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MANAGEMENT PROGRAM FOR VOLUMETRIC OUTER DIAMETER INTERGRANULAR ATTACK IN THE TUBESHEETS OF ONCE-THROUGH STEAM GENERATORS

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RECORD OF REVISION

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ACRONYMS AND ABBREVIATIONS

ANO-1	Arkansas Nuclear One – Unit 1
ARC	alternate repair criteria
ASTM	American Society for Testing and Materials
B&W	Babcock & Wilcox
BOC	beginning of cycle
CFR	Code of Federal Regulations
CMTR	certified material test report
CSA	cross sectional area
DE	destructive examination
DNB	departure from nucleate boiling
EC	eddy-current
EDM	electrical discharge machining
EFPY	effective full power years
EOC	end of cycle
EPRI	Electric Power Research Institute
FS	free span (tube is not surrounded by tubesheet or tube support plate)
FTI	Framatome Technologies Incorporated
GPM	gallons per minute
ID	inner diameter
IGA	intergranular attack
IGP	intergranular penetration
IGSCC	intergranular stress corrosion cracking
LTE	lower tube end
LTL	lower tolerance limit
LTS	lower tubesheet secondary face or lower tubesheet
MSLB	main steam line break
NDE	non-destructive examination
NQI	non-quantifiable indication
NRC	Nuclear Regulatory Commission
OD	outer diameter
ODIGA	outer diameter intergranular attack
ONS	Oconee Nuclear Station
OTSG	once-through steam generator
POD	probability of detection
RC	rotating coil technology, such as RPC or Plus-Point coil
RPC	rotating pancake coil
RSG	recirculating steam generator
SBLOCA	small break loss of coolant accident
SCC	stress corrosion cracking
SEM	scanning electron microscopy
SG	steam generator
SGDSM	steam generator defect-specific management
TPD	Tubular Products Division
TS	tubesheet
TSP	tube support plate

TW	through-wall
UTE	upper tube end
UTS	depending upon context, upper tubesheet secondary face or ultimate tensile strength
YS	yield strength

DEFINITIONS

The following definitions are adapted from reference 2.2.

accident leakage rate is the primary-to-secondary leakage rate occurring during postulated accidents other than a steam generator tube rupture. This includes the primary-to-secondary leakage rate existing immediately before the accident plus additional primary-to-secondary leakage induced during the accident. The limiting accident leakage rate condition for the OTSG is the MSLB.

active degradation mechanisms and **active defect types** means that new indications associated with these mechanisms and defect types have been identified during in-service inspection or that previously identified indications associated with these defect types have exhibited growth since the previous inspection of the subject tubes.

alternative repair criteria (ARC) means tube repair criteria which may be implemented for a specific defect type as part of an SGDSM program in lieu of the generally applicable depth-based criterion (which is 40% of the initial tube wall thickness at most plants).

burst means gross structural failure of the tube wall. Analytically this corresponds to a condition in which a critical parameter for unstable crack propagation e.g., limit load, is exceeded. Experimentally, it corresponds to unstable crack propagation limited only by testing considerations e.g., loss of bladder or depletion of the pressure reservoir.

condition monitoring means an assessment of the "as found" condition of the tubing with respect to the performance criteria. The "as found" condition refers to the condition of the tubing during an SG inspection outage, as determined from the in-service inspection results or by other means, prior to the plugging or repair of tubes.

defect size means the actual physical dimensions of the defect. For this application, defect size is expressed in terms of multiple parameters (depth, length, width as measured by NDE).

defect size measurement (or measured defect size) refers to defect size as measured during an NDE tube inspection.

defect type refers to a degradation mechanism and an associated set of general circumstances which affect determination of appropriate NDE techniques for flaw detection and sizing, flaw growth rates, and analytical models for determining structural and leakage performance. General circumstances include tube size, tube material, defect orientation, whether the defect initiates from the tube primary side or secondary side, and defect location within the tube (e.g., in straight freespan, in u-bend, at tube support plate, at expansion transition). A degradation mechanism may include several defect types.

defined region for a specific defect type means the portion of the tube where the SGDSM is to be applied.

degradation mechanism refers to a general defect morphology and its associated causes; e.g., wear induced thinning of the tube wall caused by adjacent support structures, high cycle fatigue cracking due to flow induced vibration of the tube, intergranular stress corrosion cracking caused by stress, material susceptibility, and environment.

departure from nucleate boiling (DNB) is that point at which the tubes are no longer wetted by the secondary water.

film boiling is the conversion of water to steam in a zone where the tube is dry but not all of the water has evaporated. It is characterized by greatly reduced rates of heat transfer relative to nucleate boiling.

indication means the NDE signal response to a defect or condition which is present in the tube. An indication may or may not be measurable relative to the applicable tube repair criteria.

indication size or **indication measurement** refers to defect size measurement or to the voltage amplitude of the NDE signal response to a defect.

lane region refers to the tubes surrounding the lane of the OTSG. The lane is the untubed group of tubes beginning at the periphery and ending at the center of the SG. The untubed row number is 76 in the OTSG tube numbering system.

NDE technique refers to specific data acquisition equipment and instrumentation, data acquisition procedures, and data analysis methods and procedures. "NDE technique" in this context includes the summation of techniques directed at each degradation mechanism. For example, the use of bobbin probes for performing an initial screening inspection followed by a rotating pancake coil (RPC) inspection to confirm and characterize possible indications found by the bobbin would constitute a single NDE technique for detection purposes.

nucleate boiling is the conversion from liquid to vapor state, in a zone where the tubes are wetted by secondary water. This region is characterized by very high heat transfer rates.

operational assessment means an assessment to ensure that the tubes will continue to satisfy the performance criteria until the next scheduled inspection.

performance criteria means criteria that provide reasonable assurance that tube integrity is being maintained consistent with the licensing basis.

qualified for detection means that NDE techniques and personnel have undergone performance demonstration for a given defect type and have been shown capable of reliably detecting flaws associated with the defect type before these flaws are of sufficient size to cause the performance criteria to be exceeded.

rupture means perforation of the tube wall such that primary-to-secondary leak rate exceeds the normal charging pump capacity of the primary coolant system.

steam generator defect-specific management (SGDSM) means an integrated strategy applicable to a given defect type for ensuring that the performance criteria will be satisfied. SGDSM strategies include a specific program for conducting in-service inspection (including specified NDE technique and frequency and level of sampling) and specific methodologies for conducting condition monitoring and operational assessments. SGDSM strategies may also include alternative repair criteria.

structural limit means the calculated maximum allowable flaw size or indication size consistent with the performance criteria.

superheating is the elevation of the steam temperature by continuous addition of heat.

tube repair criteria is the NDE measured flaw depth and/or length, or indication voltage amplitude at or beyond which the subject tube must be repaired or removed from service by plugging.

validated for detection means that NDE techniques and personnel have undergone supplemental performance demonstration for a given defect type as necessary to quantify defect detection performance (e.g., probability of detection (POD) of a given defect) expected under field conditions.

validated for sizing means that NDE techniques and personnel have undergone supplemental performance demonstration for a given defect type as necessary to quantify the potential error or variability of indication size measurements (e.g., measured defect depth, measured defect length, and/or measured voltage response to defect) expected under field conditions.

variability refers to the repeatability of indication size measurements for a given defect.

1.0 INTRODUCTION

The steam generator tubes in pressurized water reactors are an integral part of the reactor coolant pressure boundary. In order to ensure that the tubes are capable of performing their intended safety functions, the effects of degradation mechanisms on SG tube integrity must be addressed. Steam generator defect-specific management (SGDSM) is an integrated strategy designed to ensure that tubes degraded by a specific damage mechanism will continue to meet established performance criteria. SGDSM strategies include a program for conducting in-service inspections and methodologies for conducting condition monitoring and operational assessments against repair criteria.

1.1 Purpose

The purpose of this topical report is to present an SGDSM program for volumetric ODIGA in the upper tubesheet region of the ANO-1 OTSGs. This program includes an alternative repair criteria for ensuring that accident condition primary-to-secondary leak rate limits are maintained. The ARC is based on the use of EC inspection, growth evaluation, and in-situ leak testing.

1.2 Background

Volumetric ODIGA is defined as three-dimensional grain boundary corrosion which initiates from the outside of the tube. Volumetric ODIGA has been present in the upper tubesheet region of the ANO-1 OTSGs since the late 1970's. The cause of the ODIGA was determined to be related to the intrusion of sulfur into the secondary system. Over the years, a large amount of research and development has been performed in an attempt to qualify depth or voltage sizing techniques for ODIGA. While these projects did not succeed in their goal, the resulting analytical and experimental data is sufficient to develop a management program based on rigorous EC inspection and in-situ leak testing.

2.0 REFERENCES

1. "Bases for Plugging Degraded PWR Steam Generator Tubes," NRC Regulatory Guide 1.121, August 1976.
2. "Steam Generator Tube Integrity," NRC Draft Regulatory Guide DG-1074, December 1998.
3. "PWR Steam Generator Tube Repair Limits: PWSCC in the Roll Transition," EPRI Report 6864-L, June 1993.
4. "An Approach for Using Probabilistic Risk Assessment in Risk-Informed Decisions On Plant-Specific Changes to the Licensing Basis," NRC Regulatory Guide 1.174 July 1998.
5. Erdogan, F. "Ductile Fracture Theories for Pressure Riser Pipes and Containers," International Journal of Pressure Vessels and Piping, Volume 4, 1976.

3.0 DESCRIPTION OF OTSG

The ANO-1 nuclear power plant contains two model 177FA once through steam generators (OTSG). The plant began operation in 1974.

3.1 Functional Description

The OTSG is a straight-tube, straight-shell, vertical, counter-flow, once-through heat exchanger with shell-side boiling. By nature of its design, the OTSG eliminates the need for steam separating equipment.

In the OTSG, shown in Figure 1, primary fluid from the reactor enters through an inlet nozzle in the top head, flows down through the tubes, is collected in the bottom head and exits through two primary outlet nozzles. The feedwater enters through a series of spray nozzles near the top of the annular feedwater heating chamber. Here the feedwater is heated to saturation temperature by direct contact with high-quality or slightly superheated "bleed" steam. The resulting saturated feedwater enters the tube bundle through ports near the bottom of the tube bundle. Nucleate boiling starts immediately upon contact with the hot tubes. Steam quality increases as the secondary fluid flows upward between the tubes in counterflow to the primary fluid inside the tubes. The departure from nucleate boiling occurs at about the 348 inch level at design conditions. The mode of heat transfer then changes from nucleate to film boiling. Steam quality continues to increase but at a slower rate. After 100% quality is reached, the steam becomes superheated, leaves the tube bundle at the upper tubesheet, flows down the steam annulus, and exits through two steam outlet nozzles.

