

STRUCTURAL INTEGRITY AND LEAKING ASSESSMENT OF ANGRA 1 STEAM GENERATOR TUBING USING STATISTICAL METHODS – PAST AND PRESENT

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Abstract. Typically, there are about 5000 tubes per steam generator and all tubes should be 100% inspected. In general, they are examined using an eddy current test (ECT), which results produce intrinsic errors in the characterization of the crack depth and length and there is, also, a probability of some of them not to be detected. The latter is related with the probability of detection (PoD) associated with the inspection technique. Some other sources of error used in the tube integrity assessment are the uncertainty in the experimental correlations between the defect size and the tube burst pressure, in the material properties and in the crack growth rate. With these in-service tube inspections the defects can be detected and measured allowing an analysis to demonstrate plant compliance with regulatory safety requirements. The tube structural integrity assessment establishes the allowable dimensions for each crack at the end of the next operational cycle. At that time a defect should have its burst accumulated probability of failure $Pr \leq 5\%$ to avoid tube failure with enough margins. The leakage assessment of the tube bundle establishes the maximum allowable leaking rate (always at the end of the next plant operational cycle) 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. This is done considering the defects growing during the next plant cycle when some of them can become thru-wall. This work describes some of the interventions made in the Angra 1 SGs along their life as well as some tube structural integrity and leaking assessment performed for the most common degradations, in its 2008 outage, using the “simplified” and the “multi-cycle” approaches along with a discussion of the obtained results using industry available correlations. In short, besides the amount of repaired tubes, greater than the usual in similar plants that have already replaced their SG, all analyses had shown the Angra 1 SG had been and it is still working, within the structural and leaking parameters of safety defined by the regulatory board.

1 INTRODUCTION

The tube bundle in the steam generators (SG) of a Nuclear Power Plant (NPP) represents more than 50% of the primary system pressure barrier. Due to the irradiation, indirect examination methods such as eddy current test (ECT) should be used which produce intrinsic errors in the defects dimensions. Each chosen inspection technique has a probability of some defects be not detected, the probability of detection (*PoD*). Some sources of error are the uncertainty in the experimental correlations used in the assessments, like those between the defect size and the tube burst pressure, in the material properties and in the defect growing rate until the next outage. With these in-service tube inspections the defects can be detected and measured allowing a safety analysis to demonstrate plant compliance with regulatory safety requirements (structural and leaking). When the SG has tubes degraded by stress corrosion, the way to assure this compliance, which means a safe and reliable plant operation, is to implement the recommendations from the *Nuclear Energy Institute* (NEI) 97-06, as presented in the report *Steam Generator Program Guidelines* [1] and the EPRI report *Steam Generator Integrity Assessment Guidelines* [2]. All degradations found in the tube inspection should be analyzed accordingly the nuclear regulatory board. The analyses that should be performed are: Condition Monitoring (CM) and the Operational Assessment (OA). The CM 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 (structural integrity) and the overall SG leakage during the cycle just ended. The 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. This work describes the basis the OA analysis through its application to the Angra 1 SG tube bundle for a period of 0.60 Effective Full Power Years (EFPY) showing that, besides the amount of repaired tubes, greater than the usual in similar plants that have already replaced their SG, the Angra 1 SG had been and it is still working, within the structural and leaking parameters of safety. Angra 1 is now (Jan-Apr/2009) replacing both SGs which performed successfully with a very low operational leakage. This shows the goodness of the adopted methodology of inspection and analysis.

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 Angra 1 NPP, for instance, the probability of burst should be less than 5% [2]. Probabilistic or deterministic models are allowed and all existing degradation types should be considered. When the data (the number of a given defect found in the inspection) is great 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 example, in the Angra 1 SGs last inspection, named P15a, the following defects were deterministically analyzed: ODSCC (Stress corrosion crack originated in the tube outside) in the tube free span, *Pitting*, axial PWSCC (Stress corrosion crack originated in the tube inside) in the tube support plates (ID Axial TSP), circumferential PWSCC in the tubesheet (ID circ TTS), axial PWSCC in the tubesheet, axial ODSCC in the tubesheet and the wearing in the anti-vibration bars (AVB).

