2009 International Nuclear Atlantic Conference - INAC 2009
Rio de Janeiro,RJ, Brazil, September27 to October 2, 2009
ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR - ABEN
ISBN: **978-85-99141-03-8**

STRUCTURAL INTEGRITY AND LEAKAGE ASSESSMENT OF ANGRA 1 STEAM GENERATOR USING STATISTIC METHODS

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ABSTRACT

The structural integrity assessment of a nuclear power plant steam generator establishes the allowable dimensions for each crack at the end of the next cycle of operation in terms of its burst accumulated probability of failure. If the limit is met there are enough margins to avoid tube failure. The leakage assessment establishes the maximum leaking rate due to those defects not detected in the inspection, those ones that will appear and grow during the cycle and those ones eventually left in service, considering the defects growing during the next plant cycle when some of them can become thru-wall. The maximum allowable defect dimensions, such as length or depth, should take into account all uncertainties. Usually, a Monte Carlo analysis should be performed to establish the allowable values and it can be a simplified analysis or a multi-cycle one. The latter takes into account the data collected in all previous outages to allow a better data extrapolation for the end of the next cycle adjusting of the data to a given statistical distribution associated with the involved parameters. This work describes some tube structural integrity and leaking assessment performed for the most common degradation, in its 2008 outage, along with a discussion of the obtained results using industry available correlations. Despite the great amount of repaired tubes, all analyses have shown the Angra 1 SG worked within the structural and leaking parameters of safety defined by the regulatory board.

1. INTRODUCTION

The tube in a steam generator (SG) of a Nuclear Power Plant (NPP) should be 100% inspected. Due to the irradiation, indirect examination methods such as eddy current test (ECT) should be used which produce intrinsic errors in the defects dimensions. Some other sources of error are the uncertainty in the experimental correlations used in the assessments, like those between the defect type size and the tube burst pressure, in the material properties and in the defect growing rate until the next outage. Besides, each chosen inspection technique has a probability to detect defects. With these in-service tube inspections the defects can be detected and measured allowing an analysis to demonstrate plant compliance with regulatory requirements (structural and leaking) to assure a safe and reliable plant operation. The way to assure this compliance is to implement the recommendations from the *Nuclear Energy Institute* (NEI) [1] and the *Electric Power Research Institute* (EPRI) [2]. All tube degradations found in the inspection should be analyzed The analyses that should be performed are: Condition Monitoring (CM) and the Operational Assessment (OA). The former compares leaking and structural limits previously calculated with the inspection results to evaluate if the found defects had not challenged the safety requirements against the tube burst and the overall SG leakage during the cycle just ended. The latter (OA) considers the inspection results and the defects growth estimates to verify the requirements at the end of the next cycle. Also, with the OA analysis it is possible to establish the period between inspections. The basis the OA analysis is presented through its application to the Angra 1 SG tube bundle for a period of 0.60 Effective Full Power Years (EFPY) shows that, despite the amount of repaired tubes, greater than the usual in similar plants with the same tube material, the Angra 1 steam generators have worked within the structural and leaking safety parameters. Besides that, and also because the operational leakage was much smaller than the limits during the last five years, it is confirmed that the adopted methodology of inspection and analysis were adequately applied.

2. DEFECTS IN A TUBE

The period between two consecutive inspections is obtained once the analysis shows a probability of burst, during normal conditions, and a probability of leakage, from the primary to the secondary, in accident conditions, below the limits. For instance, the probability of burst should be less than 5% [2]. Probabilistic or deterministic models are allowed. When the number of a given defect type found is big enough to allow a statistical treatment the approach can be a probabilistic one. Otherwise, the approach/analysis should be a deterministic one.

Usually, the primary water flows inside the tubes and the secondary water flows outside. As for example, in the Angra 1 SGs last inspection, P15a, the following defects were deterministically analyzed: axial stress corrosion crack originated in the tube outside (ODSCC) in the tube free span, pitting, axial stress corrosion crack originated in the tube inside (PWSCC) in the tube support plates, circumferential PWSCC in the tubesheet, axial PWSCC in the tubesheet, axial ODSCC in the tubesheet and wear in the anti-vibration bars (AVB). Examples of defects probabilistically analyzed in the Angra 1 SG last inspection: circumferential ODSCC in the tubesheet (OD circ TTS), axial ODSCC in the first support plate (OD axial 01H), axial ODSCC in the tube support plates (OD axial TSP) and circumferential ODSCC in the tube support plates (OD circ TSP).