3.2 Design Information

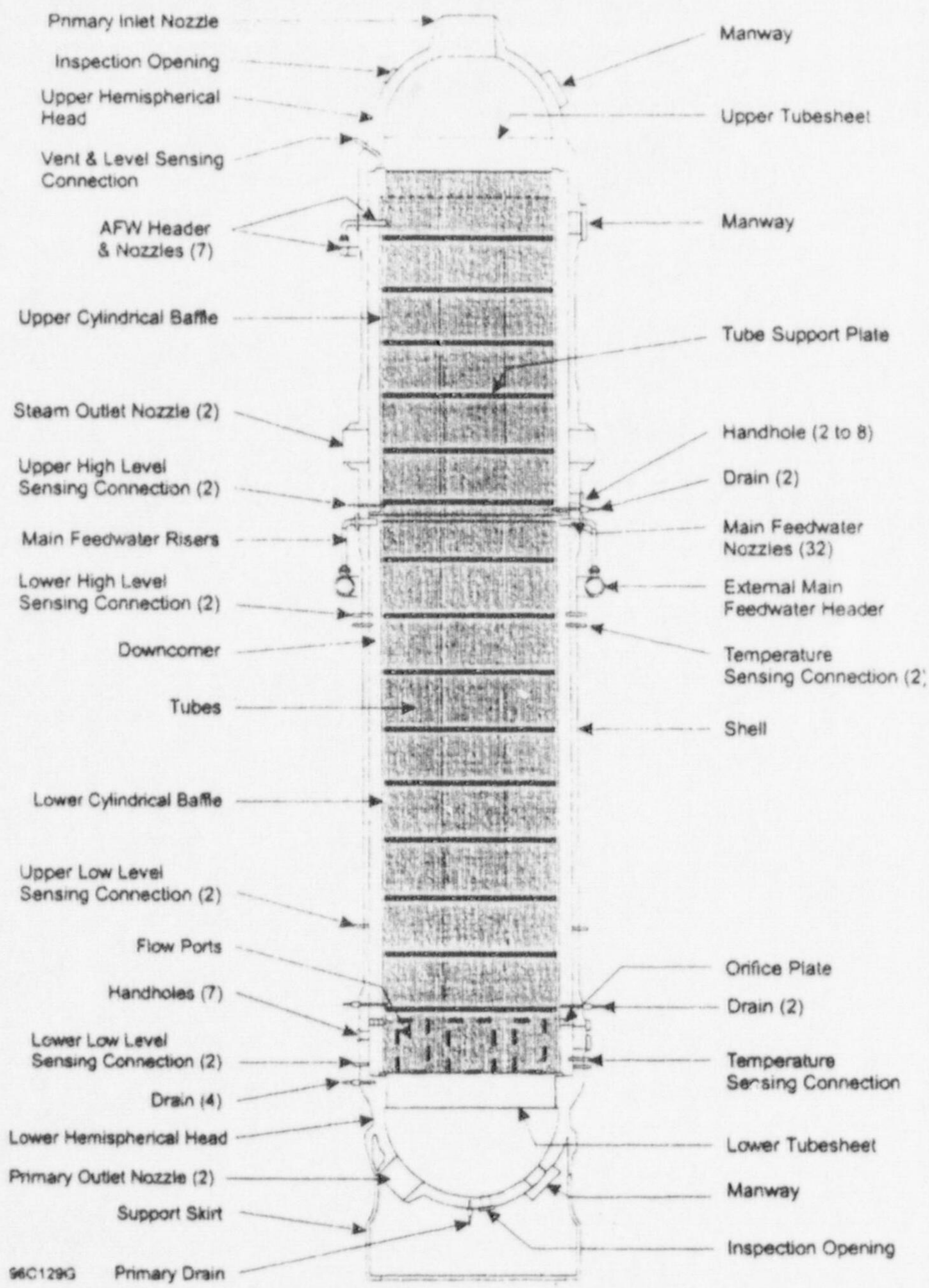
The units weigh approximately 570 tons and have an outer diameter of 150 inches and overall height of 878.5 inches. Each steam generator has more than 15,000 triangularly spaced alloy 600 tubes. These tubes are 0.625 inch OD x 0.037 inch nominal wall x 674.375 inches long. They are partially roll expanded (1 inch minimum) and attached to the upper and lower tubesheets by fillet welds. The use of straight tubes results in almost pure counterflow with resulting improved secondary flow distribution and primary-to-secondary temperature differentials. This design also has the benefit of placing the tubes in compression during normal operating conditions. This is mainly due to the fact that the alloy 600 tubes have a thermal coefficient of expansion slightly greater than that of the carbon steel shell. This compressive load tends to inhibit the initiation and propagation of stress related damage mechanisms.

Proper lateral spacing of the tubes is maintained by 15 tube support plates. They are fabricated from 1-1/2 inch thick carbon steel plate, drilled and broached to provide surface contact and support along three axes for each tube at each tube support plate. An exception is the 15th TSP periphery rows, which are not broached. The support plates are non-uniformly spaced axially to prevent resonant vibrations along the tube length, thus providing the highest possible damping factor.

3.3 Tube Material Properties

The OTSG tube material is alloy 600 (ASTM SB163). The raw materials were both melted into the alloy 600 ingots and fabricated into hollow rounds by B&W Tubular Products Division (TPD) for the OTSG tubing. The tube finishing processes (tube drawing, etc.) were performed by TPD and two outside vendors. The tube material was later thermally treated at [ ](c) for a minimum of [ ](c) hours during full furnace stress relief of the completed steam generator. As a result, the installed tubes are both sensitized and stress relieved. This results in improved resistance to stress corrosion cracking, but susceptibility to intergranular attack.

Figure 1 OTSG Longitudinal Section



4.0 DEFINITION OF VOLUMETRIC ODIGA

This section details the morphology and EC characteristics of ODIGA and defines the region where the SGDSM will be applied. Volumetric ODIGA has been found in other regions of the ANO-1 OTSGs, but this SGDSM will only be applied to the defined region as specified in section 4.4.

4.1 Operating History

[

]$^{(e)}$

Figure 2 Micrograph from 1982 Tube Pull

(c)

[

](e)

[

]^(c)

Figure 3 SEM Fractographic Data From 1996 Tube Pull

(c)

4.2 Morphology

The information discussed in the operating history was utilized to define the morphology of the volumetric ODIGA. Table 16 presents a summary of the available data on the volumetric ODIGA removed from the ANO-1 steam generators. Volumetric ODIGA is defined as three-dimensional grain boundary corrosion initiating from the outside surface of the tube. The ODIGA can occur in isolated patches or at multiple initiation sites encompassing a given area. Typically, the ODIGA exhibits a thumbnail profile. In some cases, localized fingers of grain boundary attack may extend below a layer of general ODIGA. These fingers are referred to as intergranular penetrations (IGP). Based on all available information, this damage mechanism does not appear to be active.

4.3 Eddy-Current Characteristics

During in-service tube inspections, bobbin examinations are performed to detect potential ODIGA indications. These indications are then examined with a rotating coil to characterize the indication as a specific type of indication (ODIGA, stress corrosion cracking (SCC), etc). In other words, the bobbin examination screens the tubes for potential ODIGA indications. The rotating coil examination is then used to determine whether or not the indication is volumetric ODIGA.

The volumetric ODIGA typically has a bobbin voltage amplitude (400 kHz peak-to-peak differential on Mid-Range bobbin probe) less than [ ]$^{(c)}$ volts. Figure 4 shows a typical plot of an ODIGA indication detected by the mid-range bobbin probe.

Figure 4 MR Bobbin Mix Channel Detection

(c)

A rotating coil examination is then performed to confirm and characterize the indication as volumetric ODIGA. Figure 5 shows a typical pancake coil response to ODIGA and Figure 6 shows a typical Plus-Point coil response to ODIGA. When confirming ODIGA with the pancake coil, the analyst looks for [

]$^{(c)}$

Figure 5 Typical RC Strip Chart ODIGA Response

(c)

Figure 6 Typical RC Terrain Plot ODIGA Response

(c)

4.4 Defined Region

This program is limited to ODIGA indications located in the tube span beginning at (but not including) the roll transition and ending 1 inch from the secondary face of the upper tubesheet. Indications located in the upper roll or upper roll transition are not addressed due to differences in the tube condition and EC response in this area. Indications located in the portion of tube not enclosed by the tubesheet are not precluded from tube burst and therefore not addressed at this time.

Indications located within 1 inch of the secondary face of the upper tubesheet are not addressed by this program in order to establish a buffer region from the secondary face of the upper tubesheet. The reason for this buffer region is to ensure that edge effects caused by the tubesheet face do not inhibit the proper characterization of indications detected by the bobbin coil examination.

5.0 STRUCTURAL EVALUATION

Structural evaluations were performed to determine the impact of bounding design bases conditions on tubes containing volumetric ODIGA. Due to the unique design of the OTSG, tensile loads can be developed within the tubes during certain cool-down events. The effect of the ODIGA on the ability of the tube to carry these loads was also evaluated.

5.1 Loading Conditions

The two conditions that are of concern for the structural evaluation are the limiting normal operating conditions and the limiting accident conditions. The limiting 100% power steady state and accident conditions are discussed in this section.

5.1.1 Limiting Pressure Differentials

The limiting primary-to-secondary pressure differential associated with 100% steady state power conditions is the design limit of 1350 psi. Application of the safety factor of three (reference 2.1) results in a limiting primary-to-secondary pressure differential of 4050 psi.

The limiting primary-to-secondary pressure differential associated with accident conditions is the safety relief valve setpoint of 2575 psi. This condition is associated with a MSLB condition and includes a 3% allowance for setpoint tolerance. Application of the safety factor of 1/0.7 (reference 2.1) results in a limiting primary-to-secondary pressure differential of 3679 psi.

5.1.2 Limiting Tensile Tube Loads

Tensile tube loads develop in the OTSG during cool-down events. During these events, the tubes cool faster than the surrounding shell, resulting in tensile tube loads. The primary component of these tube loads are thermal loads, which are displacement limited. This results in the majority of the tensile load being associated with secondary stresses that do not require the ASME faulted condition safety factor of 1/0.7.

The limiting tensile tube load for the ANO-1 steam generators is associated with the small break loss of coolant accident (SBLOCA). The maximum postulated tensile load associated with this condition is [ ](d). Even though this load is mainly a thermal load and therefore not considered a primary stress, the accident condition safety factor of 1/0.7 is conservatively applied. This results in a limiting accident condition tensile of [ ](d).

5.1.3 Limiting Cross Flow Loading

Cross flow loads occur in the top and bottom spans of an OTSG due to the radial flow of water and steam in these regions. The limiting case for cross flow loading is the MSLB, and the amount of cross flow is related to the size and location of the break in the steam pipe. The analyses performed for determining the cross flow bounded the worst case for these conditions.

