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PWR STEAM GENERATOR TUBE REPAIR LIMITS - TECHNICAL SUPPORT DOCUMENT FOR OUTSIDE DIAMETER STRESS CORROSION CRACKING AT TUBE SUPPORT PLATES

Revision 1

Draft Report, August 1993

TR-100407, Revision 1

Research Projects S404-15, -19, -21, -24, -29, -30, -31, -32, -33, -36, -37, -70, -71, -72

NON-PROPRIETARY VERSION

Prepared by
Committee for Alternate Repair Limits for ODSCC at TSPs

Prepared for
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, California 94304

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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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NOMENCLATURE

ARC	Alternate repair criteria
ASME	American Society of Mechanical Engineers
BC	Bobbin coil
BP	Burst pressure
CFR	Code of Federal Regulation
EC	Eddy current
ECT	Eddy-current testing
EFPY	Effective full-power year
EPRI	Electric Power Research Institute
EZ	Expansion zone
GDC	General design criteria
gpd	Gallons per day
gpm	Gallons per minute
ID	Inside diameter
IGA	Intergranular attack
ISI	In-service inspection
LBB	Leak-before-break
LOCA	Loss-of-coolant accident
l/hr	Liters per hour
NDE	Nondestructive examination
NRC	Nuclear Regulatory Commission
OD	Outside diameter
ODSCC	Outside diameter stress corrosion cracking
Q	Tube leak rate
RCS	Reactor coolant system
RG	Regulatory Guide
RPC	Rotating pancake coil
RSS	Root sum square
SCC	Stress corrosion cracking
SG	Steam generator
SLB	Steam line break
SSE	Safe shutdown earthquake
TSP	Tube support plate
UT	Ultrasonic
V	Bobbin coil voltage
VCG	Crack growth voltage correction
Vnde	NDE measurement error voltage correction
Vrl	Repair limit voltage
Vrpc	Rotating pancake coil voltage
Vsl	Structural limit voltage

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 repair 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, enhanced 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 by the industry 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.

ODSCC refers to a range of stress corrosion cracking morphologies which have been observed to occur along the outside diameter of Alloy 600 steam generator tubes within the TSP intersection. The dominant morphology of ODSCC is axial stress corrosion cracks which occur either singularly or in networks of multiple axial cracks. This network morphology has been termed cellular corrosion. Shallow cellular corrosion may contain both axial and circumferential cracks but exhibits a transition to dominantly axial cracking as the cracking progresses in depth. Limited local patches of intergranular attack (IGA) have sometimes been observed as well.

The term ODSCC, as used in this document, covers the range of degradation morphologies consistent with the above description. Leak rate and burst test databases fully cover this range of ODSCC degradation morphologies. Consequently, the repair limit recommended for ODSCC provides adequate margin against tube rupture and leakage for ODSCC degradation typically found in service.

This document is applicable for tubes where axial ODSCC is the dominant degradation mechanism. The axial ODSCC repair limit is applicable to both 3/4-inch and 7/8-inch diameter tubing and degradation lengths of up to 3/4 inch. The repair limit is not applicable to tubes having nondestructive examination (NDE) indications evaluated to be distinct circumferential cracks.

The repair limit has been developed based on an uncovered tube span where no credit is taken for confinement of the tube by the TSP. 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 broached 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 axial ODSCC degradation, the elements of this approach include:

- Confirm that axial ODSCC at TSP is the damage mechanism.

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

- 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 axial ODSCC growth between inspections.

--Allowance for ECT voltage measurement error.

--A limit on leakage during postulated faulted loads so that the predicted dose rate at the site boundary is less than 10CFR100 limits.

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

- Confirmation that axial ODSCC at TSP is the damage mechanism.

- Calculation of plant-specific ECT voltage tube repair criterion 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 150 gpd per steam generator during normal plant operation.

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

- Establishment of maximum allowable site-specific leak rate during postulated accident loads to ensure that the dose rate due to leakage is less than 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. 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 broached TSP designs.

The outer diameter stress corrosion cracks (ODSCC) are illustrated in Figure 1-1 for a drilled hole TSP design. The dominant morphology of ODSCC is axial stress corrosion cracks which occur either singularly or in networks of multiple axial cracks. This network morphology has been termed cellular corrosion. Shallow cellular corrosion may contain both axial and circumferential cracks but exhibits a transition to dominantly axial cracking as the cracking progresses in depth. Limited local patches of intergranular attack (IGA) have sometimes been observed as well.

The term ODSCC, as used in this document, covers the range of degradation morphologies consistent with the above description. Leak rate and burst test databases fully cover this range of ODSCC degradation morphologies.

This document is applicable for tubes where axial ODSCC is the dominant degradation mechanism. The axial ODSCC repair limit is applicable to both the 3/4-inch and 7/8-inch diameter tubing and degradation lengths of up to approximately 3/4 inch. The repair limit described in this document is not applicable to tubes having NDE indications evaluated to be distinct circumferential cracks.

Distinguishing between different degradation mechanisms at tube support plates can be difficult. 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.

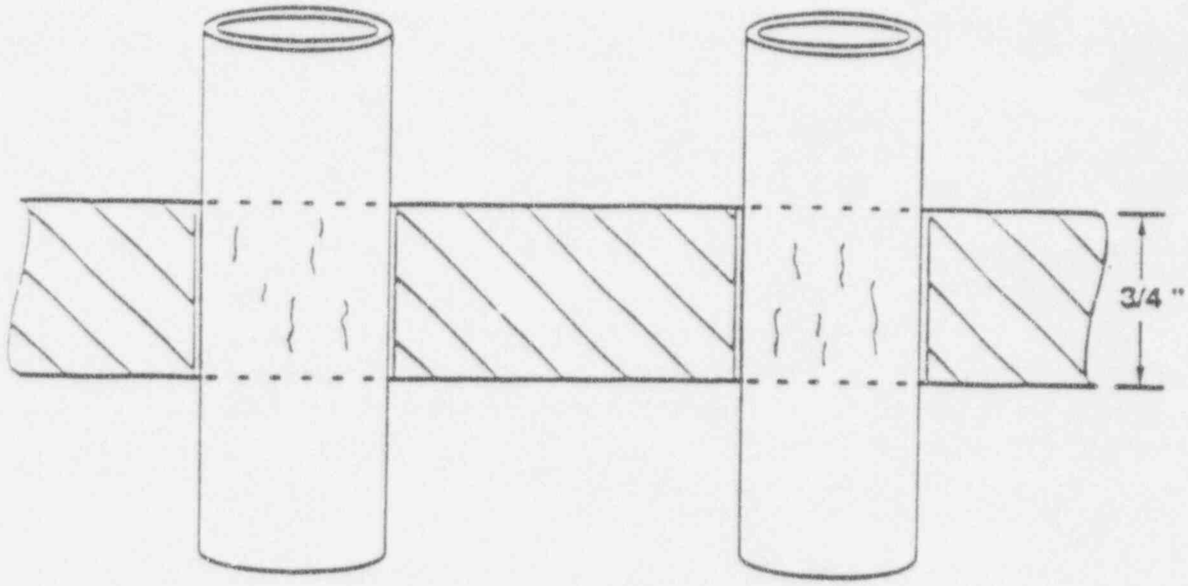

Figure 1-1. Illustration of ODSCC in Steam Generator Tubes in the TSP Region

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 150 gpd per steam generator 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 100% wall thickness.

When axial ODSCC is located entirely within the TSP for drilled hole designs, the TSP confines the tube and limits tube radial deformation. However, 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 broached designs are based conservatively on burst of an uncovered tube span.

Field application of this approach includes inspection of the TSP region by BC for 100% of the tubes in the affected regions of the steam generator. 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.

The repair criteria include margins against burst that are consistent with U.S regulatory guidelines for normal and postulated faulted loads. In addition, 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 150 gpd per steam generator has been established as the allowable primary to secondary leak rate limit during normal operation.

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 less than 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 less than 10CFR100 limits. 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 an alternative basis for leak rate predictions.

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.

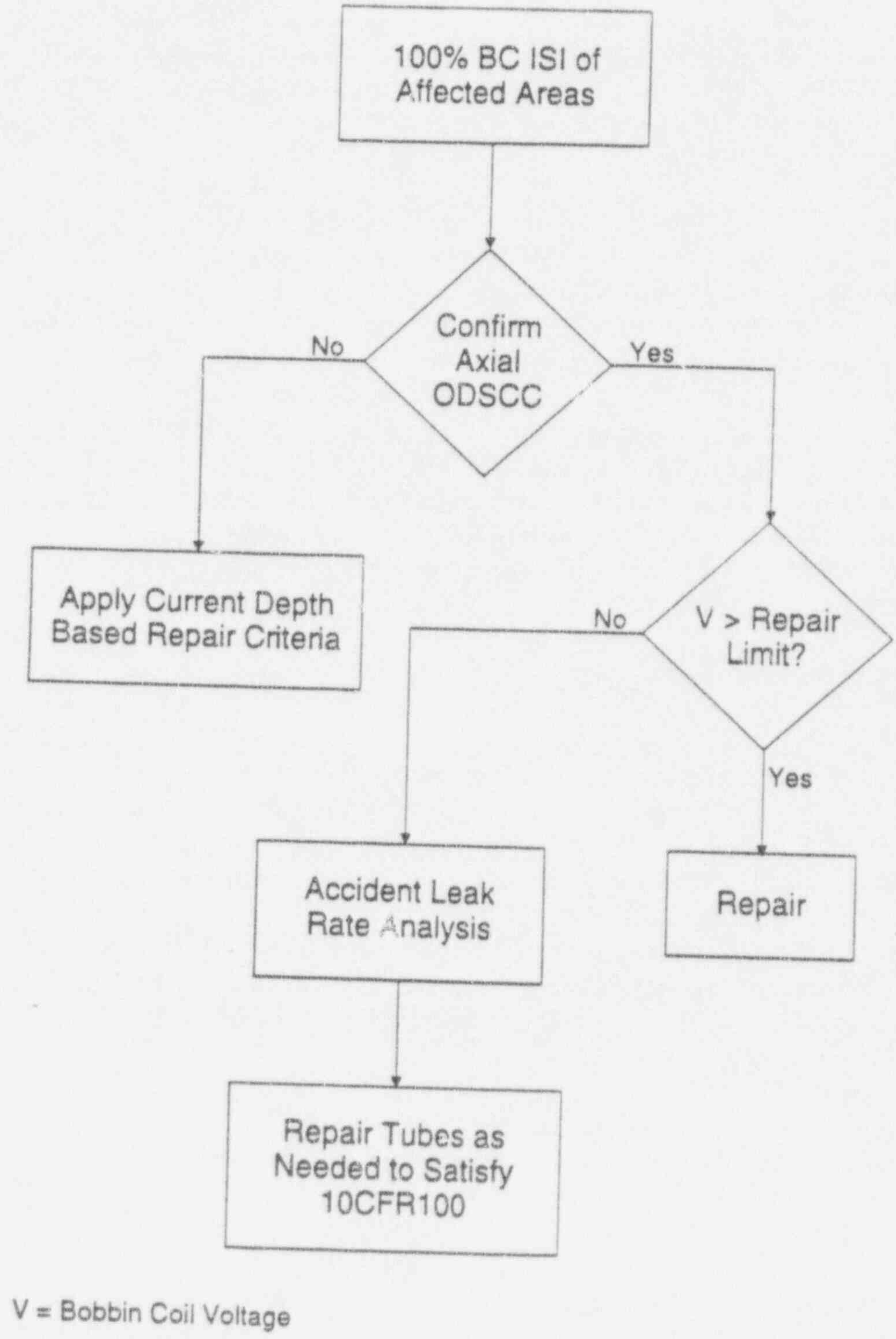

Figure 1-2. Evaluation Procedure for Implementation of an Alternative Repair Criterion for Tubes with ODSCC at TSPs.

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 to failure, and of gross rupture.

R.G. 1.121, "Bases for Plugging Degraded PWR Steam Generator Tubes " 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 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).

A maximum leak rate of 150 gpd per steam generator 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 less than 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 3 on normal pressure loads and 1.43 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 150 gpd per steam generator 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 150 gpd per steam generator is detected during normal operation, the unit will be shut down 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 (RG 1.121), (Draft for Review and Comment, July 1976), "Bases for Plugging Degraded PWR Steam Generator Tubes," (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 limiting leak rate to help ensure that degradation that progresses through-wall during an operating cycle will permit an orderly shutdown prior to tube rupture.
- 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:

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

- Tube Support Plate Primary Water Stress Corrosion Cracking - provides 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 - proposes 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 RG 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.

Table 1-1

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

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.

With few exceptions, ODSCC has been confined to the region within the TSP. A few cracks have been found outside the TSP. At one 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. Another 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. A repair limit based on BC voltage has been implemented and through-wall cracks may remain in service.

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 based on BC voltage has been implemented and through-wall cracks may remain in service.

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 within the TSP. 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 within the TSP. A crack growth per year adjustment and a allowance for NDE uncertainty are used to minimize the potential for tube leakage.

1.5 REFERENCES

1. U.S. Nuclear Regulatory Commission Regulatory Guide 1.83. "Inservice Inspection of Pressurized Water Reactor Steam Generator Tubes. Revision 1, July 1975.

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3. "NRC Integrated Program for the Resolution of Unresolved Safety Issues A-3, A-4, and A-5 Regarding Steam Generator Tube Integrity." NUREG-0844, September 1988.

4. Docket No. 50-395. "Tubesheet Region Alternative Plugging (L*) Criteria for Steam Generator in V. C. Summer Nuclear Station." WCAP-11857, April 1991.

5. "Tubesheet Region Plugging Criterion." WCAP-11225, July 1986.

6. "Tubesheet Region Plugging Criterion." WCAP-11225, Rev. 1, October 1986.

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8. "North Anna Unit 1 Steam Generator Tube Integrity Safety Evaluation." WCAP-11311, October 1986.

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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 NDE measurement error and degradation growth rate. These allowances are incorporated into the calculation of the tube voltage repair limit described in Section 5.

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:

- 3/4-inch and 7/8-inch diameter Alloy 600 tubing with a nominal wall thicknesses of 0.043 inch and 0.050 inch, respectively.

- and diameter BC probes operated in a differential mode with conventional coil dimensions, i.e., coil winding width and spacing.

- U.S. and European eddy-current data acquisition and analysis practices, e.g., probes, instrumentation, acquisition test frequencies, and reporting criteria, as specified in Appendices B and B1, respectively. Field test conditions other than that specified in these appendices, e.g., probe sizes, may be used as long as equivalent component performance is demonstrated using the protocol described in (1).

- No significant denting or copper deposits at tube support plates. These extraneous variables may modify BC signal amplitudes precluding reliable detection and measurement.

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

An example of 7/8-inch BC eddy-current data analysis process and voltage repair criterion is discussed with the data shown in Figure 2-1. The left figure shows the eddy-current graphic - primary analysis channel, i.e., differential - for a support plate signal and an indication diagnosed as ODSCC centered within the support plate. These same data are shown in the right 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 attributed to 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).

In addition to detection and measurement of ODSCC, BC tube examination results are used to identify ODSCC which extends beyond the TSP. This is accomplished by locating the ODSCC relative to the mid-thickness of the TSP (see Appendix B). If ODSCC indications extend beyond the TSP, these tubes must be repaired or removed from service. In addition, examination of the BC signal can be used to identify conditions such as denting or copper deposits which made ODSCC BC voltage measurements unreliable.

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 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. 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 indications.

Channel - Primary Analysis

Channel - Mix Analysis

Figure 2-1. Bobbin Coil Signal Amplitude Analysis

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

2.4 NDE ERROR

Various error sources have been identified which contribute to uncertainties in measuring BC signal amplitude. Sources considered herein include: (1) basic repeatability of the BC data acquisition technique and (2) data analyst analysis variability. Estimated individual error values (in percent) for these two sources are summarized in Table 2-1. The basis for each of the errors and estimates of their magnitude are discussed below.

Table 2-1

VOLTAGE MEASUREMENT ERROR ESTIMATES

2.4.1 Acquisition Technique

If a calibration standard containing a reference hole is repetitively probed using a BC, the signal obtained from the hole will show variations in amplitude during each scan. These variations are associated with the dynamics of probe translation and are inherent in the data acquisition technique. The magnitude of these variations can be controlled to some extent by (1) incorporating a proper probe centering mechanism, and (2) limiting the resultant wear of the centering device. Probe centering mechanisms are devices designed to provide opposing forces which maintain the probe axis congruent with the tube centerline. Wear occurs because of friction associated with the centering mechanism rubbing against the tube inner wall.

BC acquisition technique measurement error considering the effects of probe wear was determined experimentally (2) by making numerous 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 to simulate in-plant 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 or 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 on the buttons, to a maximum value of approximately .

Test results are summarized in Figure 2-3, which shows the average value (crosshatched bar chart data associated with the left axis scale) and standard deviation (solid data points associated with the right axis scale) of voltage readings that were obtained for ranges of probe wear that were tested (grouped along the abscissa). For each value of probe wear, the average value of signal amplitude remains approximately the same; however, the scatter in voltage readings, as measured by the standard deviation, increases with the amount of probe wear. The figure also shows that there is some scatter in the measured voltages even for the case of no probe wear, i.e., . This scatter, with a standard deviation of , 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. For example, at , the standard deviation is , while at wear, the standard deviation is .