Examples of defects probabilistically analyzed in the Angra 1 SGs 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 and circumferential ODSCC in the tube

support plates.

The analyses using the probabilistic approach 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 population. The program obtains the distribution of the defect 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 (rupture of the main steam line, SLB).

The main data to perform these analyses are, among other: the dimensions of the defects found during the ECT inspection in the tubes (length, depth, PDA - Percentage of Degraded Area, etc.), the defects growth rate (calculated using the results from two consecutive inspections or using industry data bases), the plant operational parameters (primary and secondary pressures and leakage limits) and the tubes geometric dimensions and material properties.

3 CRITERIA FOR THE INTEGRITY AND LEAKAGE ANALYSES

According to NEI 97-06 [1], three *performance criteria* should be verified:

- . *Structural Requirement* – 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 and secondary in normal operation condition and ΔP_{SLB} is the pressure difference in accident condition.
- . *Leakage Requirement in accident condition* – the primary-to-secondary leakage can not be greater than the value defined in the plant accident analysis which means 1.0 gpm – gallon per minute - per Steam Generator, in Angra 1 NPP.
- . *Leakage Requirement in normal condition* – the primary-to-secondary leakage can not be greater than the value defined in the plant operational procedure which is 75 gpd – gallon per day in Angra 1.

To assess these requirements it is necessary to perform a tube integrity analysis in normal and in accident conditions. The EPRI [2] considers both criteria fulfilled if the analyses show that each requirement is met with a probability of 0.95 with 50% of confidence. For the structural requirement the analysis should be performed on the most degraded tube. Typically, as it is in Angra 1, tubes with defect-like indication are repaired or plugged. The exceptions are those tubes with PWSCC axial defects in the tubesheet or within the 2" region bellow the tubesheet top surface (if their length is bellow 9mm or 0.35") and the tubes with AVB-type defect with a loss-of-thickness <40%. These tubes can remain in-service.

3.1 Angra 1 Historical of Repairs and ECT Results in the Last Outage

Table 1 presents the defects prioritization adopted in the Angra 1 last outage (i.e.: which degradation should be considered in the tube with more than one indication) as well as the number of tubes repaired per SG and per degradation type. Table 2 shows the history of repairs per outage for some of the analyzed defects in the operational assessment.

3.2 Basic Equations

The burst pressure and the leaking rate of a tube with a given defect can be obtained from the literature [3, 7]. From (3), eq. (1) gives the burst pressure P for a tube with a partial thru-wall axial crack-like defect in its freespan. 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 is the tube thickness, R_i and R_o are the internal and the external tube radii, respectively, PDA is the Percentage of Degrade Area (the ratio between the defect area

and the area of the tube section), S_y and S_u are, respectively, the tube material yield and ultimate stress, at the operation temperature (650 °F), L and d_{ef} are the defect length and the defect effective (or average or structural) depth.

	Origin	Type	Position	SG 1	SG 2
1	OD	Axial	Free span	1	0
2	ID	Axial	Free span	0	0
3	ID/OD	Axial	U bend	0	0
4	OD	AVB	U bend	0	0
5	OD	Circ.	TSP	61	79
6	ID	Circ.	TSP	0	0
7	OD	Axial	TSP	15	15
8	---	SVI/MVI	TSP	57	63
9	---	Pit	TSP	1	0
10	ID	Axial	TSP	2	3
11	OD	Circ.	TTS	45	42
12	ID	Circ.	TTS	10	0
13	OD	Axial	01H	64	15
14	ID	Axial	TTS	1	0
15	OD	Axial	TTS	3	2