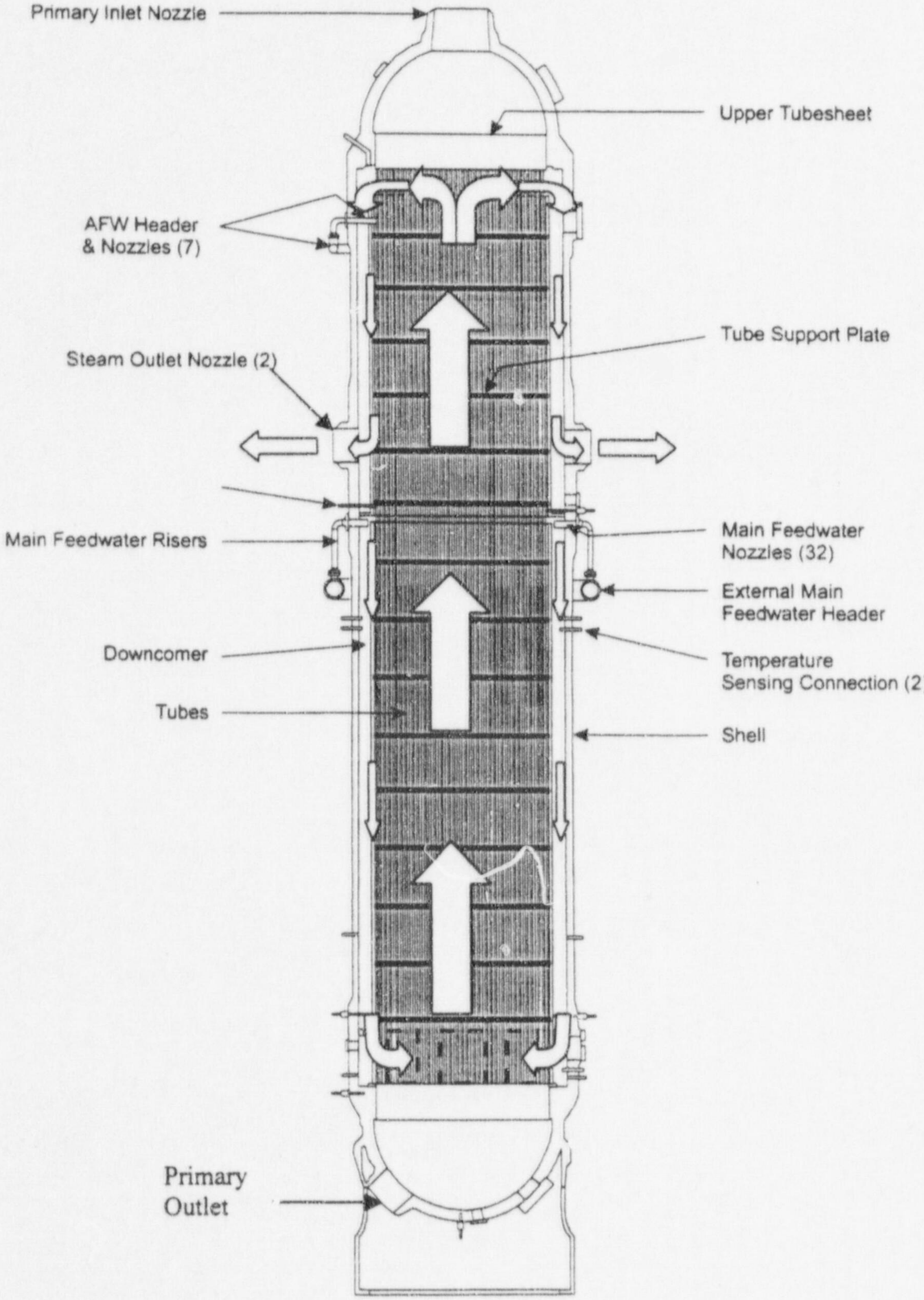
The MSLB transient initiates with the severance of the steam line. This causes a large pressure differential between the OTSG secondary side and the downstream steam line break. The resulting accelerated flow of water and steam impose cross flow loads on tubes in the top and bottom spans (see Figure 7). These loads last for the first few seconds of the transient, when the primary-to-secondary pressure differential is approximately that of normal operating conditions and the tubes are under a small compressive axial load. These loads produce bending moments on the tubes due to the lateral restraint of the tubesheets and tube support plates. The magnitude of the moment varies with elevation (because the cross flow load varies with elevation) and the condition of the tube.

The most limiting moment is located at the secondary face of the upper tubesheet. The more degraded this region is, the more plastic deformation the region could experience due to the bending moment. Analyses were conducted to determine the relationship between the lateral load, the bending moment, and location within the SG. The results of the analysis were then used to determine how far to deflect tube samples with ODIGA in order to simulate the worst case stress condition.

Two sets of leak and burst testing were performed (Table 18 and Table 19) to address any potential effects that volumetric ODIGA might have on the structural and leakage integrity of the OTSG tubes. The first set of tests utilized straight tube samples with ODIGA subjected conditions that bound the limiting tube loads and pressure discussed in sections 5.1.1 and 5.1.2. These samples are representative of tubes with ODIGA located away from the secondary face of the tubesheet. Stress calculations show this testing is applicable to ODIGA located at least [ ][(d)] inches above the secondary face of the tubesheet. The second set of testing involved bending the samples to apply the greatest stress at the ODIGA defect. This preconditioning simulates the effects of cross flow loads. Leak and burst tests were then performed in the same manner as the unbent samples.

The test results show that for the ODIGA tested, which bounds the sizes of ODIGA detected in the ANO-1 OTSGs, the cross flow loads had no measurable effect on the structural integrity of the tube. This is concluded based on comparing the burst test results and the fact that no leakage resulted from testing either set of samples. There is, therefore, no performance criteria limitations associated with cross flow loads.

Figure 7 MSLB Cross Flow Loads



5.2 Burst Rupture Evaluation

The burst rupture evaluation is presented in two parts. The first part evaluates the burst probability of volumetric defects constrained by the tubesheet. The second part evaluates the burst pressure associated with ODIGA not constrained by the tubesheet.

5.2.1 Probability of Burst in Tubesheet

Experiments have been performed to determine the burst pressures for tubes having outer diameter initiated axial cracks that are contained within a support with relatively small annular distances [reference 2.3]. The results from these experiments show that flawed tube burst below the burst pressure for an unflawed tube is precluded by the constraint of the tube radial displacement when the cracked section of the tube remains within the tubesheet and the diametral gap is less than approximately 0.030".

The bounding tube-to-tubesheet diametrical difference for ANO-1 is computed by assuming the minimum tube OD (0.625") and the maximum tubesheet bore ID [ ](d), resulting in a diametral gap of [ ](d). Based upon the results of the EPRI testing discussed above, this gap is not sufficient to allow burst of an axially cracked tube within the tubesheet.

Burst testing of machined 100%TW defects confined within a tubesheet was performed to confirm that this assumption is also applicable to volumetric defects. Each defect specimen had a transverse through-wall hole machined through one wall at the approximate midspan to conservatively simulate volumetric ODIGA. The removed material was placed back in the hole to represent tube material which has suffered from intergranular attack and has no tensile strength but fills the cavity and provides only bearing strength. A split steel block with a bore ID of [ ](d) surrounded the simulated ODIGA to represent the tubesheet.

Results of the burst testing showed no decrease in burst strength relative to the unflawed tube, as all tube ruptures occurred in the freespan portion of the tubing, typically 1.5 inches or more away from the tubesheet. These test results demonstrate that volumetric ODIGA which is located within the tubesheet is precluded from burst. This SGDSM ensures that the indications are located within the tubesheet by virtue of the defined region (section 4.4). This eliminates the need to determine a volumetric ODIGA structural limit based on burst pressure.

5.2.2 Unsupported Burst Strength

While it has already been demonstrated that the volumetric ODIGA cannot burst due to the structural reinforcement provided by the tubesheet, it is worthwhile to show the minimal impact that the volumetric ODIGA has on the structural strength of the tubing. The room temperature burst pressures associated with the pulled tube and laboratory ODIGA are presented in Table 16, Table 18, and Table 19 at the end of this report. These burst pressures were normalized to the 95/95 lower tolerance limit (LTL) flow stress at 600°F and then plotted in Figure 8. This figure shows that the depth of the

ODIGA has very little effect on burst pressure (for the axial and circumferential extents tested. In fact, all the ODIGA tested had burst pressures more than [ ](d) psi greater than [ ](d) psi (three times the 100% power steady state pressure differential).

For comparison purposes, burst test results from testing 360° uniform thinning samples are also presented. The uniform thinning data shows that 360° volumetric defects must be at least [ ](d)%TW before burst pressure margins are challenged. When it is considered that most of the ODIGA in the ANO-1 OTSGs has been sized as less than [ ](d) in circumferential extent by EC, the insignificant impact that the ODIGA has on the structural integrity of the tubing becomes apparent.

Figure 8 ODIGA Unsupported Burst Pressures

(d)

5.3 Tensile Rupture Evaluation

As discussed earlier in this section, the presence of the tubesheet precludes the volumetric ODIGA from burst rupture. This results in the structural integrity being determined by the tensile rupture load. Tensile rupture is defined as the complete severance of the tube due to tensile loads and is equivalent to the ultimate tensile strength of the tube. The OTSG tubes are subjected to tensile loads during certain cool-down transients. To develop a performance criteria for tensile rupture, the tensile failure load of OTSG tube samples with volumetric degradation is correlated to the remaining cross-sectional area. The remaining cross-sectional area is then correlated to an allowable circumferential extent assuming the defect is 100%TW. These two relationships are then used to determine the maximum allowable circumferential extent of a 100%TW volumetric defect that will not result in tensile rupture of the tube under the limiting accident condition axial tube loads with the appropriate safety margins. The tensile test data consists of OTSG tubing with 100%TW EDM holes and 360° uniform thinning. The sample data is summarized in Table 1 and Table 2.

Table 1 Tubing Information

Heat	Tube O.D. (inches)	Tube wall thickness (inches)	RT YS (psi) (See Note 1)	RT UTS (psi) (See Note 1)
		(d)		

Note 1: Yield (YS) and ultimate strength (UTS) based on average of room temperature (RT) test results.

Table 2 Sample Information

		Defect Geometry				
Sample No.	Heat No.	Axial Extent (inches)	Circ. Extent (inches)	%TW	CSA (inches^2)	Ultimate Load (lbs)
1						
2						
3			(d)			
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						

Note 1: CSA = cross sectional area remaining in defect region

As shown in Table 1, the tubes are not of the same heat of material and therefore do not have the same ultimate tensile strength. Furthermore, review of the ANO-1 CMTRs shows a 1-sided 95/95 LTL room temperature ultimate tensile strength of [ ](b), or [ ](b) when corrected to 600°F. The ultimate load data will therefore be normalized to an ultimate tensile strength of [ ](b) to provide a conservative predictor of tensile rupture load.

Table 3 Normalized Tensile Rupture Data

Sample No.	CSA (inches^2)	Ultimate Load (lbs)	Normalized Load (lbs)
1			
2			
3			
4			
5			
6		(d)	
7			
8			
9			
10			
11			
12			
13			
14			
15			

The normalized ultimate loads are plotted as a function of remaining cross sectional area in Figure 9. The 95/95 LTL for the normalized loads and the limiting accident condition tube load are also displayed. The limiting accident condition tube load is the SBLOCA condition with a postulated maximum load of [ ](d). With a safety margin of 1/0.7, the limiting load becomes [ ](d) (section 5.1.2). This load correlates to a minimum allowable cross sectional area of [ ](d).

A nominal OTSG tube has an outer diameter of 0.625 inches and a wall thickness of 0.037 inches. This results in an unflawed tube cross sectional area of 0.0683 in^2. To estimate the allowable circumferential extent that will result in at least [ ](d) of remaining cross sectional area, it will be conservatively assumed that the ODIGA is 100%TW. Figure 10 shows the relationship between remaining cross sectional area and allowable circumferential extent. This figure shows that a 100%TW hole with a circumferential extent of [ ](d) has at least [ ](d) of remaining cross sectional area. Therefore, an ODIGA patch that has a circumferential extent of [ ](d) can be concluded to have enough cross sectional area to carry the limiting accident condition tube loads with the required margin of safety. This evaluation is considered to be quite conservative because the ANO-1 ODGIA is less than 100%TW and has a "thumbnail" shaped cross section (see section 4.1), which results in quite a bit more remaining cross sectional area for a given circumferential extent.