Measurement repeatability as a function of probe wear can be limited or controlled by using a wear monitoring standard. This is accomplished by utilizing a standard for in-service monitoring of a probe during steam generator examination. For measurement error calculations, it is assumed that probe wear will be limited to . Composite voltage difference statistics for probe wear over the range of (from the data set used to construct Figure 2-3) is shown in Figure 2-4. The voltage differences have a mean value of with a standard deviation of . This standard deviation, when expressed as a percentage of the averages of the nominal voltage values for the data given in Figure 2-3 wear), equates to a percentage error of . This value is used as the margin of error for data acquisition and is the value listed in Table 2-1.

Figure 2-3. Bobbin Coil Signal Degradation Due to Probe Wear

Figure 2-4. Voltage Variability for Bobbin Probe Wear From 0-20 Mils

2.4.2 Analyst Interpretation

An additional source of error that must be considered is due to analyst interpretation. In analyzing eddy-current indications at tube support plants, an analyst assigns measurement points of a signal vector or indication in order to arrive at a voltage value. Indications at support plates can assume a variety of distortions depending on the amplitude of the indication and its location relative to the mix residual. No two analysts will read or interpret the same identical vector.

Details of a program to estimate the voltage error contributed by analyst interpretation is described in (2). data analysts were used to evaluate the largest indications from a particular plant with confirmed ODSCC at tube support plates. The steps included in the assessment of analyst variability included:

- Preparation of eddy-current analysis guidelines using examples of eddy-current data from the particular plant.
- BC eddy-current tape preparation for analysis using indications at tube support plates.
- Selection of eddy-current analysts and analysts training using the analysis guidelines described above.
- Independent evaluation of the BC indications by analysts for a total of data points.

The distribution of voltage amplitudes for the indications obtained as the average of the independent evaluations for each indication is shown in Figure 2-5. The voltages ranged from to with an average value of . The distribution of analyst differences from the mean for each of the indications is shown in Figure 2-6. The mean of the difference voltage distribution is with a standard deviation of . In terms of the average voltage, the percentage error, defined as , is . This value is used as the error for analyst data interpretation and is the value listed in Table 2-1.

Figure 2-5. Distribution of Plant L Voltages for Indications Used to Assess Analyst Variability

Figure 2-6. Distribution of Voltage Differences Between Individual Analyst

2.4.3 Calibration Standard Error

Since eddy-current voltage is used as the repair criterion in dispositioning tubes with indications at tube support plates attributed to ODSCC, a calibration method must be defined which (1) provides for the consistency setting of voltage during calibration and (2) is traceable to the original laboratory database used to establish the voltage-burst/leakage correlations.

Traceability to the experimental database is achieved by (1) using a field or in-plant standard similar in design to the laboratory calibration standard, or (2) providing a means for calibrating directly against the laboratory standard. Using a field standard of similar design will introduce small calibration errors because of variations in calibration standard dimensions, e.g., hole diameter or tube wall thickness. However, direct calibration against the laboratory standard is achieved by using a "transfer standard" which essentially eliminates the NDE system calibration procedure as an error of source.

Voltage "calibration" of the NDE system is established using a calibration standard prior to tube examination. The standard consists of sets of reference holes; set of holes is drilled from the tube outer surface with a nominal depth of through-wall; the other set consists of through-wall holes. Each set of holes are located in the same axial plane and separated circumferentially to reduce probe centering effects. Field calibration is achieved by setting the voltage scale of the analysis software to the same value used during laboratory data acquisition using the holes. Use of these holes for calibration maintains a direct tie with prior lab burst/leakage data and more adequately represents the eddy-current response to OD-originated degradation which has not progressed through-wall. The through-wall holes are used to establish a direct connection between data acquired using U.S. and European acquisition practices.

Corrections between the field and laboratory standards are made by recognizing that the bobbin coil response to a part through-wall calibration hole drilled from the outer tube surface varies linearly with hole volume to a first approximation. Again, variations in calibration standard hole volume are caused by slight differences in hole diameter and hole depth associated with manufacturing tolerances. Since the hole volumes for each of the two standards can be measured directly, a correction factor given by the ratio of the two volumes can be determined, which allows for (1) the elimination of the calibration standard error and (2) an adjustment of the field data voltages to a basis identical to the laboratory. This calibration method is referred to as a transfer standard concept and is the approach recommended in this document.

2.4.4 Total Measurement Error

When a calibration transfer standard is used, there are two sources of error: data acquisition repeatability and data analyst interpretation. The combined error for these terms is:

V_{NDE} =

$\%V_{NDE}$ =

For z = 1, these expressions give the standard deviation of the combined error. An upper one-sided value can be determined by setting z =

With σ acquisition = , σ analysis = , and z = , $\%V_{NDE}$ = ; with z = , $\%V_{NDE/95\%}$ = . These values are reported in Table 2-1.

If calibration standard is not used, a calibration standard error term should be added to the combined error due to data acquisition repeatability and data analysis interpretation. For the cause of 7/8-inch diameter tubing with possible differences in hole dimensions of 0.001 inch, the calibration standard error term is $\%V_{CAL}$ = and should be treated as a mean error.

The sample calculations of tube repair limits (Section 5) and tube leak rate under accident loading conditions (Appendix D) assume that a calibration transfer standard is used. The tube repair limit calculation utilizes the upper one-sided combined error term of . The accident leak rate calculation assumes a normal distribution for voltage measurement error with zero mean and standard deviation of .

The NDE errors due to acquisition technique and analyst interpretation are assumed to be normally distributed. In practice, acquisition technique, which is a strong function of probe wear, will be limited to and analyst interpretation error to . This results from use of a wear standard to directly measure probe wear with probe replacement when error is or greater and the reanalysis of data when two analyst interpretations for the same indication differ by or more. These limits to the components of NDE error are important when one utilizes Monte Carlo techniques to estimate the distribution of a function that includes these error terms.

2.5 ODSCC GROWTH RATE

Since the tube repair limits utilize BC signal voltage as a measure of structural integrity (burst capability and predicted accident leakage), BC voltages from consecutive operating cycles must be evaluated to develop allowances for ODSCC growth. An average growth rate is required for the tube repair limit and a growth distribution is needed for accident leakage analyses. Whenever possible, growth should be developed on a plant-specific basis for application of the ODSCC repair limits described in this document. Estimates that reasonably bound existing domestic plant data are provided for plants implementing ODSCC repair limits at tube support plates without a prior historical database for growth determinations. More detailed information on voltage growth rates is given in Appendix C.

ODSCC growth data is obtained by analyzing the results from successive BC inspections of plants with ODSCC at tube support plates. Data from six domestic plants are discussed in detail in Appendix C. Summary data from two additional domestic plants is also presented. Available data from two foreign plants have also been utilized to estimate ODSCC growth rate trends at higher bobbin coil voltages.

For tube repair limits in Section 5, average voltage growth rates at amplitudes typical of the repair limit are needed. Figure 2-7 shows average percentage voltage growth per effective full-power year (EFPY) as a function of BOC voltage ranges. The percentage growth rates tend to decrease with increasing BOC amplitudes. As there is little growth data in the range of repair limits near about , it is assumed that the percentage growths at small amplitude would apply at higher voltages. This trend is confirmed by data at higher voltages from two foreign plants. On this basis, a /EFPY appears to envelope the data.

For predicting accident leakage, a distribution of voltage growth rates is required for application to the next operating cycle. Typically, plants can use changes in voltage from the last one or two operating cycles for the growth distribution. For these distributions, the use of ΔV changes in volts is preferred over $\%\Delta V$ as the latter becomes distorted by large percentage changes at very small voltages. As shown in Appendix C, the growth distributions tend to have a small negative contribution due to measurement uncertainties and an extended, low-frequency tail of large ΔVs. A cumulative probability distribution can be used to represent growth which eliminates the need to postulate an analytical distribution, such as a normal distribution, for the growth rates. Figure 2-8 shows cumulative probability growth distributions for six domestic plants and a bounding distribution that conservatively envelopes the domestic data. For leakage analyses, it is suggested that negative growths be eliminated as shown for the bounding distribution in Figure 2-8. When growth data is not available for plants initially implementing ODSCC repair limits, the bounding distribution of Figure 2-8 can be applied. However, plant-specific growth data should be applied whenever available and any available growth data should be sown to be bounded before applying the bounding estimates of this report.

Figure 2-7. Average ODSCC Growth Rate Measured During the Last Cycle at Six Plants. Data for Initial Voltages <0.75 Volts and >0.75 Volts.

Figure 2-8. Cumulative Probability Distributions for Voltage Growth

2.6 REFERENCES

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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 axial 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 within the TSP. 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 tube burst pressure and bobbin coil (BC) voltage is developed for uncovered tubes with ODSCC. This relationship is based on tube rupture experiments performed for EPRI and reported in (1, 2). The results from these experiments are summarized here, and mean and statistical regression curves are developed to correlate burst pressure with 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 used to develop interim repair limits for ODSCC at TSPs (1, 2). These experiments utilized Alloy 600 3/4-inch diameter, 0.043-inch wall thickness, and Alloy 600 7/8-inch diameter, 0.050-inch wall thickness, 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 (2), relative to the free span burst pressure. Some pulled tubes with extensive ODSCC confined by the drilled hole TSP were burst tested and showed burst pressures not significantly lower than an unflawed tube.

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 Tables 3-1 and 3-2 and are plotted in Figures 3-1 and 3-2 for 3/4-inch and 7/8-inch diameter tubes, respectively. A linear fit to the burst pressure versus log BC voltage has been made and a lower prediction interval derived. The lower prediction interval curve has been further adjusted downward by a factor equal to a lower bound estimate of tubing mechanical properties at (3) divided by the mechanical properties of the tubes tested at room temperature. The mean and the adjusted prediction interval curves are shown in Figures 3-1 and 3-2.

Table 3-1

TUBE BURST TEST RESULTS FOR 3/4-INCH DIAMETER TUBES WITH ODSCC IN THE TUBE FREE SPAN (1)

Table 3-1 (con't.)

TUBE BURST TEST RESULTS FOR 3/4-INCH DIAMETER TUBES WITH ODSCC IN THE TUBE FREE SPAN (1)

Table 3-2

TUBE BURST TEST RESULTS FOR 7/8-INCH DIAMETER TUBES WITH ODSCC IN THE TUBE FREE SPAN (2)

Table 3-2 (con't.)

TUBE BURST TEST RESULTS FOR 7/8-INCH DIAMETER TUBES WITH ODSCC IN THE TUBE FREE SPAN (2)

Figure 3-1. Burst Pressure Versus Bobbin Coil Voltage for 3/4-Inch Diameter Tubes

Figure 3-2. Burst Pressure Versus Bobbin Coil Voltage for 7/8-Inch Diameter Tubes

The lower prediction curve, adjusted for lower tolerance limit on material properties, is defined by the equation:

$$\hat{Y} = \qquad \text{3-1}$$

where: σ is the lower tolerance limit on material properties at temperature (3) X_o = , V_o is the voltage for an individual indication, X_i is a value from the burst pressure data set ($\log_{10}$ of voltage for data point i), $\overline{X}$ is the average of the X_i values, s is the standard error of the linear regression fit, t is the tabled value of Student's t distribution with n-2 degrees of freedom, and $\hat{Y}_o$ is the predicted burst pressure from the linear regression line for a voltage of V_o;

The parameters are defined in Table 3-3.

Table 3-3

CONSTANT FOR LOWER PREDICTION ODSCC BURST CURVE

For the case where plant-specific steam generator tubing mechanical properties are not available, Eq. 3-1 is used to define the voltage structural limit (Vsl). Specifically, Vsl is the voltage (V_o) associated with burst pressure ($\hat{Y}$) equal to expected tube differential pressure times a safety margin.

If plant-specific tubing mechanical properties are available, Eq. 3-1 should be multiplied by tube yield plus ultimate strength at operating temperature divided by σ, where σ equals and for 3/4-inch and 7/8-inch diameter tubing, respectively.

3.4 APPLICATION OF SAFETY MARGINS

USNRC Regulatory Guide 1.121 (4) 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 1.43 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 1.43 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 (2). At this time, it is assumed that tube ODSCC is not confined by the TSP at either 3 x normal operating pressure differential or 1.43 x accident pressure differential. Assuming an uncovered tube during normal operation is appropriate (and may be slightly conservative) for broached and egg crate TSP designs.

Less restrictive repair limits can be used provided it can be demonstrated that the ODSCC will remain covered by the TSP for all loading conditions. If one can show that ODSCC will always 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 psi to psi, while accident differential pressures are on the order of psi. Three times maximum normal operating differential pressure would range from to psi, while 1.43 times accident differential pressure of psi is psi. Consequently, 3 times normal operating pressure is the most limiting case.

Voltage structural limits of volts and volts which correspond to pressures of and psi for 3/4-inch and 7/8-inch diameter tubing, respectively, are shown schematically in Figures 3-1 and 3-2. Sample calculations of the tube voltage repair limits based on these voltage structural limits are included in Section 5.

3.5 REFERENCES

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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. Countries following a depth-based policy 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 repair criteria which allow 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 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, more than units with ODSCC at TSP intersections have been operating for a significant period (more than 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 (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 predicted 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 to 150 gpd. While it is not feasible to have a leak rate limit that ensures LBB for all tubes (1), the recommended 150 gpd 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 at each in-service inspection 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 1.0 gpm 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 1.0 gpm 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 a 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 of 1.0 gpm.

- The 500 gpd (0.35 gpm) 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 by leakage, an operational leakage limit of 150 gpd per steam generator 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.

To ensure that leakage during design basis accident events does not result in off-site doses greater than the 10CFR100 limits, one must show that a conservatively calculated accident leak rate from tube with ODSCC at TSPs that remain in service is less than a plant allowable accident leak rate. If the predicted leak rate is greater than the allowable leak rate, additional degraded tubes must be removed from service until it can be shown that this is no longer true.

The allowable accident leak rate is that plant-specific leak rate that is acceptable under postulated accident loading conditions without exceeding 10CFR100 dose limits. If more than one form of degradation-specific damage is present and there is the possibility of tube leakage from this form of damage, the combined predicted leak rate from all damage mechanisms shall be combined and compared with the plant allowable accident leak rate.

The accidents that should be considered in calculation of predicted 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.*

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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.

This section outlines a method that can be used to predict leak rate during a postulated SLB from tubes with ODSCC at tube support plates.

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 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 BC voltage 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 voltage, 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.

To define the relationship between BC voltage and steam generator tube leakage, a series of tube rupture experiments were conducted. 3/4-inch and 7/8-inch diameter tubes with ODSCC produced in the laboratory or pulled from service were tested (1, 2). Tubes were pressurized with water in the laboratory to different pressure levels and the leak rate measured. Testing was done without the presence of a simulated TSP with the degradation in the tube free span. Most of the tubes were subsequently burst tested. Not all tubes leaked. For those tubes that did leak, tube leak rate data was corrected for temperature and scaled to tube differential pressures for psi and psi, and the results were correlated with BC voltages measured before testing. Separate correlations between BC voltage and the probability of tube leakage were also developed (see Appendix D).

The probability of tube leakage versus BC voltage and the tube leak rate versus BC voltage correlations are used to conservatively predict leak rates for ODSCC indications. The methods for making these predictions are described in detail in Appendix D. The Appendix D procedures explicitly account for degradation growth

(BC voltage growth) during the period between inspections and uncertainties associated with:

- Voltage growth due to defect progression,
- Uncertainty in the predicted probability of leakage correlation fit,
- Uncertainty in the conditional leak correlation fit,
- "Scatter" of leak rate data about the leak rate correlation, and
- Uncertainty due to eddy-current measurement variability.

4.2.3 Application

After each steam generator tubing in-service inspection, tubes with measured BC voltages which exceed the voltage repair limit will be removed from service. A predicted accident leak rate is then calculated for those tubes to TSP intersections with BC indications that are to remain in service. The steam generator predicted accident leak rate is the sum of the predicted leak rates for all BC indications. The confidence in the steam generator predicted accident leak rate is significantly greater than that for the individual tubes.

If the sum of the predicted accident leak rates for any one steam generator exceeds the plant allowable accident leak rate, tubes with the largest measured BC voltages are removed from service or repaired. This process is continued until it can be shown that the predicted accident leak rate is less than the plant allowable accident leak rate.

4.3 REFERENCES

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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 axial 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. These repair limits are not applicable to tubes having NDE indications evaluated to be distinct circumferential cracks.

The tube repair criteria are applicable to 3/4-inch and 7/8-inch diameter tubing and degradation lengths up to approximately 3/4 inch. The degradation length restriction is imposed because all supporting test data are based on ODSCC generated within 3/4-inch thick plates. It is expected, but not yet demonstrated, that the voltage limits will be acceptable for crack network lengths exceeding 3/4 inch.