The analyses were performed using the OPCON program [3] which uses the Monte Carlo method to simulate the initiation, the evolution, the detection and repair in a defect type population. The program obtains the distribution of defects at the end of a given period and, from that, it calculates the probability of burst in the tubes and their leakage rate respectively for normal operation conditions and for accident condition.

3. CRITERIA FOR THE INTEGRITY AND LEAKAGE ANALYSES

Three criteria should be verified [1]: 1st. *Structural*– the tubes should resist a pressure greater than ($3\Delta P_{NOP}$, $1.4\Delta P_{SLB}$) where ΔP_{NOP} is the pressure difference between primary side and secondary side in normal operation condition and ΔP_{SLB} is the pressure difference in accident condition; 2nd. *Leakage in accident condition* – the leakage must be = 1.0 gpm – gallon per minute - per Steam Generator (from the plant accident analysis), and 3rd. *Leakage in normal condition* – the leakage must be = 75 gpd – gallon per day (from the plant operational procedure). The EPRI [2] considers the criteria fulfilled if the analyses show that each requirement is met with a probability of 0.95 with 50% of confidence.

Typically, as it is in Angra 1 with some exceptions, tubes with defect-like indication are repaired or plugged on detection. For tubes with more than one indication there is a defect type prioritization, i.e.: which degradation should be considered as shown in Table 1. Table 2 shows history of repairs per outage in Angra 1 for some of the analyzed defects type in the operational assessment.

Table 1: Number of repaired tubes in the Angra 1 last outage (P15a).

	Origin	Type	Position		Origin	Type	Position
1	OD	Axial	Free span	9	---	Pit	TSP
2	ID	Axial	Free span	10	ID	Axial	TSP
3	ID/OD	Axial	U bend	11	OD	Circ.	TTS
4	OD	AVB	U bend	12	ID	Circ.	TTS
5	OD	Circ.	TSP	13	OD	Axial	01H
6	ID	Circ.	TSP	14	ID	Axial	TTS
7	OD	Axial	TSP	15	OD	Axial	TTS
8	---	SVI/MVI	TSP				

Table 2: Historical of repairs per outage (P*xx*) and type of degradation/defect.

Outage	P10	P11	P12	P12A	P13	P14	P14a	P15a	
EFPY	6.50	7.50	8.26	8.81	9.26	10.04	10.48	11.05	Defect
SG 1	24	105	87	126	42	72	41	44	OD circ TTS
SG 2	38	60	65	134	30	49	25	41	
SG 1	37	65	167	160	43	94	23	64	OD Axial 01H
SG 2	7	22	24	51	17	15	10	15	

4. BASIC EQUATIONS

The burst pressure and the leaking rate of a tube with a given defect type can be obtained from the literature [3]. Eq. (1) gives the burst pressure P for a tube with a partial thru-wall axial crack-like defect in its free span. The burst pressure of a circumferential defect in the tube free span is the minimum value between P, eq. (2.a), and P_o, eq. (2.b), if the defect is outside (OD) and it is the minimum value between P, and P_i, eq. (2.c) if the defect is inside (ID).

In these equations, t, R_i, R_o, PDA, S_y, S_u, L and d_{ef} are, respectively, the tube thickness, the internal and the external tube radii, the Percentage of Degrade Area (the ratio between the defect area and the area of the tube section), the tube material yield and ultimate stress, at the operation temperature (650^{o}F), the defect length and the defect effective (structural) depth.