Figure 9 Tensile Rupture Load vs Remaining Cross Sectional Area

(d)

Figure 10 Maximum Allowable Circumferential Extent vs Remaining CSA

(d)

5.4 Fatigue Evaluation

Fatigue loading on OTSG tubes can be classified as either high-cycle or low cycle. Tube degradation due to high cycle fatigue has been observed in OTSGs at the 15th (uppermost) TSP and at the secondary face of the upper tubesheet. The resulting flaw morphology is a circumferential fatigue crack that propagates rapidly around the tube once initiated. The affected tubes are located adjacent to the open tube lane, where secondary side cross flow is high. This damage mechanism was first identified in the late 1970's and confirmed through examinations of tube pull samples from the ONS plants. It was concluded that the flaws were initiated at sites of localized corrosion, and then were propagated into a fatigue crack by flow induced vibration associated with the high cross flow.

High cycle fatigue has been addressed in OTSGs by preventively sleeving the susceptible tubes. The lack of tube leaks attributed to fatigue in recent years supports the adequacy of the defined sleeving zone in bounding the susceptible area. The installed sleeves span the entire upper tubesheet and top span of the generator, so the program will not be applied to the susceptible area of these tubes. Addressing the effects of high cycle fatigue is therefore not necessary.

Fatigue due to low cycle loading results primarily from mechanical, thermal, and pressure cycling during normal plant operation. If flaws were to propagate due to low cycle fatigue, this would be evident as a change in the EC response of the flaw from one cycle to the next. Therefore, any historical effects of low cycle fatigue on tubesheet OD IGA are covered by performing an evaluation for potential growth. Since the growth will be regularly monitored during implementation of the program, and flaws will be repaired prior to becoming a leakage or structural concern, a separate repair limit for low cycle fatigue is not necessary.

5.5 Structural Performance Criteria

The structural performance criteria are the result of the evaluations described in sections 5.2 through 5.4, and are presented in Table 4. The evaluations show that the volumetric ODIGA, due to its limited size, has very little effect on the structural performance of the tubing. Tubes with ODIGA in the defined region are constrained by the presence of the tubesheet, thus preventing the burst rupture of ODIGA. Tensile rupture of tubes with ODIGA is highly improbable based on the results of tensile testing OTSG tubes with uniform thinning and 100%TW holes. The potential consequences of fatigue are mitigated by preventive sleeving and evaluating ODIGA for growth. Finally, any potential effects of cross flow loads during a MSLB conditions have been addressed through leakage and burst testing.

Table 4 Structural Performance Criteria

Condition	Performance Criteria	Comments
Burst Rupture	none	not possible due to tubesheet constraint
Tensile Rupture	EC measured Circumferential extent ≤ [ ][(d)]	conservatively assumes 100%TW and bounds all loads (including safety factors)
High Cycle Fatigue	none	addressed through preventive sleeving
Low Cycle Fatigue	none	addressed through flaw characterization and growth monitoring
Cross Flow Loads	none	testing showed no structural impact for this damage mechanism

6.0 LEAKAGE EVALUATION

At the present time, a qualified EC depth sizing technique does not exist for ODIGA. In the absence of being able to verify no leakage based on an EC depth measurement, a combination of in-situ leak testing and hot leak testing of laboratory ODIGA and EDM holes is utilized to evaluate the leakage integrity of tubes with ODIGA.

6.1 In-situ Leak Testing

As part of the 1R14 in-service tube examinations, 40 ODIGA indications were in-situ leak tested. This data is presented in Table 17. The tubes were pressurized to a representative normal operating primary-to-secondary pressure (1500 psig) and a representative accident pressure differential (2900 psig). For 36 of the indications, the 2900 psig pressure was combined with an net axial load of [ ](d) via an axial pull probe. All tests were conducted for the time recommended by the EPRI in-situ pressure testing guidelines. None of the indications tested under any of these conditions exhibited any leakage. In addition, four indications were subjected to pressure only tests up to 6500 psig. Even at this pressure, more than 2.5 times the accident pressure differential, the ODIGA indications did not exhibit any leakage.

6.2 Hot Leak Testing

High temperature leak testing was performed to establish expected leak rates for ODIGA. These conditions are given below in Table 5 and bound the conditions of section 5.1. The samples tested included 46 volumetric ODIGA samples made in a laboratory environment and 6 EDM holes. The samples are listed in Table 18 and Table 19.

Table 5 Hot Leak Test Conditions

Primary Side Parameters		Secondary Side Parameters		Specimen Conditions
Pressure psig	Temp. °F	Pressure psig	Temp. °F	Axial Load lbs
		(d)		

A summary of the range of tested flaw extents is presented in Table 6. The 52 samples tested resulted in no leakage under either axial loading condition. This is significant when one considers that sample [ ](b) had a defect [ ](b)%TW and approximately [ ](b) inches in diameter, and sample [ ](b) had a defect [ ](b)%TW and [ ](b) in diameter (see Table 18). This leak testing, along with the tensile testing described in section 5.3, underscores the remaining structural strength of tubing degraded by this damage mechanism. Unlike damage mechanisms associated with cracking, where localized stress concentrations at the crack tip tend to drive the crack through-wall and open up the crack under large hoop or axial stresses, volumetric ODIGA is merely the corrosion of grain boundaries with no localized high stresses. This type of damage mechanism, along with its typically small size, make it an unlikely candidate for primary-to-secondary leakage.

Table 6 Leak Test Sample Geometry Summary

	Max Depth (%TW)	Axial Extent (Inches)	Circumferential Extent (inches)
Count			
Minimum		(d)	
Maximum			
Average			

6.3 Predicted Leakage Condition

As discussed in the previous sections, no ODIGA patches leaked under any of the conditions tested. Based on the lack of any leakage and the following observations, it is concluded that ODIGA patches will not leak in their current state.

1. [

]$^{(b)}$

2. [

]$^{(b)}$

6.3.1 Predicted Mode of Cracking

For purposes of postulating leakage, it is therefore assumed that the ODIGA must form a crack in order to have a potential for leakage. Evaluation of the normal operating conditions results in the conclusion that the initiation of an axial crack is more probable than formation of a circumferential crack. This is based on the fact that the OTSG tubes are in compression during steady-state operation, which inhibits the initiation of a circumferential crack, and that the hoop stresses caused by primary-to-secondary pressure differential favor the formation of an axial crack. If a volumetric ODIGA patch does not develop a crack during normal operation, it is unlikely that it will crack under MSLB conditions for circumferential extents less than [ ]$^{(b)}$ based on the leak testing discussed in section 6.2. This circumferential extent bounds the in-service ANO-1 volumetric ODIGA. Therefore, for purposes of estimating leakage, it is concluded that the most probable means of developing a through-wall flaw is by axial cracking during normal operation.

6.3.2 Predicted Length of Leak Path

The depth profiles (along the axial extent) of ODIGA patches with maximum depths greater than [ ]$^{(b)}$%TW were evaluated in order to predict a representative leak path length. The [ ]$^{(b)}$%TW criteria was chosen in order to evaluate the shape of patches that had a more reasonable chance of developing a leak (note that patches up to [ ]$^{(b)}$%TW did not leak). This criteria resulted in evaluating four patches (Figure 11 - Figure 14) removed from the ANO-1 steam generators in 1996.

As described in section 4.2, the IGA has a generally elliptical profile as shown in Figure 11 and Figure 12. In other cases, the presence of small intergranular penetrations result in a maximum depth that extends over a much smaller percentage of the axial extent than if it were just an elliptical patch. This type of profile is exemplified in Figure 13 and Figure 14. In other words, the four patches are representative of the range of profile types expected to exist within the ANO-1 population.

For purposes of predicting a leak path length, the four profiles are assumed to maintain the same profile and grow to a depth necessary to initiate an axial crack. It is further assumed that the crack will occur over the axial extent [

]$^{(e)}$

Based on the lack of any leakage from the leak testing discussed in sections 6.1 and 6.2, and lack of any significant reduction in structural strength as discussed in section 5, this approach is deemed conservative.

Figure 11 ODIGA Profile [ ][(d)]

(d)

Figure 12 ODIGA Profile [ ][(d)]

(d)

Figure 13 ODIGA Profile [ ]^(d)

(d)

Figure 14 ODIGA Profile [ ]^(d)

(d)

6.4 Leakage Performance Criteria

As part of the licensing basis, the utility must provide assurance that the potential primary-to-secondary leakage rate during the limiting accident condition for leakage (MSLB) does not exceed 1 gpm for the affected SG. This criteria will be met by designating a portion of the 1 gpm limit for volumetric ODIGA and providing reasonable assurance that the designated leakage rate limit will not be exceeded.

To provide a reasonable assurance that the leakage rate will not be exceeded, MSLB primary-to-secondary leak rates must be determined as a function of the axial extent of the assumed crack (see discussion in section 6.3). KRAKFLO, an FTI computer program, was used to calculate the fluid flow rates through axial cracks in OTSG tubes subjected to bounding MSLB conditions. The crack opening diameter was calculated based on the elastic-plastic method of Erdogan (reference 2.5). The effect of the tensile load, which would act to close the crack opening, is conservatively omitted in these calculations. The MSLB conditions assumed in this analysis are a primary-to-secondary pressure differential of 2575 psi, and the tube and primary fluid temperatures are assumed to be [ ][(d)] (which correspond to the temperatures at maximum pressure). Based on these conditions, the predicted leak rates are presented as a function of 100%TW crack length in Table 7. As shown in the table, the axial extent is based on EC measurement. Due to the characteristics of EC, the indication is "seen" before the coil actually passes over the indication and is still "seen" after the coil has passed by the indication. This is referred to as EC "look ahead" and "look behind" and results in oversizing the indications most of the time. This fact is supported by the EC measurements of the pulled tube and laboratory ODIGA (see Table 16, Table 18, and Table 19) at the end of the report.

Table 7 MSLB Leak Rate for Axial Cracks

ODIGA EC Axial Extent (inches)	100%TW Crack Length (inches)	Flow Rate (lbm/sec)	Flow Rate (gpm)
	(d)		

7.0 SPECIAL CONSIDERATIONS FOR PERFORMING ASSESSMENTS

In order to successfully implement this management program, the ability of EC techniques to detect ODIGA and distinguish changes in the signals that may be interpreted as growth of the ODIGA must be evaluated.

7.1 Monitoring Growth

ODIGA growth over the next inspection interval must be estimated for purposes of projecting indication sizes expected to exist prior to the next scheduled inspection. The growth will be evaluated on the basis of the change in indication size between inspections when there is a detectable indication during both inspections.

7.1.1 Background

Volumetric ODIGA has been present in the upper tubesheet region of the ANO-1 OTSG's since the late 1970's. The cause of the ODIGA was determined to be related to the intrusion of sulfur into the secondary system. This conclusion is supported by the high levels of sulfur found in the corrosion films of tubes removed from the ANO-1 steam generators in 1978 and 1982 (section 4.1). Through improved secondary side chemistry control, the ingress of high levels of sulfur was stopped. This is apparent from the 1996 tube pull examination, which found near neutral chemistry in the corrosion films. The improved chemistry control has the effect of removing the mechanism that would cause existing defects to grow or new defects to form.

Available EC information supports the position that the ODIGA is dormant. Review of EC inspection databases shows that in spite of all the changes in EC technology, and inspection and reporting guidelines, many of the current ODIGA indications can be traced back to the early 1980's. More recently, bobbin voltage has been used to evaluate growth based on the fact that bobbin voltage amplitude increases as the volume of a tube defect increases. Voltage response has also been correlated with the depth of certain types of tube defects. Assessments of the change in bobbin voltage over the time period of 1993-1998 were performed for more than 100 indications. The results showed no increase in the mean population voltage.