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 axial 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 RG 1.121 structural guidelines for tube burst margins by establishing a conservative structural limit on BC voltage amplitude that ensures three times normal operating differential pressure and 1.43 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 less than 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 RG.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 voltage structural limit (V_{SL}) that satisfies the RG 1.121 guidelines for margin against tube burst, the burst correlation must be evaluated at the higher of 1.43 faulted pressure and three times the normal operating pressure differential. The voltage structural 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 RG 1.121 guidelines, including allowances for NDE measurement error and defect growth, can be expressed as follows:

(5-1)

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 and are $\%V_{NDE}$ = with the use of a transfer standard and $\%V_{CG}$ = /EFPY. Assuming that the next operating cycle is EFPY so that $\%V_{CG}$ = and 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 lower certainty curve from Figure 3-1 or 3-2. V_{SL} is the voltage associated with the larger of 3 times normal operating differential pressure and 1.43 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 psi and psi for 3/4-inch and 7/8-inch diameter tubing, respectively. These pressures span the range of operating differential pressures for steam generators now in service and when multiplied by 3 are all greater than 1.43 times a typical accident peak differential pressure of 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 less than 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 150 gpd per steam generator, 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 150 gpd per steam generator 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 should be performed to establish that the principal indications can be characterized as ODSCC.

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 ODSCC confirmation.

5.6.2 Tube Repair Criterion

The plant-specific voltage limit for tube repair, V_{RL}, shall be determined from Eq. 5-2. 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 are based on correlations with BC voltages (see paragraph 4.2.4).

5.6.4 Operating Leakage Limits

Plant shutdown will be implemented if normal operating leakage exceeds 150 gpd through any one steam generator.

Appendix A

PLANT EXPERIENCE WITH ODSCC
(As of 1991)

A.1 NATURE OF CRACKING

Outside diameter stress corrosion cracking (ODSCC) refers to a range of stress corrosion cracking morphologies which have been observed to occur along the outside diameter of Alloy 600 steam generator tubes within the TSP intersection. The dominant morphology of ODSCC is axial stress corrosion cracks which occur either singularly or in networks of multiple axial cracks. This network morphology has been termed cellular corrosion. Shallow cellular corrosion may contain both axial and circumferential cracks but exhibits a transition to dominantly axial cracking as the cracking progresses in depth. Limited local patches of intergranular attack (IGA) have sometimes been observed as well.

The term ODSCC, as used in this document, covers the range of degradation morphologies consistent with the above description. Leak rate and burst test databases fully cover this range of ODSCC degradation morphologies.

The discussion in this appendix is applicable for tubes where axial ODSCC is the dominant degradation mechanism.

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

ODSCC was first diagnosed in a U.S. plant about 1972 (1). The number of plants reporting ODSCC degradation has increased significantly in the last several years, and as of December 1991,   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 (2). Currently, 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, 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.

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.

Table A-1

SUMMARY OF U.S. TUBE/TSP CONDITIONS AND EXPERIENCE WITH ODSCC AT TSPs

Table A-1
(Continued)

Table A-1
(Continued)

Table A-1
(Continued)

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 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 units starting in 1994 (5). In addition, ODSCC has resulted in over of the total number of tubes being affected at 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 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 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 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 and about , significant numbers of degraded tubes can occur from ODSCC after about years 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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7. J. A. Gorman, R. W. Staehle, and K. D. Stavropoulous. Statistical Analysis of Steam Generator Tube Degradation. Palo Alto, Calif.: Electric Power Research Institute, September 1991. NP-7493.

Appendix B

EDDY-CURRENT DATA ACQUISITION AND ANALYSIS GUIDELINES FOR ODSCC - U.S. PRACTICE

B.1 SCOPE

This appendix contains NDE guidelines that provide direction in applying the outside diameter stress corrosion cracking (ODSCC) repair limits described in this report. Procedures for eddy-current testing using bobbin coil (BC) to detect ODSCC at TSPs and rotating pancake coil (RPC) techniques to confirm the presence of axial ODSCC are summarized. The following sections define specific ODSCC data acquisition and analysis parameters and methods to be used for steam generator tubing examination. The methods and techniques detailed in this appendix are to be incorporated in the applicable plant inspection and analysis procedures.

B.2 APPLICABILITY

These guidelines apply to steam generators that utilize 7/8-inch OD. x 0.050-inch wall, and 3/4 inch x 0.043 wall, Alloy 600 mill-annealed tubing.

B.3 BOBBIN COIL TUBE EXAMINATION

Table B-1 provides bobbin coil test frequencies and analysis channels for 7/8-inch OD x 0.050-inch wall, and 3/4-inch OD x 0.043-inch tubing. When specific channels are specified for data acquisition and analysis activities, the frequencies employed are as defined in the table.

Table B-1

CHANNEL/FREQUENCY RELATIONSHIPS

B.3.1 Data Acquisition

B.3.1.1 Instrumentation. Multiple frequency eddy-current instrumentation with digital recording shall be used for data acquisition.

B.3.1.2 Probes. To maximize consistency with laboratory data, differential bobbin probes with the following parameters shall be used:

a. All straight sections of tubing (including Rows 1-10) are to be tested with a required OD probe in 7/8-inch diameter tubing or a OD probe in 3/4-inch diameter tubing. (U-bends may be tested with a OD or smaller diameter probe or a OD or smaller probe in 7/8-inch and 3/4-inch diameter tubing, respectively, as required.) The use of smaller diameter probes is acceptable under circumstances described in (c) below, with due control for centering and wear.

b. coil grooves with a spacing between adjacent edges.

c. Probe designs must incorporate centering features that provide for minimum probe wobble and offset. Centering features must maintain constant probe center-to-tube ID offset for nominal diameter tubing. For sections of tubing between sleeves at tube support plate intersections or small radium tubes with a tubesheet sleeve and testing from the opposite leg, smaller diameter probe bodies may be used provided the centering device includes features for centering in the nominal tube diameter.

B.3.1.3 Calibration Standards. Two types of calibration standards are required to be consistent with the development and analyses of this report. These include (1) a probe wear standard to guide probe replacement, and (2) a voltage normalization standard used to establish signal amplitude settings. The probe wear standard is used to monitor the degradation of probe centering devices, leading to off-center coil positioning and potential variations in flaw amplitude responses. The voltage normalization standard is used to establish voltage settings in implementing a signal amplitude or voltage repair limit. It is also used to establish conventional phase-angle calibration curves for depth estimation.

Probe wear standard.

- through-wall holes (in diameter for 7/8-inch diameter tubing and in diameter for 3/4-inch tubing), spaced apart around the tube circumference with an axial spacing such that signals associated with the individual holes can be clearly distinguished from one another (see Figure B-1). The probe wear standard length shall be long enough to insure that the response from any of the drilled holes will not be distorted while the probe enters or exits the standard.

Figure B-1. Probe Wear Standard Schematic

Voltage normalization standard.

- For 7/8-inch diameter tubing, diameter through-wall holes, spaced apart in a single plane around the tube circumference. The hole diameter tolerance shall be . For 3/4-inch diameter tubing, diameter through-wall holes, spaced apart in a single plane around the tube circumference. The hole diameter tolerance shall be .

- diameter flat-bottom hole, through from the OD.

- diameter flat-bottom hole, through from the OD.

- diameter flat-bottom holes, through from the OD, spaced apart in a single plane around the tube circumference. The tolerance on hole diameter and depth shall be .

- A simulated support ring, long, comprised of SA-285 Grade C carbon steel or equivalent.

Note: All holes shall be machined using a mechanical drilling technique.

B.3.1.4 Data Acquisition Parameters.

Test frequencies. Required and recommended data acquisition channels and coil modes are summarized in Table B-2. BC eddy-current inspection for ODSCC requires the use of a Primary channel, an Aux 2 channel, a Mix 1 channel, and a Locator channel in the differential mode. The Primary channel or the Mix 1 channel is used to assess changes in signal amplitudes for the probe wear standard as well as for data screening and reporting purposes.

Table B-2

DATA ACQUISITION CHANNELS/COIL MODES

The Locator channel should be recorded to provide a positive means of verifying tube support plate edge detection for flaw location purposes. In addition, it is recommended that the Aux 2 channel be used in differential and absolute modes. This channel is often useful for flaw confirmation and flaw location purposes.

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

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

B.3.2 Data Analysis

This section discusses (1) the methodology for establishing data analysis variables such as spans, rotations, mixes, voltage scales, and calibration curves, and (2) the methodology for data evaluation.

B.3.2.1 Analysis Parameters.

Primary differential channel.

- Rotation. The signal from the through-wall holes should be set to with the initial signal excursion down and to the right during probe withdrawal.
- Voltage Scale. The peak-to-peak signal amplitude of the signal from the through-wall holes should be set to
- Calibration Curve. Establish a phase versus depth calibration curve using measured signal phase angles in combination with the "as-built" flaw depths for the holes.

Mix 1 differential mix channel.

- Mix. A bobbin coil differential mix is established with the Primary channel as the primary mixing frequency suppressing the tube support plate simulation.
- Rotation. Probe motion is set horizontal with the initial excursion of the signal from the four through-wall holes going down and to the right during probe withdrawal.
- Voltage Scale. The peak-to-peak signal amplitude of the signal from the through-wall holes should be set to volts.
- Calibration Curve. Establish a phase angle versus depth calibration curve using measured signal phase angles and the "as-built" flaw depths for the holes.

B.3.2.2 Data Evaluation.

Data screening. Any of the differential data channels including the Mix 1 channel may be used for flaw detection (though the Aux 2 channel is often subject to the adverse influence of many different effects not related to tube wall degradation). Upon detection of a flaw signal in the differential Mix 1 channel, confirmation from other raw channels, e.g., Primary or Aux 2, may be observed. A flaw-like signal may be described as a lissajous signal or vector in the Mix 1 channel that has a clear start and stop associated with a well-defined transition with vector phase angles characteristic of tube wall degradation. Confirmation may be a flaw-like response or only a distorted tube support lobe signal noted in one of the other raw frequency channels.

Reporting. Bobbin coil indications at support plates shall be reported and quantified using the Mix 1 channel.

Verifying confinement of indication(s) within the support plate region. In order to establish that a reported bobbin indication is within the support plate, the displacement of each end of the signal is measured relative to the support plate center. If this distance in either direction exceeds half the support plate axial length (0.375"), the crack will be considered to have progressed outside the support plate. Per the repair criteria, indications extending outside the support plate require identification for subsequent tube repair or removal from service.

Probe wear monitoring. During the steam generator examination, the bobbin coil probe is inserted into the wear monitoring standard. The initial (new probe) amplitude response from each of the four holes is determined and compared on an individual basis with subsequent measurements. Signal amplitudes or voltages from the individual holes must remain within of their initial amplitudes for an acceptable probe wear condition. If this condition is not satisfied for all four holes, then the probe must be replaced. If any of the last probe wear standard signal amplitudes prior to probe replacement exceed the limit, say, by as value of x%, then any indications measured since the last acceptable probe wear measurement that are within x% of the plugging limit must be reinspected with the new probe. For example, if any of the last probe wear signal amplitudes prior to probe replacement were above or below the initial amplitude, then indications that are within of the repair limit must be reinspected with the new probe.

B.3.2.3 Analysis Examples. Bobbin coil indications at support plates attributable to ODSCC are reported using the Mix 1 channel. However, this channel and other channels appropriate for flaw detection (Primary, Aux 2) can be used to locate the indication of interest within the support plate signal. The largest amplitude portion of the indication should be measured using the Mix 1 channel to establish the peak-to-peak voltage as shown in Figure B-2.

Figure B-2. Bobbin coil indication at tube support plate illustrating vector dot placement for voltage measurement. Upper left window shows initial placement using single-frequency channel; lower right window shows final placement using mix channel.

Initial placement of the dots for identification of the indication may be performed from the Primary and Aux 2 channels as shown in Figure B-3, but the final peak-to-peak measurements must be performed using the Mix 1 channel to include the full segment of the indication. It may be necessary to iterate the position of the dots between the identifying frequency data (e.g., Primary channel) and the Mix 1 channel to assure proper placement of the dots. As can be seen in Figure B-3, failure to do so can significantly change the voltage amplitude measurement due to the interference of the support plate signal in the raw frequencies. The voltage measured using the Mix 1 channel is then entered as the analysis of record and compared with the repair limit voltage.

Figure B-3. Bobbin coil indication at tube support plate illustrating conservative vector dot placement using mix channel (lower right window). Portion of support plate residual is included in final vector.

It has been observed that voltage measurements taken from the same data by different analysis may vary, even when using identical analysis guidelines. This is largely due to differences in analyst interpretation of where to place the dots on the lissajous figure for the peak-to-peak measurement for flaw identification. Figure B-4 shows dot placement based on peak-to-peak signal amplitude rather than choosing a segment of the indication associated with a maximum slope phase angle.

Figure B-4. Bobbin coil indication at tube support plate illustrating potential for analyst interpretation error. Mix channel (lower right widow) dot placement based on choosing total peak-to-peak amplitude associated with indication rather than only a portion associated at maximum phase angle observed in the analysis channel (upper left window).

Examples of the benefits of using the Aux 2 analysis channel for locating the segment of the indication in the Mix 1 channel for voltage measurement is shown in the upper right window of Figure B-5. Vector voltage measurement points for indications in the Mix 1 channel (lower right window) are identified by the arrows. Notice that the measurement points do not correspond to the most conservative voltage that can be read in the Mix 1 channel. A judgment has been made separating the indication from the mix residual. This decision process is aided by using the Aux 2 channel; it can be seen that the Mix 1 channel vector points correspond to the vector peak-to-peak measurement points in the Aux 2 analysis channel.

Figure B-5. Bobbin coil indication at tube support plate. Mix channel vector dot placement (lower right window) aided using peak-to-peak measurement point determined from the analysis channel (upper right window).

B.3.3 Reporting Requirements

B.3.3.1 Minimum Requirements. All indications at tube support plate intersections must be reported. Smaller amplitude indications provide an assessment of the overall condition of the steam generator(s) and are used for growth rate calculations.

B.3.4 Recording Requirements

For each reported indication, the following information should be recorded:

Tube Identification (row, column)	Indicated Length (in)
Signal Amplitude (volts)	Test Channel (ch#)
Signal Phase Angle (degrees)	Axial Position of Tube (location)
Indicated Depth (%)*	Extent of Test (extent)

*It is recommended that percent through-wall be reported rather than a three-letter analysis code. While this measurement is not required, this information might be found useful at a later date.

B. 4 ROTATING PROBE TUBE EXAMINATION

The RPC inspection of some support plate intersections with bobbin coil indications is recommended in order to confirm the presence of axial ODSCC and to verify the applicability of the alternate repair limit. If axial ODSCC is not diagnosed, then conventional depth-based repair criteria are applicable.

In addition, it is recommended that a sample of tube support plate intersections that exhibit an excessive (greater than the repair limit voltage) bobbin coil mix residual be examined by RPC. Mixing is used to vectorially combine eddy-current data at different frequencies to reduce the effects of an extraneous test variable. The extraneous variable is not totally suppressed. With the remnants of the vector mixing process referred to as a mix residual. This residual will contribute to the mix channel signal-to-noise, which, in turn, can impact bobbin coil flaw detection and sizing. Recognized extraneous variables that can impact inspection reliability include deposits, permeability variations, denting, and material property changes. Accordingly, mix residuals greater than the repair limit voltage should be sampled with alternate testing techniques. Detection of RPC indications should be evaluated against equivalent bobbin voltages for axial indications and the need for further RPC testing determined. The need for repair is determined based on bobbin coil voltage or depth rather than RPC voltage. Circumferential indications must be repaired or plugged.

Table B-3 provides a definition of rotating probe test frequencies and channels for 7/8-inch OD x 0.050-inch wall, and 3/4-inch OD x 0.043-inch wall tubing. When specific channels are specified for data acquisition and analysis activities, the actual frequencies employed are as defined in the table.

Table B-3

CHANNEL/FREQUENCY RELATIONSHIPS

B.4.1 Data Acquisition

B.4.1.1 Instrumentation. Multiple-frequency eddy-current instrumentation with digital recording shall be used for data acquisition.

B.4.1.2 Probes.

- Pancake coil designs (vertical dipole moment) with a coil diameter d, where d is , shall be used for examination. Rotating probes may incorporate single and multiple pancake coils.
- Rotating pancake coils incorporating other coil designs, e.g., directed axial or circumferential coils, may be used to provide supplemental diagnostic information.

B.4.1.3 Calibration Standard. For both 3/4-inch OD and 7/8-inch OD tubing, the calibration standard shall contain:

- axial EDM notches, located at the same axial position but apart circumferentially, each wide and long, and through-wall from the OD.
- Two axial EDM notches, located at the same axial position but 180° apart circumferentially, each wide and long, and through-wall from the OD.

- circumferential EDM notches, through-wall from the OD with a arc length, and through-wall with a arc length, with notches wide.

- A simulated support segment in circumferental extent, thick, comprised of SA-285 Grade C carbon steel or equivalent.

The center-to-center distance between the support plate simulation and the nearest slot shall be at least . The center-to-center distance between the EDM notches shall be at least . The tolerance for the widths and depths of the notches shall be . The tolerance for the slot lengths shall be .

B.4.1.4 Acquisition Parameters.

Probe speed. Determined in such a manner that at least overlap in coil coverage is obtained between adjacent line scans. Maximum probe pulling speed is typically limited to for probes with single pancake coils. For rotating probes with multiple pancake coils, the maximum probe pulling speed is n * where n is the number of pancake coils.

Rotation rate. A minimum digitizing rate of samples/in is required. Combinations of probe speed and instrumentation sample rates are chosen such that:

$$\frac{\text{Sample Rate (samples/sec)}}{\text{Rotating Probe Speed (in/sec)}} \geq \quad \text{(samples/in.)}$$

where Rotating Probe Speed is translated into rotations per minute as a function of the tube dimension using the following equation:

$$\frac{60 * \text{Rotating Probe Speed (in/sec)}}{3.14 * \text{Tube Outer Diameter (in)}} = \text{Rotation Rate (rpm)}$$

Maximum rotation rate is typically limited to rpm to reduce probe noise.