The leaking for the axial and the circumferential defects is given by eq. (3.a), (3.b) and (3.c) [5]. In these equations, Q_{RT}, Q_{NOP} and Q_{SLB} are, respectively, the leaking at the environment temperature, the leaking at the normal operation temperature and at accident conditions. A is the defect opening area and P is the pressure difference between primary and secondary (in the respective operational condition). The units for L, A and P are, respectively, in, in^2 and psi. As the area A depends on the defect orientation, the leakage is different for axial and for circumferential defects. The coefficients C_1, C_2, …, Cn are available in [5]. To eliminate the temperature dependence from theses expressions the leakage is given in gpm at 70ºF. The leakage for other temperature T is obtained multiplying the Q value from an equation by the ratio of the specific volumes at the temperature T and at 70ºF.

$$P = \frac{0.58(S_y + S_u)t}{R_i}.[1 - \frac{\left(\frac{Ld_{ef}}{t}\right)}{L + 2t}] \qquad \text{(axial)} \tag{1}$$

$$P = 2(S_y + S_u)\left(\frac{R_o - R_i}{R_o + R_i}\right)\left(0.55 - \frac{PDA}{100}\right) \qquad \text{(circ. ext.)} \tag{2.a}$$

$$P_o = \left(\frac{R_o^2 - R_i^2}{R_i^2}\right)\left(1 - \frac{PDA}{100}\right)\left(\frac{S_y + S_u}{2}\right) \qquad \text{(circ. ext.)} \tag{2.b}$$

$$P_i = \frac{P_o R_i^2}{R_i^2 + (R_o^2 - R_i^2)\frac{PDA}{100}} \qquad \text{(circ. int.)} \tag{2.c}$$

$$Q_{RT} = C_1 AP^{0.5}\left[1 - e^{f_1(A/L)}\right], \quad f_1(a/L) = C_2\,(A/L)^{0.5} - C_3\,(A/L) \tag{3.a}$$

$$Q_{NOP} = AP^{f_3(}\,[C_7 - C_8 e^{\left(-C_9(A/L)^{C10}\right)}], \quad f_3(A) = \left(1 - C_4 e^{\left(C_5 A^{C6}\right)}\right) \tag{3.b}$$

$$Q_{SLB} = AP^{C_{11}}\left[C_{12} - C_{13}6e^{f_2(A/L)}\right], \quad f_2(A/L) = C_{14}(A/L)^{C_{15}} - C_{16}(A/L) \tag{3.c}$$

5. ANALYSES TO ASSESS THE SG TUBE BUNDLE INTEGRITY

There are some possible approaches to assess the tube integrity and leakage limits: the so-called Deterministic Analysis, the Simplified Probabilistic Analysis and the Multi-Cycle Probabilistic Analysis. The first one is the simplest and fastest way to assess the tube integrity. The ECT as-found defect dimension is compared with a given limit (the same for all defects – usually 40% of the tube thickness). All uncertainties are taken into account in the limit. This approach can be a very conservative one.

The second one takes into account the data and all uncertainties as input to perform a Monte Carlo analysis to establish a limit (a single value or a curve) for each defect type. The Simplified Probabilistic Analysis should be done when a simple (and fast) analysis is required or when the number of defects does not allow its treatment by the multi-cycle procedure as it occurs with the axial defects in the tubesheet and those due to the AVB, for instance. In this analysis, the defect type size is estimated for the end of the next cycle (taking into account the defect dimensions as found in the inspection, its growth rate and all uncertainties) and this value is compared with the limit given as single value or as curves. It is usual to have two values or curves: the Structural Limit (SL) and the CM or OA curves. The SL is obtained using the nominal values of the parameters (material properties, defect size, etc.) according to [5]. The CM curve considers the as found defects to estimate if some of them challenged the integrity criteria while the OA curves considers, also, the defect growth rate. Both consider all uncertainties. The analysis main steps are: (1) identify the greatest defect type found in the inspection; (2) apply the uncertainties; (3) considering the defect growth and the period between inspections, estimate the defect type dimension at the end of the cycle. The NEI 97-06 performance criteria should be verified at the end of cycle.