In addition to EC examinations, SG bubble tests, tube in-situ pressure tests, tube pulls, and in-service leakage monitoring have not shown any 100%TW ODIGA or primary-to-secondary leakage associated with ODIGA. If the ODIGA defects have been growing since 1980 - even at a slow rate - it would be expected that some primary-to-secondary leakage attributable to ODIGA would be found. The lack of such evidence supports the conclusion that the ODIGA is dormant.

7.1.2 Growth Monitoring Procedure

Although there is strong evidence that the ODIGA has been dormant, the indications must continue to be monitored for growth. This will be performed by monitoring the relative changes in the EC measured voltages, axial extents, and circumferential extents of the ODIGA. Although the techniques that will be employed are not qualified, by utilizing the relative increases in the mean population as an indicator of potential growth, the random error associated with the techniques will not significantly affect the results (see section 7.1.3).

This evaluation will be performed by sizing all the ODIGA indications (voltage, axial and circumferential extent) and then comparing the information with the beginning of cycle inspection data.

STEP 1: DETERMINE THE MEAN CHANGE IN THE PARAMETER

Equation 1 Mean of the Differences

$$\Delta V_{mean} = \sum_{i=1}^{n} \frac{V_{EOC}(i) - V_{BOC}(i)}{n}$$

where:

V_{BOC} = beginning of cycle parameter measurement
V_{EOC} = end of cycle parameter measurement
n = number of ODIGA indications

STEP 2: DETERMINE THE STANDARD ERROR

Equation 2 Standard Error of the Differences

$$s_{\Delta V} = \frac{\sqrt{\dfrac{\sum_{i=1}^{n}[V_{EOC}(i) - V_{BOC}(i)]^2 - n \times (\Delta V_{mean})^2}{n-1}}}{\sqrt{n}}$$

STEP 3: DETERMINE THE 95% CONFIDENCE INTERVAL OF THE DIFFERENCES

Equation 3 95% Confidence Interval of the Differences

$$\Delta V_{95\%} = \Delta V_{mean} \pm t_{0.025,n-1} \times s_{\Delta V}$$

where:

$t_{0.025,n-1}$ = the t statistic for a 95% two-sided confidence level (α = 0.05) with n-1 degrees of freedom.

STEP 4: DETERMINE WHETHER OR NOT THE ASSUMPTION OF "NO GROWTH" IS SUPPORTED

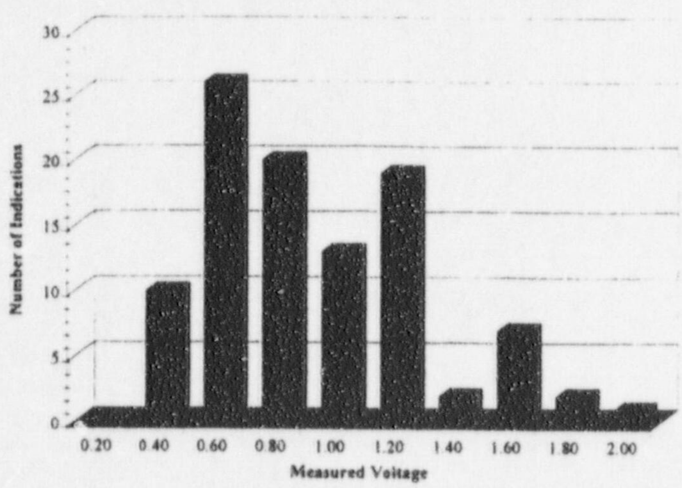
After performing the first three steps for voltage, axial extent, and circumferential extent, the assumption of no growth can be assessed for each set of measurements. [

](c)

7.1.3 Growth Monitoring Examples

Two growth monitoring examples are presented in this section to show the sensitivity of the technique to average growth of the population. Both data sets contain 100 fictitious indications with beginning and end of cycle voltage measurement. The complete data set is presented in Table 20. Figure 15 shows the beginning of cycle voltage distribution.

Figure 15 Beginning of Cycle Voltage



The distributions of the changes in voltage are shown in Figure 16 and Figure 17. From these differences, the mean and standard errors are calculated. It is evident from the distributions that the two cases are quite similar. In fact, the individual case 2 differences are equal to the individual case 1 differences plus 0.01 volts.

Figure 16 Case 1 Voltage Differences

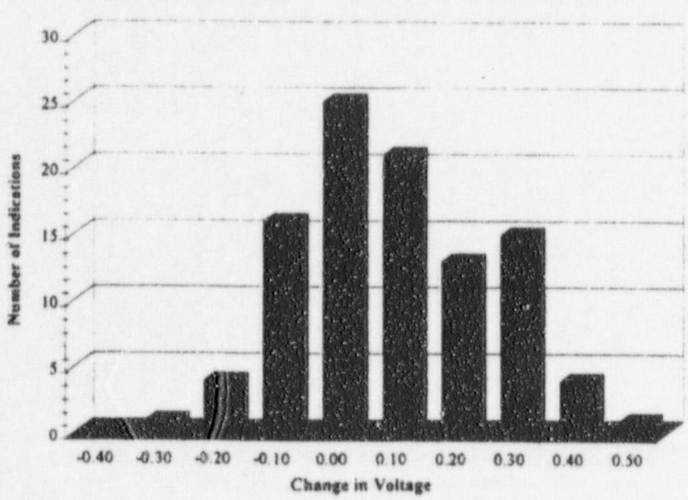
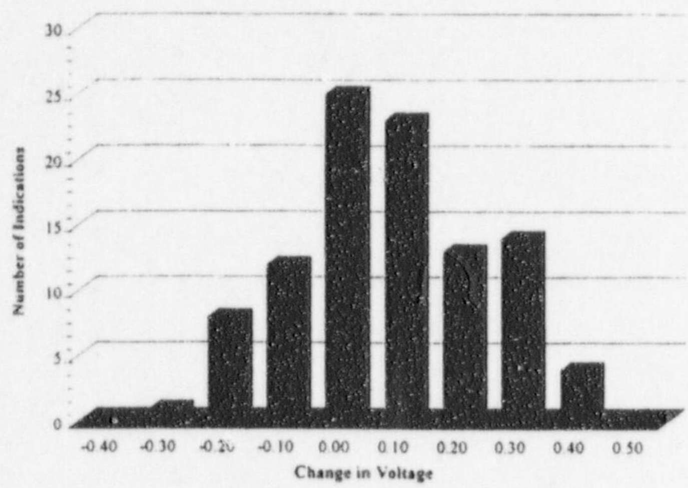


Figure 17 Case 2 Voltage Differences



Using the equations of section 7.1.3, the decision of growth or no growth is made. A summary is presented in Table 8. From this summary we can see that for case 2, the random error about the mean did not falsely result in a conclusion of growth. This is translated to mean that random EC variability will not result in a false conclusion of growth. Case 1, on the other hand, shows that even a small amount of consistent increase (remember that the case 1 EOC voltages are equal to the case 2 EOC voltages plus 0.01 volts) will result in a decision of growth.

Table 8 Summary of Growth Evaluation

Case	Sample Size	Mean	Standard Error	t Statistic	95% LCL	95% UCL	Decision
1	100	0.04	0.02	1.984	0.0003	0.0797	Growth
2	100	0.03	0.02	1.984	-0.0097	0.0697	No Growth

7.2 Probability of Detection

The purpose of POD is to quantify how reliably the ODIGA is detected. This probability is presented as a function of the maximum depth of the ODIGA. Quantifying the probability of detection is important when it is necessary to estimate the size of the ODIGA population based on the number of indications found during the EC examination.

For ODIGA, the performance criteria that requires estimating the population of the ODIGA is primary-to-secondary leakage (attributed to ODIGA) during a MSLB. The maximum depth of the ODIGA defect is the major determining factor when assessing the probability of leakage. For instance, a 10%TW ODIGA patch has almost no probability of leaking under MSLB conditions, but a 100%TW ODIGA patch has a high probability of leaking. As discussed in section 6, none of the defects that were tested under MSLB conditions leaked. That includes EDM holes up to [ ][(b)]%TW and [ ][(b)] inches in diameter. This data supports the conclusion that for ODIGA to leak, it must be nearly 100%TW.

For purposes of this management program, the importance of POD is to increase the size of the population to account for indications with a reasonable probability of leaking under MSLB conditions. It will therefore be conservatively assumed that the maximum depth of ODIGA must be at least [ ](b)%TW for there to exist a reasonable probability of leakage. To determine the POD associated with ODIGA [ ](b)%TW or deeper, the validated bobbin POD logistic regression curve for ODIGA is utilized. This curve, shown in Figure 18, shows that the 95% lower confidence limit for detecting ODIGA [ ](b)%TW or deeper is greater than [ ](b)%. For this SGDSM, it is therefore assumed that [ ](e)% of the ODIGA defects with any chance of leaking will be found during an in-service inspection.

Figure 18 POD for ODIGA

(d)

Ideally, this POD value would be applied to the number of indications that are found during the in-service inspection and sized to be greater than or equal to [ ](b)%TW. This is not currently possible, however, because there is no qualified depth sizing technique. It will therefore be conservatively assumed that all the indications found are greater than [ ](e)%TW and the entire population will be increased by [ ](e)%. This will be done by first determining the potential number of indications not detected, *n*, by multiplying the number of ODIGA indications found by [ ](e). The EC measured axial extents (this is the controlling parameter for conditional leak rate) of the indications found are then binned into 0.10 inch increments. Finally, each bin is increased by *n* multiplied by the ratio of the bin size to the number of indications found. For instance, if 100 indications are found in OTSG A, then [ ](e) indications are assumed to not be detected. The new amount is calculated in descending bin order, and fractions <1/2 are rounded down. Once the number of new indications is added, the process is stopped.

Table 9 Sample POD Adjustment

Axial Extent (inches)	Number of Indications Detected	Assumed Not Detected	ODIGA Population Size
		(d)	

7.3 New Indications

As discussed in section 4.1, the volumetric ODIGA is believed to be attributed to sulfur ingress during the late 1970's and early 1980's. Consequently, no new indications are expected to be found. Given the small geometric sizes of the ODIGA, however, it is possible that as EC techniques and equipment continue to improve, that indications not previously reported are found. When an indication not previously reported is found, the EC inspection history will be reviewed to determine whether or not the indication was present. If it is determined that the new indication was present, then available EC data on that indication will be utilized in growth monitoring. If the indication is not located in the historical review, then the indication will be considered new. Newly identified ODIGA indications will be added to the database and tracked for growth.

8.0 UTS VOLUMETRIC ODIGA MANAGEMENT PROGRAM

The volumetric ODIGA management program is designed to ensure that OTSG tubes with volumetric ODIGA meet the structural performance criteria of section 5.5 and the leakage performance criteria of section 6.4. both at the time of inspection and at the end of the next cycle of operation. The assessment process involves performing EC inspections of the defined region and then performing EC defect sizing of the indications characterized as volumetric ODIGA. The number of allowable leaking indications is determined based on postulated leak rates using the EC sizing information. Based on the number of allowable leaking indications, the required number of indications that must be in-situ leak tested is calculated for each SG and assessment. In-situ leak testing is then performed as necessary on the limiting SG to demonstrate compliance with the accident condition performance criteria.