B.4.2 Data Analysis

This section discusses (1) the methodology for establishing data analysis variables such as phase rotations, voltage scales, and calibration curves, (2) the methodology for data evaluation. It is assumed the rotating probes employ a pancake coil operated in an absolute mode as the primary analysis tool.

B.4.2.1 <u>Analysis Parameters</u>.

<u>Rotation</u>. Probe motion is set horizontal (degrees) with the initial excursion of the signal from the through-wall notch directed upwards during probe withdrawal.

<u>Voltage scale</u>. The signal amplitude from the pancake coil shall be set individually to volts for the through-wall notch on the Primary and Aux 1 channel frequencies specified in Table B-3.

B.4.2.2 <u>Data Evaluation</u>.

<u>Data screening</u>. Any of the analysis channels for tube wall degradation may be used for detection.

<u>Reporting</u>. Indications at support plates shall be reported and quantified using a rotating pancake coil data channel.

<u>Verifying confinement of indication(s) within the support plate</u>. The measurement of axial crack lengths from RPC isometrics can be determined using the following analysis practices:

- For the location of interest, the low-frequency channel (e.g.,) is used to set a local scale for measurement. Calibration of the distance scale is accomplished by setting the displacement between the absolute, upper and lower support plate transitions equal to .

- By establishing the midpoint of the support plate response, a reference point for crack location is established. The ends of the crack indication may be located using the slope-intercept method, i.e., the leading trailing edges of the signal pattern are extrapolated to cross the null baseline. The difference between these two positions is the crack length estimate.

- Alternatively, the number of scan lines indicating the presence of the flaw times the pitch of the rotating probe provides an estimate of the crack length which must then be corrected for EC field spread.

B.4.2.3 <u>Analysis Examples</u>. The nature of degradation and its orientation (axial, circumferential, or oblique) will be determined from careful examination of isometric plots of the RPC data. The presence of axial ODSCC at the support plate intersections has been well documented, but the presence of circumferential ODSCC at the support plate intersections has also been established by tube pulls at a few plants. Figures B-6 and B-7 show examples of RPC data showing single and multiple axial indications at a nondented tube support plate. Figure B-8 gives an example of multiple circumferential indications at a dented tube support plate intersection.

Figure B-6. Rotating Probe Single Axial Indication (SAI) at Tube Support Plate

Figure B-7. Rotating Probe Multiple Axial Indications (MAI) at Tube Support Plate

Figure B-8. Rotating Probe Multiple Circumferential Indications (MCI) at Tube Support Plate

If circumferential involvement results from circumferential cracks as opposed to multiple axial cracks, discrimination between axial and circumferentially oriented cracking can be generally established for affected arc lengths as small as degrees. Pancake coil resolution is considered adequate for separation between circumferential and axial cracks over this angular range. Conventional pancake coil data can also be supplemented by using rotating probes with directed axial and circumferential coils to assist in the diagnosis of circumferential and axial cracking.

For hot leg TSP locations, there is little industry experience on the basis of tube pulls for volumetric degradation, i.e., actual wall loss or general IGA. For cold leg TSP locations, considerable experience is available for volumetric degradation in the form of thinning of peripheral tubes, favoring the lower TSP elevations. Therefore, in the absence of confirmed pulled tube experience to the contrary, volumetric OD indications at hot leg tube support plates should be considered to represent ODSCC.

B.4.3. Reporting Requirements

All indications, however small, shall be reported.

B.4.4. Recording Requirements

For each reported indication, the following information shall be recorded:

Tube Identification (row, column)	Test Channel (ch#)
Signal Amplitude (volts)	Axial Position (location)
Signal Phase Angle (degrees)	Extent of Test (extent)
Indicated Length (in)	

In addition, the location of center of the cracks) relative to the center of the support plate shall be recorded. The crack axial center need not coincide with the position of the maximum amplitude. Applicable three-letter analysis codes should also be used to describe the number of indications, morphology, and orientation. Orientations may include circumferential, axial, and oblique (inclinations off axis).

Appendix B1

EDDY-CURRENT DATA ACQUISITION AND ANALYSIS GUIDELINES FOR ODSCC - BELGIAN PRACTICE

B1.1 SCOPE

This appendix contains the main differences between the Belgian practice and the data acquisition and analysis guidelines described in Appendix B. The following sections define specific parameters and methods that are currently used in Belgium for ODSCC at support plates of steam generator tubing.

B1.2 APPLICABILITY

The parameters and methods apply to steam generators that utilize 7/8-inch OD. x 0.050-inch wall, and 3/4 inch x 0.043 wall, Alloy 600 mill-annealed tubing.

B1.3 BOBBIN COIL TUBE EXAMINATION

Table B1-1 provides a definition of bobbin coil test frequencies and analysis channels for 7/8-inch OD x 0.050-inch wall, and 3/4-inch OD x 0.043-inch tubing. When specific channels are specified for data acquisition and analysis activities, the actual frequencies employed are as defined in the table.

Table B1-1

CHANNEL/FREQUENCY RELATIONSHIPS

The axial location of the probe is measured on-line with an optical encoder. This data is recorded simultaneously with the digitized eddy-current data.

B1.3.1 Data Acquisition

B1.3.1.1 Instrumentation. Multifrequency eddy-current equipment with digital recording is used for data acquisition.

B.3.1.2 Probes. The differential bobbin probes with the following parameters are currently in use:

a. All straight sections of tubing (including Rows 1-5) are tested with an probe in 7/8-inch diameter tubing or a probe in 3/4-inch diameter tubing. (U-bends of Rows 1 to 5 may be tested with a diameter probe or a in 7/8-inch and 3/4-inch diameter tubing, respectively, as required.) The use of smaller diameter probes is not accepted.

b. coil grooves with a spacing between adjacent edges.

c. Probe designs incorporate centering fingers that provide for minimum probe wobble and offset. Probes are replaced after full length tubes or an equivalent distance for partial tube length examination. For tubes with sleeves installed on the top of the tubesheet, the tubes are inspected from the cold leg side.

B1.3.1.3 Calibration Standards. Two types of calibration standards are used for the inspection. A reference tube is located in line with the probe injection system and is recorded at the end of each measured tube. The ASME calibration standard is used to establish conventional phase-angle calibration curves for depth estimation.

Reference standard.

- through holes, in diameter, spaced apart around the tube circumference.
- external groove of width and through from the OD.
- internal groove of width and through from the ID.

ASME calibration standard.

- Contains the calibration defects specified in the ASME.
- Contains the reference defects specified in the Reference Standard.
- A simulated support ring, long, composed of the same material as specified for the steam generator model to inspect.

The tolerance on the hole diameters and the depths is

Note: All holes are machined using E.D.M. technique.

B1.3.1.4 Data Acquisition Parameters.

Test frequencies. Required data acquisition channels and coil modes are summarized in Table B1-2. BC eddy-current inspection for ODSCC requires the use of all frequency channels and the Mix-TSP channel. The F2 channel is used for data screening and reporting purposes. The real-time location of the probe is provided with an axial optical encoder located below the reference tube and attached to the manipulator. This information is encoded simultaneously with the eddy-current digital data.

Table B1-2

DATA ACQUISITION CHANNELS/COIL MODES

Digitizing rate. A minimum digitizing rate of samples/mm (samples/in.) is required. Combinations of probe speeds and instrument sample rates should be chosen such that:

$$\frac{\text{Sample Rate (samples/sec)}}{\text{Pancake Coil Speed (in/sec)}} => \quad \text{(samples/in.)}$$

B1.3.2 Data Analysis

This section discusses (1) the methodology for establishing data analysis variables such as amplifications, rotations, mixes, voltage scales, and calibration curves, and (2) the methodology for data evaluation.

B1.3.2.1 Analysis Parameters.

Differential channels.

- Rotation. The signal of the through holes, diameter, apart around the circumference is set following Table B1-3 (phase is measured counterclockwise from

- Amplification. The peak-to-peak signal amplitude of the signal of the through holes, diameter, apart around the circumference is set following Table B1-3.

Table B1-3

ROTATION AND VOLTAGE SCALE FOR EACH CHANNEL AND TSP MIXING

- Calibration Curve. The phase versus depth calibration curve is established using measured signal phase angles in combination with "real" flaw depths (measured mechanically) for the holes. The parameters of each calibration curve are calculated statistically with a representative sample of probes (of the same design and OD diameter) and holes (or flaws). These parameters are considered as constants for each probe design-diameter, steam generator model, and tubing.

TSP mix. For ODSCC under support plates, the TSP mix is established with F2 channel as the primary mixing frequency and F3 as the secondary mixing frequency suppressing the tube support plate simulation. The parameters of each mixing are calculated statistically with a representative sample of probes (of the same design and OD diameter) and support plates (simulation and real).

These values are considered as constants for each probe design-diameter, steam generator model, and tubing.

- Rotation. The signal of the through holes, diameter, apart around the circumference is set following Table B1-3 (phase is measured counterclockwise from and -180 degree).

- Amplification. The peak-to-peak signal amplitude of the signal of the through holes, diameter, apart around the circumference is set following Table B1-3.

- Calibration Curve. The phase versus depth calibration curve is established using measured signal phase angles in combination with "real" flaw depths (measured mechanically) for the holes. The parameters of each calibration curve are calculated statistically with a representative sample of probes (of the same design and OD diameter) and holes (or flaws). These parameters are considered as constants for each probe design and diameter.

B1.3.2.2 Data Evaluation.

Data screening. Any of the differential data channels including the TSP Mix channel is used for flaw detection. Experience has shown that F2 differential channel produces the best correlation with destructive examination of pulled tubes. For small amplitude indications, F3 differential channel may provide an improved sensitivity though this channel is often subject to the adverse influence of many effects not related to tube wall degradation (especially with carbon steel support plates). A flaw-like signal may be described as a vector phase transition usually located at the neighborhood of the center of the support signal.

Reporting. Bobbin coil indications at support plates are reported and quantified using the F2 channel. The peak-to-peak amplitude is measured at the largest part of the flaw-like signal. The phase is measured at the most conservative vector angle found in the flaw-like signal.

Verifying confinement of indication(s) within the support plate region. The X and Y projections of the F2 differential channel and of the F3 absolute channel are superimposed. If the start and the end of the F2 differential flaw-like signal are located within the boundaries of the F3 absolute signal of the support plate, the crack is considered within the length of the support plate. For large indications, the total length of the F2 and/or F3 signal is compared to the nominal length of the signal of a sound tube and support plate.

Probe wear monitoring. Probes are replaced after , full-length tubes or an equivalent distance for partial tube length examination. This conservative value has been determined experimentally in function of the wear of the probe centering devices that was observed during on-site inspections. It is specific to the probe type and speed selected for the Belgian inspection system.

B1.3.3 Reporting Requirements

B1.3.3.1 Minimum Requirements. All flaw-like indications at tube support plate intersections are reported.

B1.3.4 Recording Requirements

For each reported indication, the following information is provided by the analysis software:

- Plant and steam generator identification
- Tube identification (row, column)
- Estimated signal peak-to-peak amplitude (volts)
- Estimated signal depth (%)
- Estimated length (mm)
- Axial position in the tube (location, mm)

B1.4 ROTATING PROBE TUBE EXAMINATION

The RPC inspection of some support plate intersections is performed only on a sample basis.

Table B1-4 provides a definition of rotating probe test frequencies and analysis channels for 7/8-inch OD. x 0.050-inch wall, and 3/4-inch x 0.043-inch tubing. When specific channels are specified for data acquisition and analysis activities, the actual frequencies employed are as defined in the table.

Table B1-4

CHANNEL/FREQUENCY RELATIONSHIPS

The axial and azimuthal locations of the probe are measured on-line with optical encoders. These data are recorded simultaneously with the digitized eddy-current data.

B1.4.1 Data Acquisition

B1.4.1.1 Instrumentation. Multifrequency eddy-current equipment with digital recording is used for data acquisition.

B1.4.1.2 Probes. Vertically mounted pancake coil designs with a coil diameter d, where d is . Rotating probes may incorporate single and multiple pancake coils, with or without a magnetic shield.

B1.4.1.3 Calibration Standards. For both 3/4-inch and 7/8-inch tubing, the calibration standard contains:

- axial EDM notch, wide and long, through-wall.
- axial EDM notch, wide and long, through-wall from the OD.
- axial EDM notch, wide and long, through-wall from the ID.

The three EDM notches are located apart around the circumference. One of their extremities ends at the same altitude for all notches. The tolerance for the widths and the depths of the notches is .. The tolerance for the slot length is .

B1.4.1.4 Data Acquisition Parameters.

Test frequencies. Required data acquisition channels and coil modes are summarized in Table B1-5. The real-time axial and azimuthal locations of the probe are measured with optical encoders. This information is encoded simultaneously with the eddy-current digital data.

Table B1-5

DATA ACQUISITION CHANNELS/COIL MODES

Probe speed. Determined in such a manner that each line scan is separated from the previous one by a distance that is less or equal to per scan line.

Rotation rate. A minimum digitizing rate of sample/mm (samples/in.) is required. Combinations of probe speeds and instrumentation sample rates are chosen such that:

$$\frac{\text{Sample Rate (samples/sec)}}{\text{Pancake Coil Speed (in/sec)}} >= \quad \text{(samples/in.)}$$

where Pancake Coil Speed is translated in rotation per minute as a function of the tube dimension:

$$\frac{60 * \text{Pancake Coil Speed (in/sec)}}{3.14 * \text{Tube OD (in)}} = \text{Rotation Rate (rpm)}$$

This calculation gives for a 7/8-inch tubing and a Laborelec MCMF instrument:

Maximum Pancake Coil Speed = in/sec
Maximum Rotation Rate = rpm.

The actual values for the Belgian inspection system are rpm for the probe rotation and for the axial probe speed.

B1.4.2 Data Analysis

This section discusses (1) the methodology for establishing data analysis variables such as amplifications, rotations, mixes, voltage scales, and calibration curves, (2) the methodology for data evaluation. The methodology assumes that the rotating probes employ vertically mounted pancake coil(s) operated in both differential and absolute modes.

B1.4.2.1 Analysis Parameters.

Rotation. The signal of the axial through-wall notch is set following Table B1-6 (phase is measured counterclockwise from

Amplification. The peak-to-peak signal amplitude of the signal of the axial through-wall notch is set following Table B1-6.

Table B1-6

ROTATION AND VOLTAGE SCALE FOR EACH CHANNEL AND TSP MIXING

B1.4.2.1 Data Evaluation.

Data screening. Any of the differential and absolute data channels is used for flaw detection.

Reporting. Rotating probe indications at support plates are reported and quantified using the F2 differential and/or absolute channels. The peak-to-peak amplitude is measured at the largest part of the flaw-like signal. The phase is measured at the most conservative vector angle found in the flaw-like signal.

Verifying confinement of indication(s) within the support plate region. The start and the end of the flaw-like signal are compared with the signal of the support plate boundaries using a waterfall plot of the X and Y projections of the F2 absolute and differential channels.

Probe wear monitoring. Pancake coils in the probe header are replaced after tube examinations.

B1.4.3 Reporting Requirements

Minimum Requirements. All flaw-like indications at tube support plate intersections are reported.

B1.4.4 Recording Requirements

For each reported indication, the following information is provided by the analysis software:

- Plant and steam generator identification
- Tube identification (row, column)
- Estimated crack orientation
- Largest signal peak-to-peak amplitude (volts)
- Deepest signal depth (%)
- Longest estimated length (mm)
- Number of flaw-like indications around the circumference
- Axial position in the tube (location, mm)

Appendix C

ODSCC GROWTH RATE

This appendix discusses the growth rate of ODSCC indications observed in operating plants. Enveloping average growth rate and a growth rate distribution (cumulative probability) are developed in this appendix for potential applications to plants implementing ARC repair for ODSCC at tube support plates. It is intended that these growth rates be used to assess the conditions of a plant compared to the industry or to estimate a bounding growth rate prior to obtaining plant-specific data.

In an attempt to make the growth rates from different plants more comparable, growth rates per effective full-power year (EFPY) have been calculated in each case. However, it must be pointed out that this treatment in itself does not make the growth rates comparable since there are myriad of other parameters that affect growth.

The growth rates (of bobbin coil voltage) are calculated for each indication by subtracting the beginning of cycle (BOC) voltage from the end of cycle (EOC) value. Further, the growth rates are divided by the operating cycle duration in EFPY. For plants with operating cycles less than 1.0 EFPY in duration, the negative growth values are not divided by the EFPY to avoid inflating the negative values.

The results described below are for indications at tube support plate (TSP) elevations only. Unless otherwise stated, the eddy-current results described in this appendix are based on procedures consistent with the eddy-current testing of model boiler specimens in the laboratory. In the case of 7/8-inch diameter (50-mil wall thickness) tubing, the data represents mix channel, with normalization of deep holes in the ASME standard set to . In the case of 3/4-inch diameter (43-mil wall thickness) tubing, the data is for mix, with normalization of the holes in the ASME standard set to volts.

In figures displaying frequency distributions, the upper ends of the bin ranges are shown on the x-axis. Where useful, cumulative frequency in percent is shown as a curve with the scale displayed on the right-hand side of the figure.