The third approach, the Multi-Cycle Probabilistic Analysis, needs a great number of a given defect once it uses the statistical distributions associated with several parameters. For a given defect, the requirements of [1] are verified by analysis using the Monte Carlo method, usually with 10000 simulations per analysis, and the statistical distributions for the material properties, detected defect dimensions (length, depth, PDA, etc.), probability of detection - PoD (which depends on the technique used in the inspection) and defect type initiation and propagation rates. This is done to predict the defect type dimensions distribution at the end of the next operational cycle. This information is necessary to obtain the distribution (in terms of accumulated frequencies curve) of burst pressures and leakage (for those predicted thru-wall defects). The structural integrity and leakage requirements are assured when the obtained burst pressure is $>3\Delta P_{NOP}$ (or $1.4\Delta P_{SLB}$) and the leakage is below the specified limit in the accident condition.

To perform the analyses, the adopted program [3] uses the multi-cycle technique to obtain the distribution of a given defect type at the end of an operational period to evaluate the probability of burst and leakage. It uses the previous inspections results (crack initiation and growth rates, PoD, uncertainties, repair criteria, number of tubes with that defect) to predict the defect distribution at the end of the next operational cycle (i.e.: the distribution of that defect in the next inspection). The obtained distribution (number of tubes and the defect dimensions, etc.) is validated when its results for the current inspection compares with those measured.

The population of defects type at the beginning of the cycle (BoC) is a combination of those ones not detected in the inspection (associated with the technique PoD), those whose size do not allow them to be detected (which is different from the previous ones) and those that will start in the cycle. The population of defects at the end of cycle (EoC) is obtained combining the BoC population with the uncertainties in the measurements (length or depth for axial and PDA for the circumferential defects) and the predicted defect distribution at the end of the cycle. Using eq. (1) and (2) it is possible to calculate the burst pressure for each defect type predicted in the EoC with a given probability and confidence level – usually probability of 95% with 50% of confidence level, the so-called 95/50 limit. The accumulated probability of burst is given by the ratio of the number of times the predicted value is below $3\Delta P_{NOP}$ (or $1.4\Delta P_{SLB}$) and the number of Monte Carlo simulations. In the leaking analysis the program verifies if the defect will be a thru-wall one and, if so, estimates the leak rate through it using eq. (3.a) to (3.c). Again the Monte Carlo method is used to obtain a total leaking distribution for each SG and the 95/50 associated value.

6. INPUT DATA FOR THE INTEGRITY AND LEAKING ANALYSES

The shown multi-cycle analyses was performed for the OD circ TTS defect and it was conducted for a period of operation of 0.6 EFPY, between Angra 1 P15A and P16 outages. The material of the tubes is the alloy 600. The main data are summarized in table 3, where N is the number of tubes per SG, E is the Young's modulus, S_y, S_u, μ and σ are, respectively, the yielding stress, the ultimate stress, the mean and the standard deviation of the (S_y+S_u) values (all material values are taken at 650^{o}F). P_{int} and P_{ext} are, respectively, the internal and the external tube pressure. The differential pressure ΔP_{NOP} is 1330 psi, so $3.\Delta P_{NOP} \approx 4000$ psi. Q_{NOP} is the primary to secondary leaking limit Q_{NOP} (corresponds to 75 gpd), ΔP_{SLB} is the accident differential pressure and Q_{SLB} is the primary to secondary leaking limit under accident.

Table 3: Main data (*) for the integrity and leaking analyses.

external diameter, D_o	thickness t, in	N	E (10^6 psi)	$(S_y+S_u)_{max}$ (psi)	$(S_y+S_u)_{min}$ (psi)	μ_{Sy+Su} σ_{Sy+Su} (psi) (psi)	P_{int}/P_{ext} (psi)	Q_{NOP} (gpm)	Q_{SLB} (gpm)	ΔP_{SLB} (psi)
0.75 in	0,043	4674	28.45	160000	121400	146605 6226	2250/920	0.052	1.0	2560

(*) all literature & reference available in this area uses the English Unit System, so it is also used here.