8.1 SG Tube Inspection

During each outage in which the management program is utilized, a 100% bobbin coil inspection of the defined region (section 4.4) of in-service unsleeved tubes will be conducted in accordance with the requirements of the Entergy ANO-1 steam generator tube inspection guidelines. All OD indications reported as a result of this inspection will then be inspected with a RC. If the morphology is characterized as:

- ⇒ volumetric, then the indication will be treated as ODIGA.
- ⇒ mixed mode, (containing both volumetric characteristics of ODIGA and characteristics of crack initiation) then the indication will be treated as ODIGA that has developed a crack and will be repaired.
- ⇒ crack-like, (either axial or circumferential) then the indication will be treated as a crack and will be repaired.
- ⇒ no defect, if no indication is found then it will be assumed that the bobbin indication is not a defect.

The number of bobbin NQI indications that are confirmed volumetric plus any additional volumetric indications not reported by the bobbin examination but detected during the RC examination are considered to make up the detected population, P_{det} for each steam generator.

8.2 Sizing of Volumetric ODIGA

All indications dispositioned as ODIGA will then be sized. Sizing includes determining a voltage amplitude, axial extent, and circumferential extent for each ODIGA patch. The NDE techniques used to perform these measurements, while not formally validated, are the best available methods and equipment available and also are chosen such that a viable comparison can be made with the previous inspection's EC data. For instance, based on extensive investigation, the best available correlation of EC voltage with ODIGA depth is the Plus-point coil. The Plus-point coil will therefore be utilized as the voltage amplitude comparison unless a better technique is found. The axial and circumferential extents shall be measured with the 0.115 inch pancake coil because it provides a more accurate measurement of axial and circumferential extent of ODIGA than the Plus-point coil.

If a new technique is used in an inspection, then the EC data from the previous inspection will be re-analyzed to provide an equivalent measurement comparison. If the new technique involves a different coil, or some other change that makes comparison with the previous outage impossible, then the current inspection's data will be re-analyzed in the manner utilized in the previous inspection and comparisons will be made using the old technique.

Table 10 EC Sizing Techniques and Notations

Sizing Parameter	EC Sizing Coil
Voltage	Plus-point
Axial Extent (inches)	0.115 inch pancake
Circ. Extent (inches)	0.115 inch pancake

Note: As stated in text, the EC sizing coil is currently the best available technique and may be changed as new techniques become available.

8.3 Condition Monitoring Assessment

Condition monitoring is the assessment of the "as found" condition of the tubing relative to the management program performance criteria. The "as found" condition refers to the condition of the tubes during an SG inspection outage, prior to any plugging or repair of tubes.

8.3.1 Apparent Growth Evaluation

The growth evaluation is performed for each SG using the process outlined in section 7.1.2 and is considered an "apparent" growth evaluation because it is based on the relative change in EC measurements as opposed to direct physical measurements. For each EC sizing parameter, the 95% confidence interval of the differences will be calculated. The number of indications includes all volumetric ODIGA indications detected and sized both at the beginning of the cycle (BOC) and the end of the cycle (EOC). Indications without BOC EC data are addressed by POD and are not included in the growth evaluation. As stated in section 7.1, if two of the three parameters do not support the assumption of "no growth", then "no growth" cannot be assumed. The effects based on the outcome of this evaluation are discussed below.

If the assumption of "no growth" is supported, then it is assumed that the volumetric ODIGA is not changing. This allows the use of past tube destructive examination data and in-situ testing to be utilized. For instance, Table 16 and Table 17 show that 35 volumetric ODIGA defects in SG A and 20 volumetric ODIGA defects in SG B have been either destructively examined or in-situ leak tested. None have resulted in any leakage. This data is from the 1R13 and 1R14 in-service inspections. Growth evaluations performed during the 1R14 inspection supported "no growth" and therefore if "no growth" is again supported during the 1R15 inspection, this data can be credited in the 1R15 leakage assessments. The notation for previous test data is presented in Table 11.

Table 11 Previous Test Data Notation

Parameter (amount)	Notation	
	SG A	SG B
Samples Tested	n_{Aprev}	n_{Bprev}
Samples that Leaked	X_{Aprev}	X_{Bprev}

8.3.2 Population Size Defined

The detected population is defined as all indications characterized by EC to be ODIGA during the current inspection (section 8.1). An additional number of indications is then included to account for limitations in the detection of indications. This adjustment for POD is made in accordance with section 7.2. If the conclusion of the apparent growth evaluation (section 8.3.1) is no growth, then previous testing data may be included in the population (section 8.3.2). In other words, if it is concluded that the population is not changing, testing performed during an earlier inspection may be treated as though it were being performed now. If it is concluded that the ODIGA indications are growing, then previous testing cannot be credited because the population is not the same and the previous testing term is set to zero. The notation for population size determination is presented in Table 12.

Table 12 Population Size Determination

	Population	
	SG A	SG B
Number of Detected Indications	P_{Adet}	P_{Bdet}
POD Adjustment	$+P_{Apod}$	$+P_{Bpod}$
Previous Testing Adjustment	$+n_{Aprev}$	$+n_{Bprev}$
Population	P_A	P_B

8.3.3 Determination of Sample Size

Many repair criteria utilize a 40%TW repair limit. These criteria require a validated EC depth sizing technique. The limited structural impact that this damage mechanism has on the tube (for the axial and circumferential extents present in the steam generators), however, makes a 40%TW repair criteria overly conservative. To provide a more realistic assessment of the ODIGA, a program involving in-situ pressure testing will be utilized for monitoring the current condition of the tubes and assessing their future operability. Therefore, the next step in this assessment is to determine the number of ODIGA patches that must be tested to provide a high level of confidence (95% confidence level) that any primary-to-secondary leakage through ODIGA patches left in service is less than the amount allocated.

8.3.3.1 Determine Allowable Number of Leaking Indications

The first step is to define the allowable MSLB leakage rate for the population of ODIGA indications. The MSLB accident is considered the limiting accident condition for primary-to-secondary leakage, and the cumulative leakage rate from all leakage sources must be less than 1 gpm. Other potential sources of leakage include plugs, sleeves, other damage mechanisms, and repair rolls. Based on the condition of the generator, the allowed leakage rate for volumetric ODIGA may change from inspection to inspection and is therefore not set in this report.

The second step is to order the EC measured axial extents of the population from largest to smallest. Individual leak rates will be assigned to each indication according to the EC size bins of Table 7. [ ](e) The leakage rates are then summed from the largest axial extent to the smallest axial extent until the allowable MSLB leakage rate is met. This means that it is conservatively assumed that only the indications with the largest axial extents would leak. The variable *a* is defined as the allowable number of leaking ODIGA indications in the SG.

8.3.3.2 Hypergeometric Distribution

The assessments make the conservative assumption that all ODIGA indications have an equal probability of leaking. The hypergeometric distribution involves sampling from a population without replacement. (Sampling with replacement would utilize the binomial distribution). The variables in the hypergeometric distribution are defined in Table 13 for each SG, but the derivation of the equations in this section uses the generic variable form.

Table 13 Hypergeometric Distribution Variables Defined

Variable	Section or Equation		Description
	SG A	SG B	
a	a_A, 8.3.3.1	a_B, 8.3.3.1	leaking indications in SG
b	$b_A = P_A - a_A$	$b_B = P_B - a_B$	non-leaking indications in SG
n	n_A, 8.3.3.2	n_B, 8.3.3.2	required sample from equation
n_{test}	$n_{Atest} = n_A - n_{Aprev}$	$n_{Btest} = n_B - n_{Bprev}$	number of samples to test
X_f	$X+X_{Aprev}$	$X+X_{Bprev}$	leaking indications in test sample
P	P_A, 8.3.2	P_B, 8.3.2	number of indications in SG

Note 1: initial assumption is no leaking indications will be found (X=0) in the tested sample size, so X_f will always be zero unless previous test results (X_{prev}) are included and resulted in leakage.

Note 2: See section 8.3.1 for definition of X_{Aprev}, X_{Bprev}, n_{Aprev}, n_{Bprev}.

The hypergeometric distribution is defined as follows: Given a population with only two types of objects (indication leaks or doesn't leak), such that there are *a* items of one kind (leaks) and *b* items of another kind (doesn't leak) and *a*+*b* equals the total population, the probability P(A) of selecting a sample size *n* with X_f items of type *a* and n-X_f items of type b is given in Equation 4.

Equation 4 Base Hypergeometric Distribution

$$P(A)=\frac{{}_aC_{X_f}\times{}_bC_{n-X_f}}{{}_{(a+b)}C_n}$$

The above equation is the probability of having exactly X_f leakers in a sample size of n. Based on this premise, if X is set to zero and X_{prev}=0, then $P(A)$ is the probability of finding no leakers in a sample size of n. Therefore, 1-$P(A)$ is the probability of finding at least 1 leaker in the tested sample. This will serve as the basis for evaluating the condition of the tubes. Setting the probability that zero leakers will be found in the sample to 0.05 results in a 95% probability that at least one leaker will be found in the tested sample if a specific number of leakers exist in the population.

Equation 5 Probability of at Least One Leaker

$$1-P(0\_leaks)=1-\frac{{}_aC_0\times{}_bC_n}{{}_{(a+b)}C_n}=0.95$$

Equation 5 is set up to determine the required sample size n that must be tested to have a 95% confidence that no more than a leakers are in the population because 0 leakers were found in the sample tested. It is reiterated at this point that this equation takes no credit for any knowledge of the EC sizing information, resulting in each indication being treated equally with respect to the probability of leakage. This is a conservative assumption because the allowable number of leaking indications is based on the assumption that the indications with the largest axial extents leak.

For the case where one or more leaking ODIGA patches is found in the tested sample, the cumulative sum of the probabilities is subtracted from one. Equation 6 represents the probability of finding d leaks in a sample size n, given a leaking patches in the population.

Equation 6 Probability of "d" Leakers in Tested Sample

$$P(d\_leaks)=1-\sum_{X_f=0}^{d}\frac{{}_aC_{X_f}\times{}_bC_{n-X_f}}{{}_{(a+b)}C_n}=0.95$$

8.3.3.3 Sample Size Defined

The required sample size, n, is therefore determined by solving either Equation 5 or Equation 6 for n. For instance, assume that it is determined that an SG has an ODIGA population of 130 indications and that this population includes 35 indications that had previously been tested with no leaking indications found. Further assume that the allowable leakage rate is set to 0.2 gpm, resulting in an allowable number of leaking indications equal to 15. Solving Equation 5 for n yields:

Equation 7 Example of Sample Size Determination

$$1 - P(0\_leaks) = 1 - \frac{{}_{15}C_0 \times {}_{115}C_n}{{}_{(130)}C_n} = 0.95$$

$$n = 22\text{, and}$$

$$n_{prev} = 35\text{, so}$$

$$n_{test} = n - n_{prev} < 0$$

The final sample size to be tested is equal to the sample size n minus the number of indications previously tested n_{prev}. In this example, comparing the number of indications previously tested (35) to the number required (22) shows that more than the required sample size has been tested, so further in-situ testing is not needed. If n_{test} is greater than zero, then in-situ leak testing must be performed on the limiting SG. The limiting SG is the SG that has the larger required sample size to test.

8.3.4 In-Situ Leak Testing

The purpose of the in-situ pressure testing is to provide a means of validating the premise that leaving tubes with ODIGA in-service will not result in MSLB primary-to-secondary leakage rates in excess of the plant technical specification allowable. As discussed in section 6.3, the most probable cause of leakage is through the development of an axial crack in the ODIGA during plant operation. Leak tests will therefore be conducted at MSLB pressure differential of 2575 psi without a specific axial load in order to maximize the hoop stress in the tube. If the indication leaks at this pressure, then the test will be repeated with the maximum axial load and the associated MSLB pressure differential.