C.1. PLANT A

Plant A has two units with steam generators of the same design. Consistent eddy-current inspection and analysis guidelines have been used for the last two outages in Unit 1 (A-1). The same guidelines have been applied during only the last outage of A-2. The guidelines include the use of the transfer standard to make the bobbin amplitudes consistent with the laboratory model boiler data, and the use of a probe wear standard to guide replacement of worn out probes. In each case, the bobbin coil eddy-current results are based on consistent analyses performed for consecutive inspections.

Plant A-1 had over indications among the three steam generators. The maximum bobbin amplitude during the 1992 inspection was volts. Figure C-1 shows a frequency distribution of the bobbin amplitudes from the 1992 inspection. Over of the indications were below volt in amplitude and were below volts. This is the EOC condition. Growth rates of these indications are plotted against their BOC amplitudes in Figure C-2. It may be noted that most of the growth rates are clustered below volt/EFPY. There are only indications (out of over) with growth rates greater than volt/EFPY. The maximum growth rate is volt/EFPY. This figure also shows that the voltage growth rate in this unit (Plant A-1) was independent of the BOC amplitude. A frequency distribution of the growth rates is shown in Figure C-3. The mode is the range of volt/EFPY. The cumulative frequency distribution shows that over of the indications had growth rates below volt/EFPY and over volt/EFPY.

Table C-1 summarizes the growth rate data for Plant A-1 for the last five cycles.

Table C-1

PLANT A-1 GROWTH RATE SUMMARY

Figure C-1. Plant A-1 Voltage Distribution

Figure C-2. Plant A-1 Voltage Growth (1990-92)

Figure C-3. Plant A-1 Voltage Growth (1991-92)

It may be noted that although eddy-current analysis guidelines have been applied consistently for all data, the ARC-recommended inspection guidelines were employed only during the 1991 and 1992 inspections. As a result, the NDE uncertainty is much smaller in the data for the last cycle. The last column shows the average growth rate as a percent of the BOC average amplitude. The indications from the last cycle were classified into two groups: indications with BOC amplitude less than volt in one group, and those with amplitudes equal to or greater than volts in the other. The averages were determined for each group as listed in the table. It may be noted that the average growth rates of the two groups are nearly equal in this unit (Plant A-1). Growth rate as a percent of the BOC amplitude is much higher for the low-voltage indications than for the other group.

Plant A-2 had over TSP indications in 1992. A frequency distribution of the EOC amplitudes are shown in Figure C-4. Nearly of the indications were less than volt in amplitude and were below volts. The largest amplitude was volts, the only indication above volts. Growth rate vs. BOC amplitude is displayed in Figure C-5. Although the 1990 EC data were reanalyzed per the ARC guidelines for the growth rate assessment, it may be noted that inspection guidelines consistent with the ARC were not applied during the 1990 inspection of this unit. This may explain the large number of negative growth values (relative to Plant A-1) observed. The growth rates are clustered below volt/EFPY. Further, the growth rates appear to decrease with increase in BOC amplitude. The highest growth rate was volt/EFPY. The frequency distribution of growth rates in Figure C-6 shows that more than of the indications had growth rates below volt/EFPY and the percentile was volt/EFPY. Only indications (out of over) had growths exceeding volt/EFPY.

Summary of the Unit 2 growth rate is shown in Table C-2. It may be noted that the growth rates are lower for the indications with larger BOC amplitudes ($V_{BOC} \geq$ volt) than for those below volt in BOC amplitude. This difference is further magnified when growth rates expressed as percent of the BOC amplitude are compared. The very low voltage growth of the larger indications suggests that the progression rate of ODSCC corrosion is very small.

Figure C-4. Plant A-2 Voltage Distribution

Figure C-5. Plant A-2 Voltage Growth (1990-92)

Figure C-6. Plant A-2 Voltage Growth (1990-92)

Table C-2

PLANT A-2 GROWTH RATE SUMMARY

C.2 PLANT D-1

Over indications were reported in Plant D-1 during the 1992 inspection. Figure C-7 shows a frequency distribution of the bobbin amplitudes. Over of the indications are less than volts in amplitude and are below volts. The highest amplitude was volts. The growth rates of the indications are plotted as a function of the BOC amplitude in Figure C-8. More negative growth values were observed at higher BOC amplitudes than at low amplitudes. The largest growth rate was about . volt/EFPY. This is the lowest value observed for maximum growth rate in any plant to date. Figure C-9 shows a frequency distribution of the growth rates. The growth rates are in the range between volt/EFPY. Well over of the indications had growth rates less than volt/EFPY and had growth rates below volt/EFPY.

The growth rate summary of Plant D-1 indications is shown in Table C-3. It may be noted that the growth rate was extremely low, the average being volt/EFPY. Further, the growth rates were significantly lower at higher BOC amplitudes than at low amplitudes. Therefore, as percent of the BOC amplitude, the average growth rate for indications at or above volt BOC amplitudes was an order of magnitude lower than the average for indications less than volt, BOC.

Figure C-7. Plant D-1 Voltage Distribution

Figure C-8. Plant D-1 Voltage Growth (1990-92)

Figure C-9. Plant D-1 Voltage Growth (1990-92)

Table C-3

PLANT D-1 GROWTH RATE SUMMARY

C.3 PLANT F

Plant F has exhibited a large number of TSP indications in the cold leg. Less than a quarter of the nearly indications reported in 1992 were in the hot leg. Figure C-10 shows the frequency distribution of bobbin amplitudes in Plant F from the 1992 inspection. More than of the indications were below volts and were below volts. The largest amplitude was volts. Growth rate vs. BOC amplitude displayed in Figure C-11 shows growth rates clustered below volt/EFPY. A relatively large number of negative growth values were observed, with of them approaching volt/EFPY. A slight negative dependency on BOC amplitude is visible. The frequency distribution of voltage growth rates is shown in Figure C-12. About of the indications were below volt/EFPY and were below volt/EFPY. Seven indications had growth rates about volt/EFPY.

A summary of the Plant F growth rate data is provided in Table C-4. The 1991-92 data shows that the average growth rate for indications with BOC amplitudes less than volt is nearly equal to that for indications of higher BOC amplitude. Average growth rate as percent of BOC amplitude for the low amplitude indications is nearly twice that of the larger BOC voltage indications.

Figure C-10. Plant F Voltage Distribution

Figure C-11. Plant F Voltage Growth (1991-92)

Figure C-12. Plant F Voltage Grc wth (1991-92)

Table C-4

PLANT F GROWTH RATE SUMMARY

C.4 PLANT R-1

Plant R-1 is a unit with 3/4-inch diameter tubing in the steam generators. Nearly indications were reported in the 1992 inspection of this unit. Figure C-13 shows a frequency distribution of the EOC bobbin amplitudes from the 1992 outage. It may be noted that well over of the indications are less than volt in amplitude and more than have amplitudes less than volt. Only of the nearly indications have amplitudes greater than) volts. The largest indication signal was volts. A scatter plot of the voltage growth rates against BOC amplitudes is shown in Figure C-14. A negative sloped correlation between growth rate and BOC amplitude is clearly visible. Figure C-15 shows a frequency distribution of the growth rates. More than of the indications had growth rates below volt/EFPY. Only of the nearly indications had growth rates exceeding volt/EFPY, the largest being volt/EFPY.

A summary of the growth rate statistics from the last two cycles is listed in Table C-5. It may be noted that both the absolute and the percent growth rates are very low. The average growth rate of the entire population is only volt/EFPY. The average growth rate of the indications with BOC amplitudes at or above volt is negative (volt/EFPY). These facts suggest that the progression of ODSCC during the 1991-92 cycle was negligible.

Figure C-13. Plant R-1 Voltage Distribution

Figure C-14. Plant R-1 Voltage Growth (1991-92)

Figure C-15. Plant R-1 Voltage Growth (1991-92)

Table C-5

PLANT R-1 GROWTH RATE SUMMARY

C.5 PLANT S

Plant S has three steam generators with 3/4-inch diameter tubing. During the 1993 outage, five large indications were reported at the flow distribution baffle in one steam generator. In each case, most of the growth had occurred during the last operating cycle. Not only were the indication amplitudes and their growth rates large, but they were all at the flow distribution baffles (FDBs) in S/G B. This is highly atypical. In Plant R-1, in contrast (see paragraph C.4), only of the nearly indications were at the FDB and their growth rates were negligibly low. Thus, in Plant S, the number of indications at the FDB and the growth rates of the largest of these were unique.

All large indications in the FDB were in the same steam generator. The eddy-current inspection results of the indications are summarized in Table C-6. These results are based on reevaluation of the field eddy-current data performed as per the ARC eddy-current analysis guidelines. The bobbin amplitudes of these indications ranged from about volts at volts. All remaining indications were below volts in amplitude.

Figure C-16 shows a frequency distribution for Plant S indications as a function of bobbin amplitude without the indications at the FDB. About of the indications were below volts in amplitude and were below volts. A plot of the voltage growth rate as a function of BOC amplitude is shown in Figure C-17. The data appears similar to that observed at other plants. Although there is scatter, the growth rates in general appear to decrease with BOC amplitude.

Table C-6

SUMMARY OF 5 LARGEST FDB INDICATIONS FROM PLANT S

Figure C-16. Plant S Voltage Distribution

Figure C-17. Plant S Voltage Growth (1991-93)

Figure C-18 shows a frequency distribution of the growth rates. It may be noted that about of the indications had growth rates below volt/EFPY and had growth rates below volt/EFPY.

Figure C-18. Plant S Voltage Growth (1991-93)

The TSP indication growth rates (excluding the largest indications in the FDB) from Plant S are summarized in Table C-7. The average growth rates during the last cycle appear similar to those observed at other plants and are smaller than the prior cycle at Plant S. The indications with BOC amplitudes at or above volts exhibited lower growth than those below volts. Differences in these average growth rates as a percent of BOC amplitude was over a factor of (/EFPY for the low BOC amplitude indications vs. /EFPY for the larger ones).

Table C-7

PLANT S GROWTH RATE SUMMARY

C.6 EFFECT OF TSP ELEVATION

ODSCC growth rates as a function of TSP elevation in the steam generator has been examined for each of the six plants discussed in this appendix. For example, distribution of the indications among various TSP elevations and the corresponding growth rates for Plant A-1 are shown in Figures C-19 and C-20. Figure C-19 shows a frequency distribution of the indications with hot leg TSP elevation. TSP 1H is the lowest TSP location in the Plant A-1 steam generators and 7H is the highest. Figure C-19 also shows average bobbin amplitudes at each TSP elevation, from the 1992 inspection. This shows that the bobbin amplitudes were independent of TSP elevation. Figure C-20 (average growth rates vs. TSP designation) shows that the growth rates were also independent of TSP elevation. Similar results were obtained for the other five plants.

Figure C-1º. Plant A-1 TSP Indications (1992)

Figure C-20. Plant A-1 Voltage Growth (1991-92)

C.7 BELGIAN & FRENCH PLANTS

To increase the supporting database, it is desirable to be able to use data from Belgian and French plants. Eddy-current test frequencies and calibration procedures used in those plants are different from the standard U.S. practice. Hence, it is necessary to renormalize available data to the calibration values used in this report. When mix or data normalized to an ASME standard are available, the renormalization is a straightforward ratio of the calibration voltage values. However, when different frequencies are used, normalization ratio is phase angle or depth dependent. The depth dependence is accommodated in developing voltage renormalization by defining a correlation between ARC and French/Belgian voltages as described in References C-1 and C-2.

C.7.1 Belgian Plants

Growth rate data were obtained for Plant E-4 for the 1991-1992 cycle. A wide range of growth rates was found with a tendency for the growth to increase with increasing BOC voltage. Growth rates up to a maximum of volts were obtained in this cycle. The average growth rate for indications was found to be volts with a standard deviation of volts. These rates are considerably higher than average growth rates for domestic plants.

C.7.2 French Plants

Voltage growth data were obtained for French Plant H for 3 cycles and Plant J-1 for 1 cycle. The data for Plant H are described followed by the data for Plant J-1.

Figure C-21 shows the 1990 EOC voltage distribution for Plant H. Voltages up to volts were obtained in this cycle. The voltage growth per EFPY as a function of BOC amplitude is shown in Figure C-22. Voltage growth is seen to increase with BOC amplitudes up to volts. The frequency distribution for growth in the 1989-90 cycle is shown in Figure C-23. Table C-8 summarizes the growth rate. The overall average growth rate is volt/EFPY, which corresponds to a average growth. Average percentage growth rates are seen to be approximately independent of BOC voltage while ranging from

Similar data is shown for Plant J-1 in Figures C-24 to C-26 and Table C-8. Growth rates up to volts/EFPY are shown in Figure C-26. As found for Plant H, the percentage growth rates are essentially independent of BOC amplitude

Figure C-21. Plant H Voltage Distribution

Figure C-22. Plant H Voltage Growth (1989-90)

Figure C-23. Plant H Voltage Growth (1989-90)

Figure C-24. Plant J-1 Voltage Distribution

Figure C-25. Plant J-1 Voltage Growth (1990-91)

Figure C-26. Plant J-1 Voltage Growth (1990-91)

Table C-8

PLANTS H AND J-1 GROWTH RATE SUMMARY

C.8 CONCLUSION

ODSCC voltage growth rates are used in calculation of tube repair limits and for accident leakage analyses. For the repair limits, which incorporate Regulatory Guide 1.121 safety margins of three times normal operating pressure differential, a bounding average growth rate for the next operating cycles is required. For predicted accident leakage analyses, a distribution of growth rates for the next operating cycle is required. When available, plant-specific data should be applied for growth rates. The growth data described in this section can be used for initial cycle ARC applications until plant-specific data are obtained.

Table C-9 summarizes average percent growth per EFPY for domestic plants. The data show a tendency for lower percentage growth in the later cycles. For the eight plants, the largest growth in the last cycle was ΔV per EFPY. Except for one cycle in Plant L and an early cycle in Plant A-1, the domestic growth rates are bounded by ΔV per EFPY.

Assessment of ODSCC growth in a French and Belgian plant show that growth rates are much higher than observed in domestic plants. This difference may be due to a combination of factors, but most likely it is due to differences in secondary water chemistry. Domestic plants utilize boric acid secondary water chemistry treatment while French and Belgian plants do not.

Insight into growth rate trends can be obtained by assessing average growth as a function of BOC voltage. Figure-C-27 shows this trend for the last cycle of the plants in this appendix. A decreasing percent growth for initial BC voltages is noted. In spite of the larger growth rates, the French data at higher BOC voltages show the same trend.

For alternate repair limit applications, a growth rate is required at about volts which exceeds the current domestic data. It is conservative to assume that growth rates will show percentage growths near volts comparable to that found for the low-voltage range (volts). And, it appears that a domestic growth rate of ΔV per EFPD will bound average growth rates near volts. This growth allowance is suggested for repair limit development for plants without available growth histories for at least two cycles.

Table C-9

SUMMARY OF AVERAGE PERCENT GROWTH
PER EFPY FOR DOMESTIC PLANTS

For SLB leakage analyses, it is only necessary to obtain growth distributions applicable to the next operating cycle as contrasted to projecting domestic growth rates to the volt range for repair limits. Typically, a plant can use changes in voltage from the last one or two cycles for the growth distribution. The use of ΔV changes is preferred over %ΔV as ΔV is distorted by large percentage changes at very small voltages. As can be seen by the frequency distributions for the change in amplitude (ΔV per EFPY) given in this appendix, the growth distributions do not follow a normal distribution. The growth distributions typically have a small negative contribution due to measurement uncertainties and an extended, low-frequency tail to larger ΔV values. Peak frequencies are typically in the volt range for domestic data. In general, a cumulative probability distribution, such as shown for the growth frequency distributions in this appendix, can be used for the growth distribution. This eliminates the need to postulate an analytical representation, such as a normal distribution, for the growth rates. It is suggested that the negative growths be eliminated by defining a cumulative probability with a step change from zero to an appropriate cumulative percentage at ΔV = 0.

To define a voltage growth distribution for plants without historical data, a bounding cumulative probability distribution can be developed from the data in this appendix. Figure C-28 shows such a bounding distribution which envelopes the growth distributions for Plants A-1, A-2, D-1, F, R-1, and S in this appendix. Table C-10 provides a tabulation for this distribution. The voltage growth distribution of Table C-10 is a reasonable estimate of a bounding growth distribution for applications to plants without plant-specific growth rates.

Figure C-27. Average ODSCC Growth Rate Measured During the Last Cycle at Six Plants. Data for Initial Voltages <0.75 Volts and >0.75 Volts.

Figure C-28. Cumulative Probability Distribution for Voltage Growth

Table C-10

BOUNDING VOLTAGE GROWTH DISTRIBUTION
FOR DOMESTIC PLANTS

C.9 REFERENCES

1. A. J. Baum et al. Outside Diameter Stress Corrosion Cracking of Steam Generator Tubing at Tube Support Plates - A Database for Alternate Repair Limits, Volume 2: 3/4 Inch Diameter Tubing. Palo Alto, Calif.: Electric Power Research Institute. NP-7480-L, Vol. 2, March 1993 (Draft).