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

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
SG 2	38	60	65	134	30	49	25	41	TTS
SG 1	37	65	167	160	43	94	23	64	OD
SG 2	7	22	24	51	17	15	10	15	Axial 01H
SG 1	4	5	12	5	3	15	23	61	OD circ
SG 2	8	6	11	2	2	14	15	79	TSP

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

$$P = \frac{0.58(S_y + S_u)t}{R_i} \cdot \left(1 - \frac{\left(\frac{Ld_{ef}}{t}\right)}{L + 2t}\right) \quad (\text{axial}) \quad (1)$$

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

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

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

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} is the leaking at the environment temperature, Q_{NOP} and Q_{SLB} are the leaking at the normal operation temperature and at accident conditions, respectively. 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, in² and psi. As the area A depends on the defect orientation, the leakages values are different for axial and for circumferential defects. The coefficients C_1, C_2, \dots, C_n are available in [5].

To eliminate the temperature dependence from these expressions the leakage is given in gpm at 70°F. 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 70°F.

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

$$Q_{NOP} = AP \left(1 - C_4 e^{(C_5 A^{C_6})} \right) [C_7 - C_8 e^{(-C_9 (A/L)^{C_{10}})}] \quad (3.b)$$

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

3.3 Multi-Cycle Probabilistic Analysis

For a given defect, the requirements of [1] are verified 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 (of a given defect, which depends on the technique used in the inspection) and defect initiation and propagation rates. This is done to predict the defect 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 at the end of a given 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.

As an example, for the axial defect in the 01H TSP and for circumferential ones in the tubesheet, the criterion is repair on detection. The population of defects at the beginning of the cycle (BoC) is a combination of those ones not detected in the inspection (associated with the ECT technique PoD), those whose size do not allow them to be detected by the technique (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 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.

3.4 Simplified Probabilistic (or Deterministic) Analysis

The Simplified Probabilistic Analysis, sometimes called Deterministic 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.

In this analysis, the defect 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 the uncertainties. The analysis main steps are: (1) identify the greatest defect (L_{ECT} , D_{ECT}) found in the inspection; (2) apply the uncertainties (L_{ERR} , D_{ERR}); (3) considering the defect growth (cg) and the period between inspection (t_o), estimate the defect dimension at the end of the cycle (L_{EOC} , D_{EOC}) using eq. (4.a) and (4.b) – L , D are the defect length and maximum depth respectively. Usually, when it is necessary to use the defect effective depth (d_{ef}) the relation $D/d_{ef} = 1.2$ applies [6]. For Angra 1 specific case the relation is $D/d_{ef} \approx 1.3$.

The NEI 97-06 [1] performance criteria should be verified at the end of cycle. They are also presented in the eq. (4).

$$L_{EOC} = L_{ECT} + L_{ERR} + cg \times t_o < SL \text{ or } CM/OA \text{ curves} \quad (a) \quad (4)$$

$$D_{EOC} = D_{ECT} + D_{ERR} + cg \times t_o < SL \text{ or } CM/OA \text{ curves} \quad (b)$$

4 INPUT DATA FOR THE INTEGRITY AND LEAKING ANALYSES

The input generic data are presented firstly, followed by the specific data needed for the multi-cycle analyses of the OD circ TTS and OD axial 01H defects. The input data for the deterministic analyses are presented in section 5. All analyses were conducted for a period of operation of 0.6 EFPY, between P15A and P16.

4.1 Generic Input data

In these data are included the tube geometry and material as well as the operational conditions (in normal and in accident conditions) and the uncertainties associated with the inspection technique.

The tubes in the Angra 1 SGs have an external diameter $D_o = 0.75$ in and a thickness $t = 0.043$ in. The number of tubes per SG is $N = 4674$. The tube material is the alloy Inconel 600 with Young's modulus $E = 28.45 \cdot 10^6$ psi, $(S_y + S_u)_{max} = 160000$ psi, $(S_y + S_u)_{min} = 121400$ psi, $\mu_{S_y + S_u} = 146605$ psi e $\sigma_{S_y + S_u} = 6226$ psi). μ and σ are, respectively, the mean and the standard deviation of the $(S_y + S_u)$ values taken at 650 °F.