Upon completion of the leak testing, the results are compared against the required sample size to ensure that enough indications were tested. If any indications leaked, then the required sample size must be recalculated using Equation 6, and more tests may have to be performed.

8.3.5 Reporting Requirements

The results of the inspection and assessment of tubes with volumetric ODIGA in the defined region shall be included in the in-service inspection report. This report shall include the number of detected ODIGA indications in each SG, the number of ODIGA indications left in service, and the total MSLB leakage predicted for the limiting SG.

8.4 Operational Assessment

The operational assessment is performed to ensure that the performance criteria will be maintained over the next scheduled steam generator in-service inspection interval. The length of the operating cycle prior to the next scheduled inspection is utilized to determine appropriate growth rates for the volumetric ODIGA. It is noted that although general procedure appears to be the same for both the condition monitoring and operational assessments, the specific requirements change due to assessing the predicted population at the end of the next cycle of operation.

8.4.1 Apparent Growth Evaluation

The growth evaluation is performed for each SG using the process outlined in section 7.1.2 and is considered an "apparent" growth evaluation because it is based on the relative change in EC measurements as opposed to direct physical measurements. For each EC sizing parameter, the 95% confidence interval of the differences will be calculated. The number of indications includes all volumetric ODIGA indications detected and sized both at the beginning of the cycle (BOC) and the end of the cycle (EOC). Indications without BOC EC data are addressed by POD and are not included in the growth evaluation. As stated in section 7.1, [

]$^{(e)}$ The effects based on the outcome of this evaluation are discussed below.

8.4.1.1 Credit for Previous Testing

This portion of the assessment is the same for both assessments. Refer to section 8.3.1.

8.4.1.2 Projected EOC Indication Sizes

When performing the operability assessment for each SG, the EOC measurements used in the growth evaluation become the BOC measurements for the next cycle of operation. The operability assessment, however, is based on the projected EOC measurements for the next cycle. If the "no growth" assumption is not supported, the projected EOC measurements of axial and circumferential extents are estimated by increasing the BOC measurements by the upper 95% confidence value for growth. This growth term is determined by multiplying the upper 95% confidence value calculated in Equation 3 by the ratio of the next cycle's run time to the just completed cycle run time (in units of EFPY). If the "no growth" assumption is supported, then the projected EOC measurements are simply the BOC measurements. The equations to calculate the projected EOC measurements are given in Equation 8 and Equation 9.

Equation 8 Projected EOC Axial Extent

$$A_{EOC} = A_{BOC} + A_{\Delta 95} \times \left(\frac{EFPY_{projected}}{EFPY_{completed}}\right)$$

Equation 9 Project EOC Circumferential Extent

$$C_{EOC} = C_{BOC} + C_{\Delta 95} \times \left(\frac{EFPY_{projected}}{EFPY_{completed}}\right)$$

8.4.2 Tube Repairs

The operational assessment considers all indications that will be in-service during the next cycle of operation. Indications in tubes that will be repaired or taken out of service during the current inspection are therefore not considered in this assessment. As part of this management program, all tubes with volumetric ODIGA projected to have circumferential extents in excess of [ ]$^{(e)}$ at the end of the next cycle of operation must be repaired or removed from service. This extent limit is conservatively applied to ensure that the circumferential extents of the volumetric ODIGA remain bounded by what has been tested (section 6.2).

8.4.3 Population Size Defined

The detected population is defined as all indications characterized by EC to be ODIGA during the current inspection (section 8.1). All indications that are repaired or removed from service in accordance with section 8.4.2 are removed from consideration. An additional number of indications is then included to account for limitations in the detection of indications. This adjustment for POD is made in accordance with section 7.2. If the conclusion of the apparent growth evaluation (section 8.4.1) is no growth, then previous testing data may be included in the population. In other words, if it is concluded that the population is not changing, testing performed during an earlier inspection may be treated as though it were being performed now. If it is concluded that the ODIGA indications are growing, then previous testing cannot be credited because the population is not the same and the term is set to zero. The notation for population size determination is presented in Table 14.

Table 14 Population Size Determination

	Population	
	SG A	SG B
Number of Detected Indications	P_{Adet}	P_{Bdet}
Indications Repaired/Plugged	P_{Arep}	P_{Brep}
POD Adjustment	$+P_{Apod}$	$+P_{Bpod}$
Previous Testing Adjustment	$+n_{Aprev}$	$+n_{Bprev}$
Population	P_A	P_B

8.4.4 Determination of Sample Size

Many repair criteria utilize a 40%TW repair limit. The limited structural impact that this damage mechanism has on the tube (for the axial and circumferential extents present in the steam generators), however, makes a 40%TW repair criteria overly conservative. To provide a more realistic assessment of the ODIGA, a program involving in-situ pressure testing will be utilized for monitoring the current condition of the tubes and assessing their future operability. The next step in this assessment is, therefore, to determine the number of ODIGA patches that must be tested to provide a high level of confidence (95% confidence level) that any primary-to-secondary leakage through ODIGA patches left in service is less than the amount allocated.

8.4.4.1 Determine Allowable Number of Leaking Indications

This portion of the assessment is the same for both assessments. Refer to section 8.3.3.1, but use the EOC data determined in section 8.4.1.2.

8.4.4.2 Hypergeometric Distribution

The assessments make the conservative assumption that all ODIGA indications have an equal probability of leaking. The hypergeometric distribution involves sampling from a population without replacement. (Sampling with replacement would utilize the binomial distribution). The variables in the hypergeometric distribution are defined in Table 15 for each SG, but the derivation of the equations in this section use the generic variable form.

Table 15 Hypergeometric Distribution Variables Defined

Variable	Section or Equation		Description
	SG A	SG B	
a	a_A, 8.4.4.1	a_B, 8.4.4.1	leaking indications in SG
b	$b_A = P_A - a_A$	$b_B = P_B - a_B$	non-leaking indications in SG
n	n_A, 8.4.4.2	n_B, 8.4.4.2	required sample from equation
n_{test}	$n_{Atest} = n_A - n_{Aprev}$	$n_{Btest} = n_B - n_{Bprev}$	number of samples to test
X_f	$X+X_{Aprev}$	$X+X_{Bprev}$	leaking indications in sample
P	P_A, 8.4.3	P_B, 8.4.3	number of indications in SG

Note 1: initial assumption is no leaking indications will be found (X=0), so X_f will always be zero unless previous test results (X_{prev}) are included and resulted in leakage.
Note 2: See section 8.4.1.1 for definition of X_{Aprev}, X_{Bprev}, n_{Aprev}, n_{Bprev}

The hypergeometric distribution is defined as follows: Given a population with only two types of objects (indication leaks or doesn't leak), such that there are a items of one kind (leaks) and b items of another kind (doesn't leak) and $a+b$ equals the total population, the probability P(A) of selecting a sample size n with X_f items of type a and n-X_f items of type b is given in Equation 10.

Equation 10 Base Hypergeometric Distribution

$$P(A) = \frac{{}_aC_{X_f} \times {}_bC_{n-X_f}}{{}_{(a+b)}C_n}$$

The above equation is the probability of having exactly X_f leakers in a sample size of n. Based on this premise, if X is set to zero and X_{prev}=0, then $P(A)$ is the probability of finding no leakers in a sample size of n. Therefore, 1-$P(A)$ is the probability of finding at least 1 leaker in the tested sample. This will serve as the basis for evaluating the condition of the tubes. Setting the probability that zero leakers will be found in the sample to 0.05 results in a 95% probability that at least one leaker will be found in the sample.

Equation 11 Probability of at Least One Leaker

$$1 - P(0\_leaks) = 1 - \frac{{}_aC_0 \times {}_bC_n}{{}_{(a+b)}C_n} = 0.95$$

Equation 5 is set up to determine the required sample size n that must be tested to have a 95% confidence that no more than a leakers are in the population because 0 leakers were found in the sample tested. It is reiterated at this point that this equation takes no credit for any knowledge of the EC sizing information, resulting in each indication being treated equally with respect to the probability of leakage. This is a conservative assumption because the allowable number of leaking indications is based on the assumption that the indications with the largest axial extents leak.

For the case where one or more leaking ODIGA patches is found in the tested sample, the cumulative sum of the probabilities is subtracted from one. Equation 12 represents the probability of finding *d* leaks in a sample size *n*, given *a* leaking patches in the population.

Equation 12 Probability of "d" Leakers in Tested Sample

$$P(d\_leaks) = 1 - \sum_{X_f=0}^{d} \frac{{}_{a}C_{X_f} \times {}_{b}C_{n-X_f}}{{}_{(a+b)}C_n} = 0.95$$

8.4.4.3 Sample Size Defined

The required sample size, *n*, is therefore determined by solving either Equation 11 or Equation 12 for *n*. For instance, assume that it is determined that an SG has an ODIGA population of 130 indications and that this population includes 20 indications that had previously been tested with no leaking indications found. Further assume that the allowable leakage rate is set to 0.2 gpm, resulting in an allowable number of leaking indications equal to 15. Solving Equation 11 for *n* yields:

Equation 13 Example of Sample Size Determination

$$1 - P(0\_leaks) = 1 - \frac{{}_{15}C_0 \times {}_{115}C_n}{{}_{(130)}C_n} = 0.95$$

$$n = 22, \text{ and}$$
$$n_{prev} = 20, \text{ so}$$
$$n_{test} = n - n_{prev} = 2$$

The final sample size to be tested is equal to the sample size *n* minus the number of indications previously tested n_{prev}. In this example, comparing the number of indications previously tested (20) to the number required (22) shows that 2 indications must be in-situ leak tested in order to justify the projected cycle length. If n_{test} were less than or equal to zero, then no additional in-situ leak testing must be performed.

8.4.5 In-Situ Leak Testing

The purpose of the in-situ pressure testing is to provide a means of validating the premise that leaving tubes with ODIGA in-service will not cause MSLB primary-to-secondary leakage rates in excess of the plant technical specification allowable. The testing will be conducting on the SG which requires the greatest number of samples in order to meet the leakage performance criteria at the end of the next cycle of operation. As discussed in section 6.3, the most probable cause of leakage is through the development of an axial crack in the ODIGA during plant operation. Therefore, leak tests will be conducted at the MSLB pressure differential of 2575 psi without a specific axial load in order to maximize the hoop stress in the tube. If the indication leaks, then the test will be repeated with the limiting MSLB axial load and the associated pressure differential.

Upon completion of the leak testing, the results are compared against the required sample size to ensure that enough indications were tested. If any indications leaked, then the required sample size must to be recalculated using Equation 6, and more tests may have to be performed.

8.4.6 Reporting Requirements

The results of the inspection and assessment of tubes with volumetric ODIGA in the defined region shall be included in the in-service inspection report. This report shall include the number of detected ODIGA indications in each SG the number of ODIGA indications left in service, and the total MSLB leakage predicted for the limiting SG.

9.0 RISK ASSESSMENT

The NRC has established five key principals that should be met in order to implement risk-informed decision making relative to license basis changes. These principals are listed in reference 2.4. The principles are as follows:

1. The proposed change meets the current regulations unless it is explicitly related to a requested exemption or rule change, i.e., a "specific exemption" under 10 CFR 50.12 or a "petition for rulemaking" under 10 CFR 2.802.