For most of the cases the ETSS specifications [4] give the uncertainties associated with each inspection technique. Other sources for the uncertainties values are information on similar plants, industry data, etc. The values of the structural defect type parameter X (length L, depth D, PDA, etc.) measured in the inspection (by an ECT technique) correlates with the actual value Y by a linear regression, like $Y = a.X + b$, with the uncertainty given by the correlation standard deviation, s_Y. Besides the ECT, also the analyst uncertainty is taken into account as half of the ECT one. The total uncertainty value is taken as the square root of the sum of the squares.

The circumferential defects at the tubesheet (OD circ TTS) are in a quantity that allows the multi-cycle approach. Only the SG 1 will be analyzed once it has the greater number of defect as indicated in table 2. The specific input data needed for the multi-cycle analysis are:

. *Number of tubes at risk*. All 4674 tubes can be degraded by circumferential cracks in the tubesheet so that is the population at risk. The analysis includes the sleeved (repaired) tubes which, theoretically, have no risk to be damaged. One defect per tube is admitted.

. *Crack initiation*. Are determined using the three parameters of a Weibull distribution obtained from the last five outages. The values were obtained using a specific OPCON preprocessor after several simulations trying to adjust the predicted number of defects to the observed ones.

. *Operational history*. The length of each cycle was already presented in table 2. As mentioned, all OD circ TTS indications are repaired on detection. The uncertainties were obtained from [4] and the next operational cycle is about 0.6 EFPY.

. *Probability of Detection, PoD*. As there is no specific function for Angra 1 it was assumed a *PoD* typical for the plus-point probe valid for all inspections performed in Angra 1 amd represented by the log-logistic distribution in figure 1.

. *Crack Growth Rate*. According to EPRI [2], the maximum of this parameter is given by a log-normal distribution with a median and a 95% percentile, respectively, 7%/EFPY and 21%/EFPY, as depicted in figure 2. The PDA growth rate values for this defect (OD circ TTS), between the last two outages (0.57 EFPY), were calculated and these values were adjusted after some simulations to reproduce the measured results. Figure 2 compares the curve used in the analyses with the one proposed in [2].

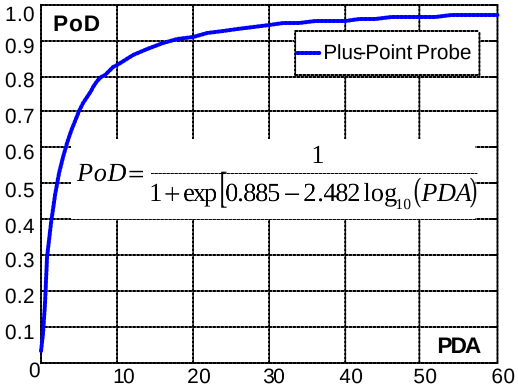

Figure 1: *POD* - OD circ TTS.

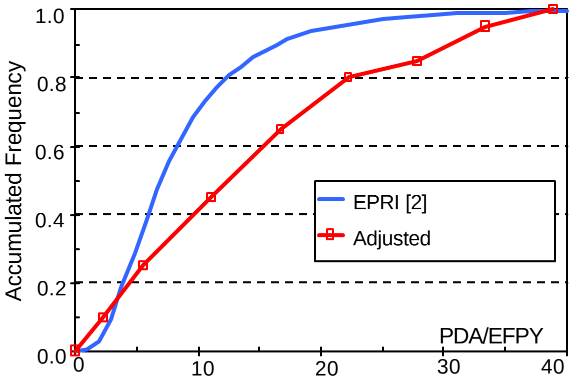

Figure 2: Crack growth rate distribution for OD Circ TTS defects.

7. RESULTS

Initially, in the multi-cycle analysis it is necessary to validate the predicted results, in terms of the defect type number and size, against those ones obtained in the previous outages to assure the structural integrity and leakage analyses with predicted data at the end of the next operational cycle are consistent and conservative. This validation is performed in two ways. The first one compares the OPCON predicted number of tubes/defects types with the detected ones found in the outages P12a to P15a. This is done in figure 3, for the SG 1, where one can see the predictions are near the observed values assuring good values to be used in the next outage, P16. The second way to validate the predictions is to compare the defects accumulated frequency with the one obtained in the most recent inspection/outage, P15a. Figure 4 shows this comparison in terms of PDA. One can notice the predicted values are very near the measured ones assuring the predictions (and of the analyses results) are consistent.