2. A. J. Baum et al. Outside Diameter Stress Corrosion Cracking (ODSCC) of Steam Generator Tubing at Tube Support Plates - A Data Base for Alternate Repair Limits, Volume 2: 7/8 Inch Outside Diameter (OD) Tubing. Palo Alto, Calif.: Electric Power Research Institute. NP-7480-L, Vol. 1, Draft Revision 1, June 1993.

Appendix D

ANALYSIS METHOD FOR LEAK RATE CALCULATION

D.1 INTRODUCTION

This appendix describes a method for predicting the primary-to-secondary leakage which may occur during a main steam line break (MSLB) design basis accident in a pressurized water reactor (PWR) steam generator with axial through-wall outside diameter stress corrosion cracking (ODSCC) at the tube support plate intersections. The method is based on correlation of individual tube leak rates vs. eddy current bobbin coil voltage using test data obtained for pulled tubes and model boiler specimens which exhibited ODSCC. Correlations are provided for both 3/4" and 7/8" mill-annealed Alloy 600 tubing.

Predicted individual tube leak rates are calculated at a high probability/confidence level. Predicted total leak rate for the limiting steam generator is thereby established at a suitably conservative level.

D.2 OVERVIEW

The experimental program and test results which were used to assemble the leak rate data base for 3/4" and 7/8" mill-annealed tubing is discussed in references [D.1, D.2]. These data include result from pulled tubes from the field and model boiler specimens. The model boiler test results are conservatively restricted to open crevice conditions (see discussion in other parts of this document). The data which were used to develop the leak rate correlations are provided in tables D-1 and D-2. These data are provided for two differential pressure conditions: psi and psi. It is noted that MSLB differential pressure is typically predicted to be psi. Data and the corresponding correlations will be provided for that differential pressure in a future revision to this report.

Based on a review of the leak rate test data, it can be concluded that not all tubes (with confirmed ODSCC at TSPs) leak when subjected to the differential pressure of the design basis faulted load accident. This was the case, even for those tubes with through-wall ODSCC.

These facts lead naturally to a model where the amount of leakage which may occur under applicable design basis faulted loads is determined by calculating the product of two factors:

1. the probability that the tube will leak,

2. the conditional leak rate (i.e., the leak rate for those tubes which do leak)

Such an approach was used to develop equations for predicting the leak rate for an individual tube based on eddy-current bobbin coil voltage measurements obtained from steam generator inspections. Details of the data analysis which was performed are described in section D.3.

The leak rate model can be used to predict individual leak rates under accident conditions for a particular tube intersection with a specified measured voltage. The probability of leakage correlation and the conditional leak rate correlation provide a best-estimate prediction which is based on the available field and laboratory data. Due to a number of uncertainties in the input variables to the leak rate model, the leak rate for an individual tube may deviate from the value predicted by these correlations. The following uncertainties are explicitly addressed in the predicted EOC leak rates:

1. voltage growth by EOC due to defect progression,

2. uncertainty in the predicted probability of leakage correlation fit,

3. uncertainty in the conditional leak correlation fit,

4. "scatter" of the leak rate data about the leak rate correlation,

5. uncertainties due to eddy current measurement variability

A statistical approach has been applied to account for uncertainties in the predicted leak rates. Predicted leak rates are adjusted, in a conservative direction, by an amount which is termed the leak rate *margin*. For a particular tube intersection, the predicted leak rate at end of cycle (EOC) - with margin applied for uncertainties is:

$$\dot{Q}_{EOC} =$$

where:

$\dot{Q}_{EOC}$	is the predicted tube leak rate at EOC
$\dot{Q}(V_{BOC})$	is the predicted conditional leak rate at BOC
$P_{leakage}(V_{BOC})$	is the probability of leakage at BOC
$\Delta\dot{Q}$	is the margin to cover voltage growth by EOC and uncertainties calculated at the level

Predicted accident leak rates at the end of the operating cycle (EOC) are based on a (predicted) distribution of EOC voltage measurements. The predicted distribution of EOC voltage measurements is determined by statistically combining the "as-measured" BOC voltage distribution for a steam generator with a statistical distribution of voltage increase due to defect growth. The amount of growth any given indication will experience is uncertain; however, industry experience and plant-specific inspection results over operating cycles can be used to characterize this uncertainty statistically.

The prediction of individual tube leak rates is based on bobbin coil voltage measurements which are made in the field. Measured voltages are subject to variations due to the following factors:

1. probe wear,
2. calibration of field equipment to standards,
3. analyst interpretation, and
4. probability of detection.

Details of the method which is applied to account for these uncertainties and thereby to determine the leak rate margin are described in section D.4

The procedure for site-specific analysis of predicted accident leak rate is described in section D.5. Examples of the application of this procedure to typical inspection results are provided in section D.6.

Table D-1

3/4 INCH LEAK RATE DATA FOR ODSCC AT TUBE SUPPORT PLATES

Normal Operating Condition and MSLB Accident Conditions

Table D-1 (cont'd)

3/4 INCH LEAK RATE DATA FOR ODSCC AT TUBE SUPPORT PLATES

Normal Operating Condition and MSLB Accident Conditions

Table D-1 (cont'd)

3/4 INCH LEAK RATE DATA FOR ODSCC AT TUBE SUPPORT PLATES

Normal Operating Condition and MSLB Accident Conditions

Table D-1 (cont'd)

3/4 INCH LEAK RATE DATA FOR ODSCC AT TUBE SUPPORT PLATES

Normal Operating Condition and MSLB Accident Conditions

Table D-2

7/8 INCH LEAK RATE DATA FOR ODSCC AT TUBE SUPPORT PLATES

Normal Operating Condition and MSLB Accident Conditions

Table D-2 (cont'd)

7/8 INCH LEAK RATE DATA FOR ODSCC AT TUBE SUPPORT PLATES

Normal Operating Condition and MSLB Accident Conditions

Table D-2 (cont'd)

7/8 INCH LEAK RATE DATA FOR ODSCC AT TUBE SUPPORT PLATES

Normal Operating Condition and MSLB Accident Conditions

Table D-2 (cont'd)

7/8 INCH LEAK RATE DATA FOR ODSCC AT TUBE SUPPORT PLATES

Normal Operating Condition and MSLB Accident Conditions

Table D-2 (cont'd)

7/8 INCH LEAK RATE DATA FOR ODSCC AT TUBE SUPPORT PLATES

Normal Operating Condition and MSLB Accident Conditions

D.3 PREDICTED LEAK RATES FOR TUBES WITH ODSCC AT TUBE SUPPORT PLATES (TSPs)

This section describes elements of the method for predicting individual tube leak rates under MSLB accident conditions for Alloy 600 steam generators with ODSCC at TSPs. Leak rate uncertainty analysis by Monte Carlo calculation is described insection D.4. Implementation in the field is described in section D.5. Example calculations for both 3/4" and 7/8" tubing sizes are described in section D.6.

D.3.1 Probability of Leakage Under Accident Conditions

Not all tube support plate locations with confirmed ODSCC indications will leak under accident conditions. It is unlikely that a tube will leak for indications exhibiting small bobbin coil voltage measurements. There are a number of factors which may contribute to whether or not a specific indication will leak; these factors are discussed in references [D.1, D.2]. The probability of tube leakage will be treated explicitly in the overall leak rate calculations.

The probability of leakage is determined from the magnitude of the bobbin coil voltage measurement for a specific TSP intersection. For a number of TSP intersections with equal amounts of degradation (i.e. eddy current bobbin coil voltage) a proportion are predicted to be "leakers" and the complementary proportion to be "non-leakers".

The logistic function represents the probability of leakage for the leak rate model. This probability distribution is appropriate for binary-type variables such as the leak/no-leak designation. The logistic function relates the magnitude of a bobbin coil voltage measurement at a specific TSP intersection to the probability of leakage for that measurement.

The probability of leakage for an ODSCC produced voltage measurement at a specific TSP location is determined by the bobbin coil voltage based logistic function:

$$P_{leakage}(V) = \qquad [D\text{-}1]$$

Logistic functions arise as the solutions to a differential equation which relates the rate of change (in this case of the probability of leakage) to the logarithm of bobbin coil voltage. [D-1] is equivalent to the differential equation form:

$$\frac{dP}{dx} =$$

where x represents the logarithm of measured voltage and $g(x)$ is termed the *logit* function; that is, the linear form within brackets in [D-1]:

$$g(x) =$$

Equation [D-1] is equivalent to:

$$\ln\left(\frac{P}{1-P}\right) =$$

From the differential equation form, it can be seen that the rate of change of the probability of leakage is proportional to both the probability for a given voltage, the probability of no-leakage and the linear function $g(x)$.

The parameters of this logistic function are determined by an iterative maximum likelihood procedure which is applied to the leak/no-leak data. Probability of leakage correlations are obtained for 3/4 inch tubing and for 7/8 inch tubing. Values of the logistic coefficients are calculated by using a commercial software package (reference D.5). These coefficients, and the related variance-covariance values $(\Gamma_{11}, \Gamma_{12}, \Gamma_{22})$ are provided in Table D-3. The application of these values is described in section D.4.2.5.

Table D-3

PROBABILITY OF LEAKAGE CORRELATION PARAMETERS

Mill-Annealed Alloy 600 Tubes with ODSCC at TSPs

Predicted probability of leakage for an indication with a specified bobbin coil voltage is then determined by evaluating equation [D-1]. Figures D-1 and D-2 provide graphs of the predicted probability of leakage versus bobbin coil voltage based on the coefficients listed in Table D-3 for 3/4 and 7/8 inch tubing, respectively. A tabulation of the predicted probability of leakage for measured bobbin coil voltages for both 3/4 and 7/8 inch tubing with ODSCC at TSPs is provided in Table D-4.

Table D-4

PROBABILITY OF LEAKAGE UNDER ACCIDENT CONDITIONS

Mill Annealed Alloy 600 Tubes with ODSCC at TSPs

Figure D-1. Probability of Leakage for 3/4 Inch Tubes with ODSCC at TSPs

Figure D-2. Probability of Leakage for 7/8 Inch Tubes with ODSCC at TSPs

D.3.2 Predicted Conditional Leak Rate Under Accident Conditions

The experimentally obtained leak rate data for both 3/4 inch and 7/8 inch tube sizes indicate a bi-logarithmic relationship exists between measured leak rate and measured bobbin coil voltage amplitude. These data have been used to develop the conditional leak rate correlations for the two tube sizes. The conditional leak rate correlation will be used to predict the leak rate for an individual tube (at a TSP location with confirmed ODSCC) from the measured bobbin coil voltage amplitude.

The relationship between individual leak rate and measured bobbin coil voltage is of the form:

$$\dot{Q} = \qquad \text{[D-2]}$$

Taking the logarithms of both sides of [D-2] yields the equivalent linear form:

$$\log_{10}(\dot{Q}) = \qquad \text{[D-3]}$$

where $\beta_0 =$ and $\beta_1 =$.

The following correlations were developed from the field and test data for two differential pressure conditions (psi and psi):

[D-4]

[D-5]

[D-6]

[D-7]

It is noted that psi is a typical predicted MSLB differential pressure for many plants; correlations for 3/4 inch and 7/8 inch tubes will be developed in the future and incorporated in subsequent revisions to this report.

Detailed discussion of the regression analysis methods which were used to develop these correlations are provided in sections D.3.2.1 - D.3.2.5.

A measured leak rate for a particular data point k will deviate from the leak rate relationship defined by equation [D-3] by a random amount. This random deviation[1] is represented by the symbol ε and is added to the equation:

$$\log_{10}\left(\dot{Q}_k\right) =$$

The standard least squares linear regression analysis (reference [D.6]) was applied to the leak rate data sets to obtain:

1. values of the linear coefficients,
2. value for the variance of the residual deviations,
3. verification of a statistically significant non-zero slope,
4. demonstration of the normality of residual variations, and
5. one-sided prediction limits for leak rate given a measured voltage

From this analysis it was demonstrated that the random variation of the data about the correlation line is defined by a normal distribution with mean of zero and variance σ_ε^2.

These results are described for data taken at the test condition of psi and the data which were scaled (references [D.1 and D.2]) to psi. A conservative procedure for scaling of predicted leak rates to lower differential pressures is described in section D.3.5.

---

[1]The difference between an individual leak rate data point and the correlation line is designated the residual deviation for that data point. The residual deviation is assumed to be normally distributed about the regression line with a mean value of zero and a variance σ_ε^2.

D.3.2.1 Linear least-squares regression analysis Least-squares regression analysis methods have been applied to the 3/4 inch and 7/8 inch leak rate data listed in Tables D-1 and D-2. Results from the linear regression analysis are described in section D.3.3. The least-squares method for calculating the slope and intercept of the underlying linear model consist of evaluating two equations based on the available field and test data:

$\hat{\beta}_1 =$

$\hat{\beta}_0 =$

with the following nomenclature:

$m_{XX} =$

$m_{XY} =$

$\overline{Y} =$

$\overline{X} =$

$Y_i =$

$X_i =$

D.3.2.2 Analysis of variance table and standard error Linear regression analysis provides estimates of the coefficients in the relationship between log leak rate and log bobbin coil voltage by minimizing the least squared deviation between the line and the data points with respect to the leak rate axis. The portion of the total variation of the data set which is explained by the assumed model used in the regression analysis (equation D-3) is obtained from the standard analysis of variance (ANOVA) table.

The ANOVA results for the accident conditions of psi and psi for 3/4 inch and 7/8 inch tubes are presented in Tables D-5 to D-8. From these tables it can be concluded that each of the four linear regressions explains a statististically significant portion of the variability of the data set. The support which these data provide for a non-zero linear relationship between log-voltage and log-leak rate can be inferred from these tables; this is discussed further in section D.3.2.3.

Table D-5

ANALYSIS OF VARIANCE RESULTS FOR 3/4 INCH TUBES

Table D-6

ANALYSIS OF VARIANCE RESULTS FOR 3/4 INCH TUBES

Table D-7

ANALYSIS OF VARIANCE RESULTS FOR 7/8 INCH TUBES

Table D-8

ANALYSIS OF VARIANCE RESULTS FOR 7/8 INCH TUBES

The mean square about the regression provides an estimate, based on n-2 degrees of freedom, of the variance of the unexplained residual deviation of the data about the regression; σ_ε^2. If the regression line was determined from an infinitely large number of measurements, the variance about the regression line would represent a measure of the error with which any observed value of log leak rate could be predicted from a given value of log bobbin coil voltage using the determined equation. The standard error, $\hat{\sigma}_\varepsilon$, is determined directly as the square root of the mean square about the regression and is used in the calculation of one-sided prediction limits and in the Monte Carlo calculations which are described in section D.4.

As previously stated, results from the ANOVA table form the basis for standard tests of the statistical support for a hypothesis of non-zero slope in the linear regression line which is described below.

D.3.2.3 Statistical test for non-zero slope It is routine to evaluate, based on the data, whether significant evidence exists for a linear regression line with zero slope. Such evidence would indicate that log leak rate does not have a linear relationship to log bobbin coil voltage; but rather, that only a spurious relationship may exist. The standard approach to evaluate this important issue is termed the "F-test for Significance of Regression" (reference [D.6]).

Because the log leak rate values are random variables, any function of them is also a random variable. This means that both the mean square due to regression and the mean square about the regression are random variables. The significance of this is that both these quantities have probability distributions.

It can be shown that the mean values of these variables are as follows:

$$E\left[MS_{Reg}\right] =$$

$$E\left[\hat{\sigma}_\varepsilon^2\right] =$$

where E[ ] represents the expected or mean value of the variable enclosed within the parens. If the relationship expressed by equation [D-3] has zero slope, $(\beta_1 = 0)$, the ratio of these two values is equal to one.

If the random deviations of the log leak rate values about the linear regression line are independent and normally distributed then it is known that the ratio

$$F = \quad [D\text{-}8]$$

follows a standard F distribution with 1 and n-2 degrees of freedom, provided that there exists a zero slope ($\beta_1 = 0$).

A standard statistical test of the extent to which a data set supports the hypothesis of a zero slope is therefore performed by comparing the calculated value of F with the value of the F(1, n-2) distribution from published statistical tables.

If the calculated value of F is less than the value from published tables, it is concluded that the data provide *insufficient* evidence to support a hypothesis of zero slope. Conversely, if the calculated value of F exceeds the published value, it is concluded that the data provide sufficient evidence to support a hypothesis of zero slope. Results from applying this standard test will be provided in subsequent sections.

D.3.2.4 Examination of residual variations The residual deviation is that variation which remains between a measure value and the value predicted by the linear regression line:

$$\varepsilon_i =$$

In other words, the residual deviation is the amount of variation in the data set which the regression line is unable to explain. In performing the regression analysis, the following assumptions have been made:

1. deviations are independent,

2. deviations have zero mean and constant variance,

3. deviations follow a normal distribution

If the fitted linear regression line is correct, then the residual deviations should tend to confirm these assumptions. This section describes two procedures for judging the adequacy of the proposed linear form of the relationship between log leak rate and log bobbin coil voltage. These procedures are based on evaluating the residual deviations from the linear regression line.

D.3.2.4.1 Normal probability graph If the linear regression line is the correct model of the relationship between log leak rate and log bobbin coil voltage then graphing the residual deviations on normal probability paper is expected to result in essentially a straight line. While somewhat subjective, this does provide one measure of the correctness of the regression line.