2. The proposed change is consistent with the defense-in-depth philosophy.

3. The proposed change maintains sufficient safety margins.

4. When proposed changes result in an increase in core damage frequency of risk, the increase should be small, and consistent with the intent of the commission's Safety Goal Policy Statement.

5. The impact of the proposed change should be monitored using performance measurement strategies.

The implementation of the ARC relative to each of these principals is discussed in the following paragraphs.

9.1 Satisfaction of Current Regulation

The analyses and testing performed in support of this SGDSM have demonstrated that if the SGDSM is applied consistent with the requirements set forth in this report, the deterministic structural integrity criteria of the plant's current licensing basis as defined in the plant Technical Specifications is satisfied. This appropriate margins for failure under normal operating conditions and postulated accidents established in Regulatory Guide 1.121 have also been met. In addition, the impact on postulated leakage during a design basis accident has been assessed, and it has been shown (see section 6) that the leakage will be less than the limit established to satisfy 10 CFR 100 limits for off-site dose defined in the plant licensing documents. The approach taken to conservatively quantify the leakage is similar to the methodology outlined in NRC Generic Letter 95-05, which established an acceptable framework for submittal of alternate repair criteria which could result in leaving tubes with known through-wall degradation in service. Therefore, it is concluded that the proposed change to the plant's licensing basis meets all current regulations set forth for implementation of this SGDSM.

9.2 Defense in Depth

The proposed ARC will allow ODIGA with depths that are potentially greater than 40%TW to remain in service, which potentially compromises the leakage integrity of one barrier between the public and the fission products in the reactor core, namely the primary-to-secondary pressure boundary. However, as discussed earlier, the structural integrity of the tubes is maintained under application of this SGDSM, thus preventing rupture of the boundary. Leakage that could be attributed to these indications during a design basis accident has been conservatively estimated and shown to be less than the plant acceptance criteria when the SGDSM is applied in accordance with the requirements in this document. Furthermore, the SGDSM has no effect on the remaining containment structures or on any plant process or procedure that would increase the likelihood or consequences of any accident. Therefore, it is concluded that the defense-in-depth design attributes are satisfactorily maintained under application of this SGDSM.

9.3 Safety Margins

It has been shown that the indications that this SGDSM manages cannot burst due to the support provided by the tubesheet. It is therefore concluded that safety margins consistent with the design basis of the plants have been maintained.

9.4 Effect of ARC on Core Damage Frequency

The SGDSM for ODIGA will be applied only to indications that are located in the portion of tubing that is within the upper tubesheet. Burst of these indications is not possible due to the constraint provided by the tubesheet, so the thermal challenge conditions associated with a severe accident do not affect the probability of tube burst at this location. Therefore, application of this SGDSM will not increase the probability of tube rupture and thus will have no impact on the Core Damage Frequency or Large Early Release Frequency.

9.5 Performance Monitoring

All indications remaining in service as a result of this SGDSM will be inspected in each planned future inspection outage in order to ensure that performance criteria are satisfied. The inspection will be conducted in accordance with the EPRI Steam Generator Examination Guidelines, as supplemented by the requirements in this report. In addition, primary-to-secondary leakage monitoring during normal operation serves to ensure that the tubes are not degrading at a rate significantly higher than that which is assumed in this application. Therefore, it is concluded that sufficient monitoring measures are in place to ensure the continued satisfactory performance of any tubes with indications left in service as a result of this SGDSM.

Table 16 Pulled Tube Data Summary

Identification					Direct Measurement				EC Measurements		
Type	OTSG	Row	Tube	Position	Max Depth (%TW)	Axial Extent (inches)	Circ. Extent (inches)	Burst Pressure (psi)	Bobbin Voltage	RC Axial Extent (inches)	RC Circ. Extent (inches)
						(d)					

Notes:

(1) test not performed due to sample type
(2) data not available
(3) burst away from defect
(4) detected as one indication by EC

Table 17 In-Situ Pressure Testing Data Summary

(d)

Identification					EC Measurements			In-situ
Index No.	OTSG	Row	Tube	Position	Bobbin Voltage	RC Axial Extent (inches)	RC Circ. Extent (inches)	Test Condition Codes

Identification					EC Measurements			In-situ
Index No.	OTSG	Row	Tube	Position	Bobbin Voltage	RC Axial Extent (inches)	RC Circ. Extent (inches)	Test Condition Codes
					(d)			

Test Conditions:

(1) [ ]$^{(d)}$

(2) [ ]$^{(d)}$

(3) [ ]$^{(d)}$

Table 18 Unbent Lab Sample Data Summary

Identification		Direct Measurement				EC Measurements		
Type	Sample Number	Max Depth (%TW)	Axial Extent (inches)	Circ. Extent (inches)	Burst Pressure (psi)	Bobbin Voltage	RC Axial Extent (inches)	RC Circ Extent (inches)
					(d)			

Identification		Direct Measurement				EC Measurements		
Type	Sample Number	Max Depth (%TW)	Axial Extent (inches)	Circ. Extent (inches)	Burst Pressure (psi)	Bobbin Voltage	RC Axial Extent (inches)	RC Circ Extent (inches)
					(d)			

Notes:

(!) test not performed due to sample type

Table 19 Bent Sample Data Summary

Identification		Direct Measurement				EC Measurements		
Type	Sample Number	Max Depth (%TW)	Axial Extent (inches)	Circ. Extent (inches)	Burst Pressure (psi)	Bobbin Voltage	RC Axial Extent (inches)	RC Circ Extent (inches)
					(d)			

Notes:

(1) test not performed due to sample type

(2) data not available

Table 20 Growth Evaluation Data Summary

BOC	Case 1 EOC		Case 2 EOC	
Volts	Volts	Delta	Volts	Delta
1.13	1.42	0.29	1.41	0.28
1.06	1.14	0.08	1.13	0.07
1.16	1.26	0.10	1.25	0.09
1.34	1.32	-0.02	1.31	-0.03
0.67	0.64	-0.03	0.63	-0.04
0.41	0.33	-0.08	0.32	-0.09
0.81	1.10	0.29	1.09	0.28
0.66	0.86	0.20	0.85	0.19
0.69	0.73	0.04	0.72	0.03
1.06	1.14	0.08	1.13	0.07
0.8	0.72	-0.08	0.71	-0.09
0.34	0.26	-0.08	0.25	-0.09
0.85	0.79	-0.06	0.78	-0.07
0.6	0.81	0.21	0.80	0.20
0.64	0.88	0.24	0.87	0.23
0.32	0.63	0.31	0.62	0.30
0.41	0.44	0.03	0.43	0.02
0.73	0.77	0.04	0.76	0.03
0.47	0.82	0.35	0.81	0.34
0.4	0.40	0.00	0.39	-0.01
1.2	1.14	-0.06	1.13	-0.07
1.19	1.06	-0.13	1.05	-0.14
0.36	0.44	0.08	0.43	0.07
0.52	0.63	0.11	0.62	0.10
0.74	0.73	-0.01	0.72	-0.02

BOC	Case 1 EOC		Case 2 EOC	
Volts	Volts	Delta	Volts	Delta
0.41	0.66	0.25	0.65	0.24
1.55	1.55	0.00	1.54	-0.01
0.92	1.12	0.20	1.11	0.19
1.48	1.69	0.21	1.68	0.20
0.66	0.89	0.23	0.88	0.22
0.91	0.98	0.07	0.97	0.06
0.58	0.74	0.16	0.73	0.15
0.51	0.76	0.25	0.75	0.24
0.37	0.12	-0.25	0.11	-0.26
1.07	1.14	0.07	1.13	0.06
0.5	0.59	0.09	0.58	0.08
0.32	-0.01	-0.33	-0.02	-0.34
1.14	1.19	0.05	1.18	0.04
0.35	0.55	0.20	0.54	0.19
0.63	0.66	0.03	0.65	0.02
0.86	0.68	-0.18	0.67	-0.19
0.87	1.04	0.17	1.03	0.16
0.9	0.95	0.05	0.94	0.04
0.56	0.70	0.14	0.69	0.13
0.33	0.31	-0.02	0.30	-0.03
0.83	0.97	0.14	0.96	0.13
0.48	0.46	-0.02	0.45	-0.03
0.47	0.29	-0.18	0.28	-0.19
0.53	0.79	0.26	0.78	0.25
0.67	0.97	0.30	0.96	0.29

BOC	Case 1 EOC		Case 2 EOC	
Volts	Volts	Delta	Volts	Delta
0.58	0.46	-0.12	0.45	-0.13
1.11	1.23	0.12	1.22	0.11
0.49	0.44	-0.05	0.43	-0.06
1.8	1.82	0.02	1.81	0.01
0.6	0.55	-0.05	0.54	-0.06
1.46	1.4	-0.06	1.39	-0.07
1.05	0.92	-0.13	0.91	-0.14
1.06	0.98	-0.08	0.97	-0.09
0.78	0.89	0.11	0.88	0.1
0.55	0.68	0.13	0.67	0.12
0.73	0.55	-0.18	0.54	-0.19
0.61	0.49	-0.12	0.48	-0.13
0.22	0.31	0.09	0.3	0.08
0.45	0.37	-0.08	0.36	-0.09
1.16	1.13	-0.03	1.12	-0.04
1.51	1.54	0.03	1.53	0.02
0.9	0.71	-0.19	0.7	-0.2
1.04	1.38	0.34	1.37	0.33
1.27	1.3	0.03	1.29	0.02
0.44	0.66	0.22	0.65	0.21
0.51	0.92	0.41	0.91	0.4
0.99	0.98	-0.01	0.97	-0.02
0.46	0.69	0.23	0.68	0.22
1.17	1.39	0.22	1.38	0.21
1.47	1.45	-0.02	1.44	-0.03

BOC	Case 1 EOC		Case 2 EOC	
Volts	Volts	Delta	Volts	Delta
0.34	0.21	-0.13	0.20	-0.14
0.67	0.47	-0.20	0.46	-0.21
0.66	0.73	0.07	0.72	0.06
0.62	0.65	0.03	0.64	0.02
1.14	1.48	0.34	1.47	0.33
1.47	1.45	-0.02	1.44	-0.03
0.96	0.92	-0.04	0.91	-0.05
0.68	0.46	-0.22	0.45	-0.23

BOC	Case 1 EOC		Case 2 EOC	
Volts	Volts	Delta	Volts	Delta
1.85	1.81	-0.04	1.80	-0.05
1.62	1.59	-0.03	1.58	-0.04
0.51	0.61	0.10	0.60	0.09
1.1	0.86	-0.24	0.85	-0.25
1.46	1.70	0.24	1.69	0.23
1.14	1.10	-0.04	1.09	-0.05
0.81	0.62	-0.19	0.61	-0.20
0.56	0.44	-0.12	0.43	-0.13

BOC	Case 1 EOC		Case 2 EOC	
Volts	Volts	Delta	Volts	Delta
1.03	1.13	0.1	1.12	0.09
1.01	1.3	0.29	1.29	0.28
0.77	0.67	-0.1	0.66	-0.11
0.63	0.46	-0.17	0.45	-0.18
0.76	0.92	0.16	0.91	0.15
0.41	0.57	0.16	0.56	0.15
0.83	0.69	-0.14	0.68	-0.15
0.54	0.29	-0.25	0.28	-0.26
0.51	0.13	-0.38	0.12	-0.39