amplitude (in V)
n = slope of regression line
$\log K$ = intercept of regression line

While other correlation assumptions could be made, the "power law" has been selected for its simplicity.

The detailed results of the statistical analysis are given in table D-6.

- Slope with associated standard error
- Intercept with associated standard error.
- Standard error of estimate.
- Correlation coefficient.

The following observations can be made:

- The data scatter is significantly larger for BC than for RPC data (larger standard error of estimate and lower correlation coefficient). This is assumed to result from the fact that, while leak rate is dominated by a single larger flaw, the BC signal amplitude may integrate several more indications in the same TSP intersection.
- The slope is significant larger for SLB than for NOP conditions. This is assumed to result from the fact that, for increasing signal amplitude, the average ratio of SLB to NOP leak rate should increase because more (plastic) deformation and/or ligament failure is likely to occur.

Thus, the statistical analysis for the four subsets of data points shows a consistent overall picture meeting the logical expectations. This provides added confidence in the selected model.

Only the SLB leak rates are to be considered for practical purpose. The following average correlations are assumed for performing a probabilistic assessment as described in section D-4:

- On basis of BC inspection data:

  Q =

- On basis of RPC inspection data:

  Q =

where

Q = leak rate (in l/hr) under SLB conditions

A = signal amplitude (in V), under a well-defined examination procedure (see appendix B for the case of BC inspection; for the case of RPC inspection, A is the maximum amplitude from any signal in the same TSP intersection).

The various plots indicate the limits for the relevant population on basis of a t distribution (applicable to small samples); the upper limit is also a upper bound.

These limits are generated as curved lines in the log-log diagram, but can be reasonably approximated by straight lines over the range of practical interest. Thus, upper bounds are given by:

Q_m = for BC data

Q_m = for RPC data

D.4 LEAK RATE CALCULATION METHODOLOGY

The structural repair limit together with the reduced in-service allowable leak rate remove the possibility of leaving large defects in-service and assure that the allowable leak rate under faulted loads will not be exceeded by a single (or a few) leaking tubes. The cumulated leakage from a large number of small leakers remains to be addressed, taking into account the uncertainties of all parameters participating in the selected leak rate model. This is best achieved by a probabilistic methodology, providing a stochastic combination of the statistical distributions assumed for each of the relevant parameters.

Also, the amplitude A, in the leak rate model, is that expected at the end of the next operating cycle. To generate a predicted end-of-cycle (EOC) distribution curve of the signal amplitude, a "propagation model" is needed. Information is available that indicates amplitude growth may be proportional to initial amplitude (see section 2 and appendix C).

The overall structure of the recommended probabilistic approach can thus be built in accordance with the flow diagram illustrated by figure D-5.

The plant-specific inspection data generate a beginning-of-cycle (BOC) distribution curve of the RPC signal amplitude, cut-off at the assumed plugging limit. This distribution is transformed by the propagation model (amplitude growth), and the distribution curve of NDE voltage measurement uncertainty allows to build the desired distribution curve of EOC signal amplitude. Combination is then made with the distribution curve of the leak rate model coefficients K and/or n (only a distribution curve of K is illustrated in figure D-4) to generate the distribution curve of tube leak rate.

The latter curve is then combined with the number of leakers to generate the final distribution curve of (integrated) steam generator leak rate, from which a value can be selected, at any predefined confidence level, to be compared with the allowable leak rate at faulted loads. Should the result not be acceptable, the whole process is iterated with a lower plugging limit, until compliance is achieved.

The probabilistic methodology, outlined hereabove, is quite similar to the one proposed for the equivalent problem of EZ-PWSCC in roll transitions (2); it can be solved by a Monte Carlo type algorithm (in the same way as used by the available LABOLEAK software program) as soon as the appropriate leak rate and propagation models are substantiated by a sufficiently large database.

D.5 ALTERNATE DETERMINISTIC APPROACH

An alternate deterministic approach can be followed, on a conservative basis, using either RPC or BC signal amplitude data.

D.5.1 Use of RPC Data

The upper bound correlation established under paragraph D-3 can be used in a deterministic way.

The requested RPC data may be limited to those TSP intersections with a BC signal amplitude in excess of , as it has been shown (1) that below this threshold no significant SLB leakage should be expected at the end of the next cycle.

All such RPC data are to be increased by:

- The NDE voltage measurement uncertainty.
- The voltage growth rate per inspection interval as defined in section 2.

A conservative upper bound evaluation of SLB leak rate is then obtained by

$$Q =$$

D.5.2 Use of BC Data

The upper bound correlation established under paragraph D-3 can be used in a deterministic way.

The requested BC data may be limited to those in excess of , as it has been shown (1) that below this threshold no significant SLB leakage should be expected at the end of the next cycle.

All such BC data are to be increased by:

- The NDE voltage measurement uncertainty.
- The voltage growth rate per inspection interval as defined in section 2.

A conservative upper bound evaluation of SLB leak rate is then obtained by:

Q =

D.6 REFERENCES

1. T. A. Pitterle et al. Steam Generator Tubing Outside Diameter Stress Corrosion Cracking at Tube Support Plates - Data Base for Alternate Repair Limits - Volume 1: 7/8 Inch Diameter Tubing. Palo Alto, Calif.: Electric Power Research Institute. NP-7480-L, vol. 1. (to be issued in March 1992).

2. PWR Steam Generator Tube Repair Limits - Technical Support Document for Expansion Zone PWSCC in Roll Transitions, Revision 1. Palo Alto, Calif.: Electric Power Research Institute, December 1991. EPRI NP-6864-L, Revision 1.

Table D-1

LEAK RATE DATABASE
(Open Crevices Only)

Table D-2

DATABASE FOR CORRELATION OF LEAK RATE, UNDER NOP CONDITIONS WITH RPC INSPECTION DATA
(See figure D-1)

Table D-3

DATABASE FOR CORRELATION OF LEAK RATE, UNDER NOP CONDITIONS WITH BC INSPECTION DATA
(See figure D-2)

Table D-4

DATABASE FOR CORRELATION OF LEAK RATE, UNDER SLB CONDITIONS WITH RPC INSPECTION DATA
(See figure D-3)

Table D-5

DATABASE FOR CORRELATION OF LEAK RATE, UNDER SLB CONDITIONS WITH BC INSPECTION DATA
(See figure D-4)

Table D-6

CORRELATIONS OF LEAK RATE WITH SIGNAL AMPLITUDE
SUMMARY OF STATISTICAL REGRESSION ANALYSIS

Figure D-1. Regression of NOP Leak Rate on RPC Amplitude

Figure D-2. Regression of NOP Leak Rate on BC Amplitude

Figure D-3. Regression of SLB Leak Rate on RPC Amplitude

Figure D-4. Regression of SLB Leak Rate on BC Amplitude

Figure D-5. Schematic of Probabilistic Approach for Leak Rate Calculation for ODSCC at TSPs