If the linear regression model is incorrect (for example, if a second order term should be specified), then the residual deviations will consist of two parts:

a. the true normally distributed residual error, and
b. the (possibly systematic) deviation from the correct model. This term is also referred to as the contribution to the residual sum of squares due to *lack of fit*.

In this case, a normal probability plot of the residuals may indicate a lack of normality due to the presence of the lack of fit component.

The method consists of graphing the ordered residual deviations versus the plotting position 100(i-0.5)/n for i=1,...,n on a normal probability graph. If the plotted points lie approximately on a straight line, then it is concluded that the data support assumption 3 of section D.3.2.4.

These graphs were prepared using the fitted linear regression lines for MSLB Δp of psi and psi and are presented in section D.3.3. These graphs resulted in approximately straight line relationships as was expected if the deviations are normally distributed.

D.3.2.4.2 Residuals vs. fitted variable graph A second conventional approach is to graph the residual deviation versus the predicted (log leak rate) value for all data points. The expected result is a horizontal band of constant variance. Abnormality of the graph would be indicated if any of the following occur:

1. variance does not appear to be constant,
2. systematic departure from the fitted equation (negative residuals for low predicted values and positive residuals for high predicted values), and
3. "curvature" in scatter of the residual deviations, indicating need to account for other variables

These graphs were prepared using the fitted linear regression lines for MSLB Δp of psi and psi and are presented in section D.3.3. These graphs resulted in approximately horizontal bands of the plotted residual deviations, consistent with a correctly specified model.

D.3.2.5 One-sided prediction limits A one-sided upper prediction limit specifies, with a given level of confidence, an upper limit for an individual leak rate based on a measured bobbin coil voltage, V_0. These are limits in the statistical sense; that is, the probability that an individual tube will have a leak rate which exceeds the limit is small, conventionally no more than %. This is equivalent to a 100α% level of confidence where in this case α= .

That is, the probability is at least 100α% that an individual (log) leak rate value will be less than the limit:

[D-9]

where t is the 100α% value of Student's t distribution with n-2 degrees of freedom, $\hat{\sigma}_\varepsilon$ is the square root of the mean residual sum of squares as calculated from the ANOVA table, and X_0 is the value of log of the measured BC voltage for which the prediction limit is to be calculated. Equation [D-9] is also used in the Monte Carlo simulation calculation described in section D.4.

Graphs of the field and test data and the corresponding fitted correlation lines are presented in Figures D-3 to D-6.

Figure D-3. Leak Rate Correlation for 3/4 Inch Tubes at $\Delta p =$ psi

Figure D-4. Leak Rate Correlation for 3/4 Inch Tubes at $\Delta p =$ psi

Figure D-5. Leak Rate Correlation for 7/8 Inch Tubes at Δp = psi

Figure D-6. Leak Rate Correlation for 7/8 Inch Tubes at Δp = psi

D.3.3 Regression Analysis of Accident Leak Rate on Measured Voltage

The following sections provide the results of the linear regression analyses which were performed using the and psi data sets for the 3/4 inch and 7/8 inch tubes. These sections also provide the graphs which were prepared to examine the residual deviations from the fitted regression lines as discussed in section D.3.2.4.4.

D.3.3.1 Regression analysis results for 3/4 Inch Tubes

Table D-1 lists the leak rate data base for 3/4 inch tubes. The results of the linear regression analysis of the leak rate data for accident condition differential pressures of psi and psi are provided in Table D-5. Data for psi were individually scaled in accordance with the procedures described in references [D.1 and D.2] from the original test conditions.

While the data points are different, the coefficients of the fitted regression lines are similar. Based on ANOVA results for these data sets, it is concluded that they do not support a hypothesis of zero slope for either differential pressure condition.

The predicted leak rate for a tube support plate location with a BC indication of V_0 volts is then given by the following expressions for the appropriate accident condition:

[D-10, D-11]

The standard error values listed in Table D-5 are very similar; this means the amount of scatter about the regression lines is similar for both accident conditions. Figures D-3 and D-4 give the fitted leak rate correlation and were presented in section D.3.2.

The adequacy of the linear regression lines was evaluated by examining the residual deviations of the data. Figures D-7 through D-10 present the following graphs for the two accident conditions:

- residual variation vs. predicted (log leak rate) value, and
- normal probability plot of residual variation

These graphs do not indicate any abnormalities in the trends of the residuals.

From this analysis of the residuals it is concluded that the linear regression lines as specified by the coefficients of Table D-5 constitute a statistically valid set of prediction equations for predicting leak rates for Alloy 600 tubing with ODSCC at tube support plate locations. This conclusion is based on the examination of the residuals and from the results of the F test for the significance of the regression.

Table D-5

REGRESSION ANALYSIS FOR 3/4 INCH LEAK RATE CORRELATION

Accident Leak Rates for Alloy 600 Tubes with ODSCC at TSPs

Figure D-7. Residual Deviation vs. Predicted Leak Rate

Figure D-8. Normal Probability Plot of Residual Deviations

Figure D-9. Residual Deviation vs. Predicted Leak Rate

Figure D-10. Normal Probability Plot of Residual Deviations

D.3.3.2 Regression analysis results for 7/8 inch tubes

Table D-2 lists the leak rate data base for 7/8 inch tubes. The results of the linear regression analysis of the leak rate data for accident condition differential pressures of psi and psi are provided in Table D-6. Data for psi were individually scaled in accordance with the procedures described in references [D.1 and D.2] from the original test conditions.

While the data points are different, the coefficients of the fitted regression lines are similar. These results do not support a hypothesis of zero slope for either differential pressure condition.

The predicted leak rate for a tube support plate location with a BC indication of V_0 volts is then given by the following expressions for the appropriate accident condition:

[D-12, D-13]

The standard error values listed in Table D-6 are very similar; this means the amount of scatter about the regression lines is similar for both accident conditions. Figures D-5 and D-6 give the fitted leak rate correlations for 7/8 inch tubes and were presented in section D.3.2.

The adequacy of the linear regression lines was evaluated by examining the residual deviations of the data. Figures D-11 through D-14 present the following graphs for the two accident conditions:

- residual variation vs. predicted (log leak rate) value, and
- normal probability plot of residual variation

These graphs do not indicate any abnormalities in the trends of the residuals.

From this analysis of the residuals it is concluded that the linear regression lines as specified by the coefficients of Table D-6 constitute a statistically valid set of prediction equations for predicting leak rates for Alloy 600 tubing with ODSCC at tube support plate locations. This conclusion is based on the examination of the residuals and from the results of the F test for the significance of the regression.

Table D-6

REGRESSION ANALYSIS FOR 7/8 INCH LEAK RATE CORRELATION

Accident Leak Rates for Alloy 600 Tubes with ODSCC at TSPs

Figure D-11. Residual Error vs. Predicted Value

Figure D-12. Normal Probability Plot of Residual Deviations

Figure D-13. Residual Error vs. Predicted Value

Figure D-14. Normal Probability Plot of Residual Deviations

D.3.5 Procedure for scaling leak rates to lower Δp

The individual leak rate data points for psi can be re-scaled to other differential pressures using the procedure described in references (D.1 and D.2). The resultant re-scaled data can then be used to develop a leak rate correlation for the specified accident differential pressure.

Leak rate predictions under accident loading conditions are based on correlations between tube leak rate and bobbin coil voltage (as described in sections D.3.2) which were developed from leak rate tests conducted with pulled tubes and laboratory prepared specimens. To account for test differences, an adjustment procedure was developed to scale test conditions to prototypical accident differential pressures and temperatures (cf. references D.1, D.2).

The 3/4 inch and 7/8 inch tube leakage correlations presented and utilized in this appendix are for an accident differential pressure of psi. This differential pressure is representative of primary system pressure equal to the PORV relief pressure of psi[2] minus atmospheric pressure of 15 psi assumed for the secondary system. Leak rate correlations for an accident differential pressure of psi are also presented in this appendix for reference purposes. It has been noted that an accident differential pressure of psi is also typical for some plants. Data are not included in this report for psi, but may be in future revisions of this report.

As an alternative to the re-scaling procedure described in references D.1, D.2, the following simple but conservative scaling factor can be determined if it is necessary to predict accident leak rates at differential pressures between and psi or below psi. If the data are re-scaled by either method, an adjustment to the leak rate versus bobbin coil correlation is required.

A conservative downward adjustment factor can be determined, relative to the reference differential pressure (i.e. either or psi) by multiplying by the ratio:

$C =$ [D-14]

where: Δp represents the plant-specific accident differential pressure and Δp_{ref} represents the reference accident differential pressure for the leak rate correlation which is to be scaled (downward). That is, Δp_{ref} is either psi or psi.

[2]PORV relief pressure is plant-specific.

For example, if one were to calculate accident leakage at a differential pressure of psi, the psi correlation can be scaled down conservatively by multiplying by C= . If the calculation was to be for psi, the psi correlation can be scaled down conservatively by C= .

This conservative differential pressure correction relationship is based on the assumption that the ODSCC crack opening area varies linearly with pressure and flow and therefore is proportional to pressure to the 1/2 power. In reality, the crack opening area will be more strongly dependent on pressure than this relationship assumes. Consequently, it would be non-conservative to scale leak rates upward to higher differential pressures using the relationship but for the same reason is conservative to scale leak rates downward to lower differential pressures.

D.4 PREDICTION OF EOC ACCIDENT LEAK RATES

The probability of leakage correlation and the conditional leak rate correlation provide the basis for a best-estimate prediction of accident leak rates which has been developed from available field and laboratory data. Due to a number of uncertainties in the input variables to the ODSCC leak rate model, the leak rate for an individual tube may deviate from the value predicted by these correlations. A suitably conservative statistical method is described in this section which accounts for these uncertainties in predicted EOC accident leak rates. The following uncertainties are explicitly addressed:

1. voltage growth by EOC due to defect progression,
2. uncertainty in the predicted probability of leakage correlation fit,
3. uncertainty in the conditional leak correlation fit,
4. "scatter" of the leak rate data about the leak rate correlation, and
5. uncertainties due to eddy current measurement variability

Predicted leak rates are adjusted, in a conservative direction, by an amount which is termed the leak rate *margin*. The leak rate margin is determined by the systematic combination of these uncertainties. Margin is determined at the probability confidence level. Tables of predicted leak rate, with margin applied to cover these uncertainties, are presented in the example calculations of section D.6.

D.4.1 Progression of ODSCC during Operating Cycle

US and European steam generator inspection data indicate that tube support plate locations with confirmed ODSCC will, with high probability, have somewhat higher voltage indications by the end of the ensuing operating cycle. This measure of the progression of the ODSCC damage mechanism has been termed "voltage growth"; analogous to crack growth for other damage mechanisms. A detailed discussion of world-wide industry experience can be found in Appendix C of this report.

As described in Appendix C, specific experiences have varied although in general the average amount of increase is small; typically less than volts. It is not uncommon, both in the US and Europe for a small number of indications to increase by factors of 5 (corresponding to perhaps a volt increase or more) relative to the voltage which was measured at the beginning of cycle (BOC). This behavior has been limited to less than of the indications in US steam generators.

Appendix C describes an empirical probability distribution of voltage growth which conservatively bounds industry experience. This bounding distribution is presented in Figure C-28.

As an alternative to the conservative bounding distribution, plant-specific data can be used, if available, to develop a distribution of voltage growth.. Figure D-15 provides a typical graph of the probability distribution of voltages at both BOC and end of cycle (EOC) for indications at TSPs with confirmed ODSCC. A related graph of the empirical probability distribution of the voltage growth over the operating cycle can be derived from these data and is provided as Figure D-16. These figures indicate the shift to higher voltages which is expected by EOC.

A limited number of indications do not exhibit higher voltages by EOC; this corresponds to those cases where the voltage change was less than or equal to zero. While it is typical for a small percentage (typically less than) of the voltage changes to be less than zero, no credit is taken for the possibility of "negative growth". Therefore, all negative voltage changes have been assigned a value of zero.

Figure D-16 indicates the intrinsic statistical nature of the change in BC voltage. Since negative voltage changes have been precluded, this distribution describes the amount of voltage increase which is expected by EOC.

A plant-specific probability distribution of voltage growth is therefore specified by the product of two factors:

1. the probability of a positive voltage increase, and

2. the conditional probability of voltage increase given that an increase has occurred

The product of these factors yields the probability distribution of voltage growth which can then be expressed as

$$F[\Delta V]= \qquad [D\text{-}15]$$

The probability of zero voltage increase can be calculated from the inspection results. Similarly, the emprical data on voltage growth can be used to develop the (conditional) probability distribution from the non-zero voltage measurements.

The probability of non-zero voltage increase can be determined from the ratio of the number of positive voltage increases ($n_{\Delta V>0}$) to the total number of indications (n) for which voltage change data are available:

$$1 - P_{\Delta V=0} = \qquad [D\text{-}16]$$

The conditional voltage growth distribution describes the probability of incremental amounts of voltage increase expected by the end of the operating cycle. This is the second term on the right hand side of [D-15].

A skew probability distribution such as the lognormal, can be evaluated for representing this uncertainty in leak rate predictions. If the quantity:

$$Z =$$

is a standard normal deviate, then the voltage growth, ΔV , is lognormally distributed with parameters μ and σ. The parameters of this probability distribution can be determined by standard methods.

Figure D-15. Typical Frequency Distributions of Measured BC Voltage

Figure D-16. Typical Frequency Distribution of BC Voltage Increase by EOC

D.4.2 Treatment of Leak Rate Uncertainties in the Monte Carlo Analysis

This section describes details of the models and algorithms which are used in the Monte Carlo analysis to predict leak rate by explicitly accounting for uncertainties.

<u>D.4.2.1 Linear regression fit to the data</u> Because the applied regression analysis is based on a linear function of the individual leak rate data points and assuming that the deviations of the log-leak rate data about the regression line are: normally distributed, pairwise uncorrelated and have constant variance, the standard results from linear regression theory (reference [D.6]) can be applied to specify confidence limits for the slope of the (conditional) leak rate correlation:

[D-17]

For a specified confidence level, the appropriate Student's t distribution value would be substituted into equation [D-17].

The approach applied in the present methodology is derived from this basic relationship. In order to systematically combine the slope uncertainty with other uncertainties it is necessary to generate values from the entire probability distribution (as opposed to the single value which is calculated to specify a particular confidence limit on slope).

The following algorithm is used to calculate the slope distribution:

1. A random number from the uniform distribution, U_k, is calculated ($0 < U_k < 1$),
2. A random number from the Student's t distribution, T_k, is calculated corresponding to U_k (this can be accomplished in various ways; see reference [D.7] for details),
3. A random regression line slope, β_{1k}, is obtained by substituting the value of T_k into [D-17] and evaluating the equation,
4. Steps [1-3] are repeated many times, the result being the Student's t distribution of β_1.

The uncertainty in the regression line intercept is addressed by considering the joint confidence region for the true values of the slope and intercept. This approach properly accounts for the fact that the slope and intercept of the regression line are correlated. The joint confidence region is the set of slope and intercept values which satisfy the following inequality for a specified confidence level (reference [D.6]):

[D-18]

This equation defines an ellipse in the (β_0, β_1) plane for a specified level of confidence.

The approach applied in the present methodology is derived from this basic relationship. Systematic combination of the slope and intercept uncertainties with other uncertainties requires that values from the joint probability distribution surface be generated (as opposed to a single ellipse which is calculated for a specific value of α - that is, a single confidence level.)

This is accomplished as described in the following algorithm:

1. A random number from the uniform distribution[3], U_i, is calculated ($0 < U_i < 1$),
2. A random number from the F distribution, F_i, is obtained with 2, n-2 degrees of freedom which corresponds to U_i (this can be accomplished in various ways; see reference [D.7] for details),
3. A random regression line slope, $(\beta_1)_i$, is then determined by the procedure described previously,
4. A random regression line intercept is obtained by substituting F_i and $(\beta_1)_i$ into equation [D-18] and then by solving for $(\beta_0)_i$,
5. Steps [1-4] are repeated many times, resulting in the joint distribution for the regression line slope and intercept.

In this way the uncertainties in the linear regression fit (that is, in the coefficients of the line) are treated explicitly. Details of how these uncertainties are combined with the other leak rate uncertainties are described in section D.4.2.

Each pair of randomly generated coefficients thereby defines a unique prediction equation for the average log leak rate:

$$\left(\hat{Y}_0\right)_i = \qquad \text{[D-19]}$$

D.4.2.2 Residual deviations about the regression line Section D.3.2.5 discusses the calculation of prediction limits for a given bobbin coil voltage value, V_0. The fact that the leak rate data exhibit "scatter" about the linear regression line is addressed by representing the prediction limit in a somewhat different form for the purpose of the uncertainty analysis.

The algorithm to generate the probability distribution of the residual deviations about the regression line is specified by:

1. A random number from the uniform distribution[4], U_j, is calculated ($0 < U_j < 1$),
2. A random number from the Student's t distribution, T_j, is calculated with n-2 degrees of freedom corresponding to U_j (this can be accomplished in various ways; see reference [D.7] for details),

---

[3]Subscript i is used here to differentiate from the (different) uniform random values generated for the regression slope (subscript k).

[4]Subscript j is used here to differentiate from the (different) uniform random values generated for the regression slope and intercept.

3. A random residual deviation, ε_i, from the predicted mean (log) leak rate is then determined by substituting T_j and equation [D-19] into equation [D-9],
4. Steps [1-3] are repeated many times to generate the probability distribution of the prediction limit of log leak rate for the given log-voltage.