Once the predicted data are validated the quantity and size of the defect type predicted until the next outage (P16) are useful for the integrity and leakage analysis purpose. The final results of these analyses for the OD circ TTS defects are presented in table 4 as probability of burst in normal operation condition and leakage rate in accident condition, both calculated at 95% probability. Both values are far below the allowable ones.

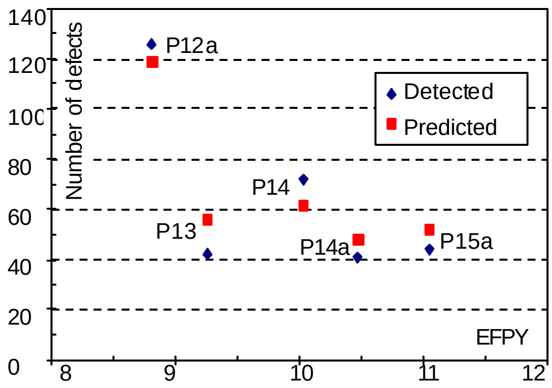

Figure 3. Number of detected X predicted defects - OD circ TTS.

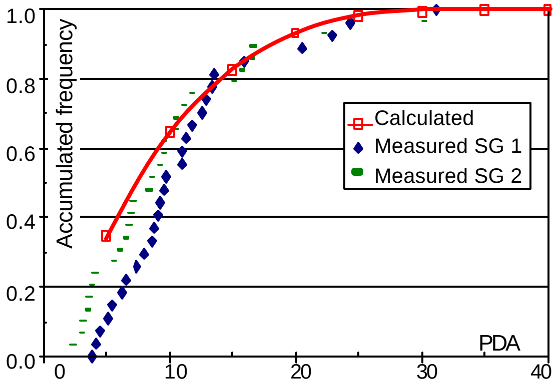

Figure 4. *PDA* predicted X measured in the P15a - OD circ TTS.

Table 4. Final results - SG 1 accumulated probabilities for Burst & Leakage (OD Circ TTS).

	ΔP_{SLB}	$3\Delta P_{NOP}$	GV1
Probability of burst, Pr	---	$<10^{-5}$	OD Circ TTS
Leakage (gpm@70°F)	$<10^{-5}$	---	

8. FINAL RAMARKS AND CONCLUSIONS

The tubes with other defects that are in a small quantity, like the OD Axial in the free span type of defect, as happens for many other defects, are repaired on detection. However, an evaluation should be performed assuming a non-detected defect was left in-service. There are two ways to define the dimension of this non-detected defect: 1st) from the *PoD* associated with the used technique (usually, in this tube region, the bobbin coil is used) and 2nd) based on the defects detected in the last inspections. Other defects as Pitting, axial inside at a support plate, axial inside or outside at the tubesheet should also be verified. For each defect type, the data should be adequately adapted for the adopted inspection technique (ETSS) and crack growth (always using the involved uncertainties).

This work presented, in a condensed form, how the defect assessment, in terms of structural integrity and tube leakage, can be done for the SG tube bundle of a NPP. A practical example was used in the text based on Angra 1 NPP data obtained in its last outage. The safety analyses scope performed for all defects found in the inspection is to show the NEI 97-06 [1] safety criteria are met for the next operational cycle which means: the tube burst probability (in normal operational condition) as well as the leakage probability (in accident condition) is below the allowable vales. Regardless their location, orientation and dimensions, all defects detected in the Angra 1 SGs tubing were found to met the regulatory safety limits (burst probability < 5% at $3\Delta P_{NOP}$ and probability of leakage < 5% at P_{SLB}).

The Angra 1 steam generators were replaced in the first semester of 2009. In the last five years before the SG replacement the presented assessment methodology was used for the Angra 1 SG tubing assessment. It showed it suitability with its adherence to the observed inspection results as well as the measured operational leaking rate, in its very last cycle, of about 5 gpd, which is far less the limit (75 gpd).

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