D.4.2.3 Eddy current measurement and evaluation Uncertainties associated with eddy current measurement by bobbin coil inspection and evaluation by certified analysts can be grouped into three types:

1. accuracy fluctuations due to probe wear,
2. analyst variability, and
3. manufacturing tolerances in probe calibration standards.

Each type is discussed in detail elsewhere in this report. If a transfer standard is employed, then only the first two uncertainties apply.

These uncertainties are assumed to be characterized by a normal distribution with a mean of zero and a standard deviation expressed as a percentage of the nominal voltage value. Further, a maximum value for the error may be specified for each type. Values for the standard deviations of these uncertainties are cited in Table 2-1of this report.

The algorithm to generate the probability distributions of these eddy current uncertainties (applied separately for each) is specified by:

1. A random number, U_i, is calculated ($0 < U_i < 1$),
2. A random normal variate, Z_i, is calculated corresponding to U_i (this can be accomplished in various ways; see reference [D.7] for details),
3. A random eddy current uncertainty value is then generated as:

$$(\varepsilon_{ECT})_i = \qquad [D\text{-}20]$$

4. The magnitude of the random error value is constrained so as not to exceed the maximum error (cut-off value)

$$\varepsilon_i \leq$$

5. Steps [1-4] are repeated many times to generate the probability distribution of the eddy current uncertainty.

This 5-step algorithm is applied to each of the three uncertainties to generate the respective probability distributions (three independent sets of random normal deviates, Z_i, are required).

D.4.2.4 Voltage increase by EOC

The uncertainty in voltage growth over the operating cycle is treated by randomly sampling from either the bounding growth distribution described in Appendix C or from a plant-specific voltage growth distribution. If a plant-specific voltage growth distribution is used, a lognormal probability distribution may be fit to the plant-specific data.

The algorithm to generate the bounding probability distribution of the voltage growth uncertainty is specified by:

1. A random number from the uniform distribution, U_i, is calculated ($0 < U_i < 1$),
2. A random number from the bounding empirical probability distribution, ΔV_i, is obtained by the inverse method (reference D.11):

   $\Delta V_i =$

3. Steps [1-2] are many times, resulting in the probability distribution of voltage growth by EOC.

The algorithm to generate the voltage growth probability distribution when a plant-specific lognormal distribution is developed is specified by:

1. A random number, U_i, is calculated ($0 < U_i < 1$),
2. A random normal variate, Z_i, is calculated corresponding to U_i (this can be accomplished in various ways; see reference [D.7] for details),
3. A random voltage increase is then generated as:

   $\Delta V_i =$ [D-21]

4. Steps [1-3] are repeated in only $100(1-P_{\Delta V=0})\%$ of the total number of trials (the remaining trials are defined to give a zero voltage increase), resulting in the probability distribution of voltage increase at EOC.

D.4.2.5 Probability of leakage The fitted logistic function is used to predict the probability of leakage for a specified bobbin coil voltage measurement. Due to random fluctuations in the leak/no-leak result for tubes which were leak-tested, there exists some uncertainty between the predicted value and the "true" value of the probability of leakage. As more and more data are accumulated the predicted value of the probability of leakage will converge to the true value for a given voltage measurement. To address the uncertainty in the predicted probability of leakage, a confidence limit on the true (but unknown) probability of leakage can be calculated from:

$$P_{leakage}(V) = \qquad \text{[D-22]}$$

where (for example, for a limit), z_α is the point of the standard normal distribution and the standard error of the logistic argument for a voltage measurement is determined by substituting log(V) for x in:

$$\sigma_\eta(x) = \qquad \text{[D-23]}$$

The value of σ is analogous to the standard error of a conventional linear least squares fit for two variables.

When expressed in terms of the logit function, the $100(1-\alpha)\%$ confidence limit on the probability of leakage, as defined by equation [D-22], results in a simpler form:

$$\text{logit}_\alpha\left(P_{leakage}\right) = \qquad \text{[D-24]}$$

Equation [D-23] indicates the dependence of the standard error of the probability of leakage on the logarithm of measured voltage (x). The variance-covariance matrix (Γ) of the calculated logistic coefficients is calculated by evaluating the inverse of the following matrix:

$$\Gamma^{-1} = \qquad \text{[D-25]}$$

where:

$$w_i = \qquad \text{[D-26]}$$

as predicted by the fitted logistic function.

Values of the variance-covariance matrix were calculated for the 3/4 inch and 7/8 inch leak rate data and are listed in Table D-3 in section D.3.1.

The approach adopted in this report is to treat uncertainty in the predicted probability of leakage explicitly. This is accomplished by implementing the following algorithm.

The algorithm to generate the uncertainty in the probability of leakage is specified by:

1. A random number from the uniform distribution, U_i, is calculated ($0 < U_i < 1$),
2. A random number from the Gaussian (normal) distribution, Z_i, is calculated corresponding to U_i (this can be accomplished in various ways; see reference [D.7] for details),
3. A random number from the logit distribution, $logit_i$, is then generated as:

$$\text{logit}_i =$$

4. A random number for the probability of leakage (about the "average" value determined from equation [D-1]) is then obtained as:

$$\left(P_{leakage}\right)_i = \qquad [D\text{-}27]$$

5. Steps [1-4] are repeated many times, resulting in the probability distribution of predicted probability of leakage under accident conditions.

The algorithms which have been presented in the preceding sections are then incorporated in a Monte Carlo analysis which is described in the next section.

D.4.3 Monte Carlo Analysis Method for Combination of Uncertainties

A Monte Carlo-type method is described in this section which is used to systematically combine the various analysis uncertainties which enter predictions of an individual tube leak rate for the faulted load event of a main steam line break.

Monte Carlo-type methods are standard techniques for determining the probability distribution of a specified function of input variables; each of which may exhibit uncertainty. This approach is used to calculate the probability distribution of individual tube leak rate for a specified bobbin coil voltage value. Repeated computer sampling of random values from the probability distributions described in section D.4.2 is performed and the predicted leak rate evaluated on each simulation trial. Figure D-17 provides an overview of the calculation steps.

Monte Carlo analysis can be performed prior to obtaining the inspection results so as to eliminate the need for outage-specific probabilistic evaluations. Field implementation is simplified to a table lookup procedure which allows prediction of leak rates. This does not preclude performing outage-specific analysis which may be required if the plant-specific voltage growth data are, in fact, not bounded by the bounding voltage growth distribution of Appendix C.

The Monte Carlo method consists of repeated evaluation of the probability of leakage and leak rate correlations for a specified voltage measurement; the product of these quantities is the predicted leak rate for an individual tube. Each evaluation is termed a *trial* and is performed with a new set of random numbers for the input variables. By performing a large number of trials, the probability distribution of leak rate is generated.

The percentiles of the leak rate distribution then can be determined by ordering the Monte Carlo predictions from smallest to largest. Predicted individual leak rates for a specified voltage measurement can then be established at a high level of probability/confidence.

Figure D-17. Combination of Leak Rate Uncertainties by Monte Carlo

The details of each Monte Carlo trial ($i=1,\ldots,N_{trials}$) for a voltage indication of V_{BOC} at a tube support plate intersection which has confirmed ODSCC are as follows:

1. Predict EOC voltage by adding a random voltage increase due to voltage growth over the next operational cycle by sampling from either the bounding voltage growth distribution described in Appendix C or the plant-specific voltage growth distribution which has been modeled by a lognormal distribution:

   $$(V_{EOC})_i =$$

   where ΔV_i is calculated according to [D-23].

2. Add randomly generated eddy current measurement uncertainties, $(\varepsilon_{ECT})_{ik}$ $k = 1,2,3$, which are calculated according to equation [D-20]:

   $$(V_0)_i =$$

   This is the predicted EOC bobbin coil voltage adjusted for probe wear, manufacturing tolerances in probe calibration standards and analyst variability.

3. Calculate a random value for the probability of leakage for the voltage indication at EOC in accordance with equation [D-29]:

   $$\left(P_{leakage}\right)_i =$$

4. Generate random leak rate correlation intercept, slope and residual error values as described in sections D.4.2.1 and D.4.2.2. Calculate the predicted conditional leak rate at EOC, $\dot{Q}_i$, as:

   $$\log_{10}\left(\dot{Q}_i\right) =$$

   $$\dot{Q}_i =$$

5. Calculate the predicted accident leak rate at end of cycle for the i^{th} Monte Carlo trial:

   $$\left(\dot{Q}_{EOC}\right)_i =$$

Steps [1-5] are repeated a large number of times ($i=1,\ldots,N_{trials}$) to calculate the probability distribution of the accident leak rate at EOC.

Figure D-18 provides an example of the results of the Monte Carlo simulation, presented in histogram form for a volt BOC indication. The long tail of the distribution is attributable to the bi-logarithmic relationship between bobbin coil voltage and predicted leak rate and the skew distribution of voltage increase over the operating cycle.

Figure D-18. Probability Distribution of Predicted EOC Leak Rate

Industry believes that a suitably conservative measure of the leak rate for an individual tube can be determined from the Monte Carlo analysis by taking the probability /confidence level, as the upper limit on leak rate for an individual tube under MSLB conditions. That is, for the i^{th} voltage interval between 0 and V_{RL} volts (the repair limit), the leak rate is calculated as

$$\dot{Q}_i = \qquad \text{[D-28]}$$

These results are tabulated in section D.6 for 3/4 inch and 7/8 inch tubes.

D.4.4 Total Leak Rate for Limiting Steam Generator

The total leak rate for the limiting steam generator under the postulated accident conditions is predicted by summing the contributions of all indications over the range 0 to V_{RL} volts. Let the number of indications which were confirmed as ODSCC at TSPs at BOC (within a voltage interval specified by) be designated by m_i.

The total predicted leak rate for the limiting steam generator is obtained by summing the product of the number of indications and the corresponding leak rate (as specified by [D-28]):

[D-29]

where n is the number of voltage intervals between and the repair limit V_{RL}.

D.5 CALCULATION PROCEDURE

This report provides a simplified implementation of the prediction of total leak rate under postulated accident conditions without sacrificing the level of detail in addressing uncertainties which is afforded by the Monte Carlo analysis procedure. This can be achieved when it is recognized that, for a given bobbin coil voltage indication at BOC, the limit on an individual tube leak rate can be equated to the sum of two parts:

1. the leak rate predicted based on the BOC voltage, and

2. a margin factor, dependent on the BOC voltage, which accounts for voltage growth by EOC and for leak rate correlation and eddy current uncertainties at the 95/95 probability/confidence level.

$$\dot{Q}_{EOC} = \qquad \text{[D-30]}$$

where:

$\dot{Q}_{EOC}$	is the predicted tube leak rate at EOC for an indication at a tube support intersection with a measured voltage of V_{BOC} at BOC
$\dot{Q}(V_{BOC})$	is the predicted conditional leak rate at BOC
$P_{leakage}(V_{BOC})$	is the probability of leakage at BOC
$\Delta\dot{Q}$	is the margin to cover voltage growth by EOC and uncertainties calculated at the level

In words, the limit for individual tube leak rate at EOC is equal to the sum of the predicted leak rate at BOC and a margin (allowance) to cover uncertainties. The margin for uncertainties is determined by the Monte Carlo analysis described in section D.4.3; it is tabulated as a function of the BOC voltage.

Figure D-19 indicates the relationship between the predicted leak rate at BOC and the margin for uncertainties which is required to obtain a value of leak rate equivalent to the value determined by Monte Carlo. A computer-calculated probability density function of leak rate is provided to indicate how uncertainties in the leak rate analysis result in adjustments of the predicted leak rate at BOC in a conservative direction.

Tables D-7 and D-8 summarize the Monte Carlo results for voltage measurements between and volts. These tables list the probability of leakage, conditional leak rate, margin factor and limit on leak rate, calculated at the probability/confidence level. These tables are based on the bounding voltage growth dist-ibution described by Figure 2-9 of this report.

If the plant-specific voltage growth is bounded by the bounding voltage growth distribution of Appendix C, then corresponding values of the leak rate in the last column of these tables can be used for each indication. This is illustrated in the examples which are provided in section D.6.

Figure D-19. Margin for Individual Leak Rate

Table D-7

PREDICTED LEAK RATE FOR Δp =   psi AT EOC FOR 3/4 INCH TUBES

Table D-8

PREDICTED LEAK RATE FOR Δp = psi AT EOC FOR 3/4 INCH TUBES

Table D-9

PREDICTED LEAK RATE FOR Δp = psi AT EOC FOR 7/8 INCH TUBES

Table D-10

PREDICTED LEAK RATE FOR $\Delta p =$ psi AT EOC FOR 7/8 INCH TUBES

The procedure for field implementation of the leak rate analysis is as follows:

1. Tabulate (BOC) indications by voltage; generate a histogram of the number of indications in each voltage interval:

   m_1 = number where (volt < V_{BOC} ≤ volt)

   m_2 = number where (volt < V_{BOC} ≤ volt)

   .

   .

   .

   m_n = number where (volt < V_{BOC} ≤ volt)

   and enter these values in column "A" of the worksheet (Table D-13 or D-14).

2. If the plant-specific voltage growth distribution is not bounded by the bounding distribution of Figure 2-9, then the limiting leak rate values listed in the right-most columns of Tables D-7 through D-10 are not applicable. In that case, calculations must be performed using the plant-specific voltage growth distribution and the calculated values should be entered into column "B" of the worksheet.

   If the plant-specific voltage growth distribution is bounded by the bounding distribution, then the limiting leak rate values listed in the worksheets in Tables D-13 and D-14 are appropriate and no further calculations are required to establish the leak rate for an individual indication.

3. Calculate the contribution of each voltage interval to the total leak rate by multiplying the number of indications (column "A") by the predicted leak rate (column "B"); place the result in column "C".

4. Calculate the total predicted leak rate for the postulated accident conditions: $\dot{Q}_p$ by summing the values in column "C" and placing the result next to the box labelled "TOTAL". This is the total predicted leak rate at EOC in l/hr for all tubes with BOC indications which will be returned to service without repair.

This procedure lends itself to calculation by computer spreadsheet programs.

D.6 EXAMPLES

Examples are provided in this section to illustrate the calculation procedure for predicting the total leak rate for a limiting steam generator under postulated accident conditions. For the purpose of these examples it is assumed that a volt alternate repair limit (ARL) has been established. These examples are for illustrative purposes only. Blank worksheets are provided as Tables D-13 and D-14 for use by the utility engineer in performing this analysis.

D.6.1 Example for Steam Generator with 3/4 Inch Alloy 600 Tubes

Table D-11 provides a completed worksheet for calculating the total leak rate under accident conditions at the EOC. This table lists number of indications which will be returned to service without repair, the predicted accident leak rate (95/95 probability/confidence level), the total leak rate contribution by voltage interval and the total leak rate for the overall steam generator. It is assumed in this example that the plant-specific voltage growth distribution is bounded by the bounding voltage growth distribution of Appendix C.

From these values, calculation of the leak rate for each voltage interval is illustrated by multiplying the number of indications in an interval (column "A") by the predicted leak rate (column "B"); the result being placed in column "C". The total leak rate for the steam generator is then obtained by summing the values in column "C" and entering the result at the bottom of the table.

Table D-11

EXAMPLE FOR 3/4 INCH ALLOY 600 TUBES WITH ODSCC AT TSPs

Predicted Total Leak Rate for Limiting Steam Generator

D.6.2 Example for Steam Generator with 7/8 Inch Alloy 600 Tubes

Table D-12 provides a completed worksheet for calculating the total leak rate under accident conditions at the EOC. This table lists number of indications which will be returned to service without repair, the predicted accident leak rate (95/95 probability/confidence level), the total leak rate contribution by voltage interval and the total leak rate for the overall steam generator. It is assumed in this example that the plant-specific voltage growth distribution is bounded by the bounding voltage growth distribution of Appendix C.

From these values, calculation of the leak rate for each voltage interval is illustrated by multiplying the number of indications in an interval (column "A") by the predicted leak rate (column "B"); the result being placed in column "C". The total leak rate for the steam generator is then obtained by summing the values in column "C" and entering the result at the bottom of the table.

Table D-12

EXAMPLE FOR 7/8 INCH ALLOY 600 TUBES WITH ODSCC AT TSPs

Predicted Total Leak Rate for Limiting Steam Generator

D.6.3 Worksheets for Site Implementation

Site-specific leak rate analysis is performed by following the steps listed in section D.5.2 and the examples provided in sections D.6.1 or D.6.2. If plant-specific voltage growth a are available, then the probability distribution of voltage growth must be bounded by the growth distribution of Figure 2-9 in order to apply the leak rate values in the right-most columns of Tables D-7 through D-10; this will be confirmed explicitly.

If the voltage growth distribution of Figure 2-9 does not bound the plant-specific growth, then plant-specific values of predicted leak rate will be determined by the Monte Carlo procedure which implements the method of section D.4.2.

Tables D-13 and D-14 provide worksheets for use by utility engineers for site-specific leak rate analysis.

Table D-13

LEAK RATE ANALYSIS WORKSHEET FOR 3/4 INCH TUBES

Predicted Total Leak Rate for Limiting Steam Generator

Table D-14

LEAK RATE ANALYSIS WORKSHEET FOR 7/8 INCH TUBES

Predicted Total Leak Rate for Limiting Steam Generator

D.7 REFERENCES

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