The normal conditions are: internal tube pressure $P_i = 2250$ psi, external pressure $P_e = 920$ psi, differential pressure $\Delta P_{NOP} = 1330$ psi, so $3 \cdot \Delta P_{NOP} \approx 4000$ psi. Primary to secondary leaking limit $Q_{NOP} = 0.052$ gpm (75 gpd). The accident conditions are: differential pressure $\Delta P_{SLB} = 2560$ psi, primary to secondary leaking limit $Q_{SLB} = 1.0$ gpm).

For most of the cases the EPRI specifications [4] give the uncertainties associated with

each inspection technique. Other sources for the uncertainties values are information on similar plants, industry data (obtained via EPRI), etc. The values of the structural defect 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, σ_Y .

Some of the inspection techniques (ETSS) and their uncertainties used in the Angra 1 last outage are presented in table 3 along with their limits. 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 Pitting is included as an example but it is not a challenge for the structural criteria but should be considered for leaking.

Defect type and Location	ETSS (probe type)	ECT parameters	R^2 ⁽¹⁾	Limit ⁽²⁾
OD Axial 01H	21411.1 (+Point)	$L=0.64L_{ECT} + 0.11$; $\sigma_L= 0.177\text{in}$ $D=1.116D_{ECT} - 2.27$; $\sigma_D= 9.1\%$	0.73 0.84	Fig.9 Fig.10
OD Circ TTS	21410.1 (+Point)	$PDA=0.84PDA_{ECT} + 19.3$; $\sigma_D= 12.06\%$	0.68	CA < 180° or: PDA<50%
Pitting	96005.2 (Circular)	$D=0.27 D_{ECT} + 28.42$; $\sigma_D= 13.36\%$	0.41	

⁽¹⁾ ETSS correlation coefficient.

⁽²⁾ The structural limit for thru-wall defects is $L_{STR} = 11 \text{ mm}$ (0.43 in) [8].

Table 3: Some Inspection techniques and their uncertainties used in Angra 1 last outage.

4.2 Input Data for Circumferential Defects - OD circ TTS

These defects 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.

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. Table 5 shows the three parameters Weibull distribution obtained from the last five outages which gives a better picture of the reality once all inspection improvements are considered (the use of the *plus-point* probe is one of them). The values were obtained using a specific pre-processor [3] 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 presented in table 3 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 and valid for all inspections performed in Angra 1 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].

4.3 Input Data for Axial Defects - OD axial 01H

As in the previous case, only SG 1 will be analyzed once it has the greater number of this

type of defect as shown in table 4.

Number of tubes at risk. The tube population at risk is all 4674 tubes due to the same arguments used in the previous case.

Crack initiation. Table 5 shows the three parameters Weibull distribution obtained from the last 5 outages.

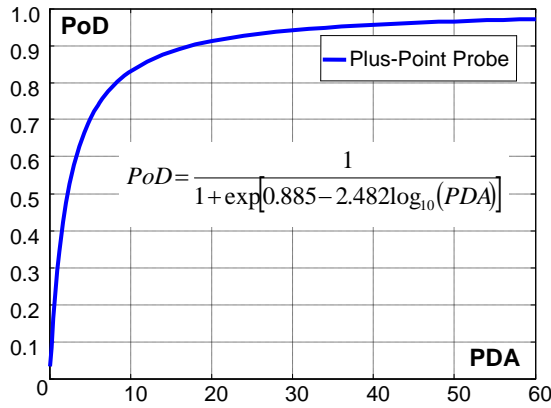


Figure 1: *PoD* - circumferential defects - OD circ TTS.

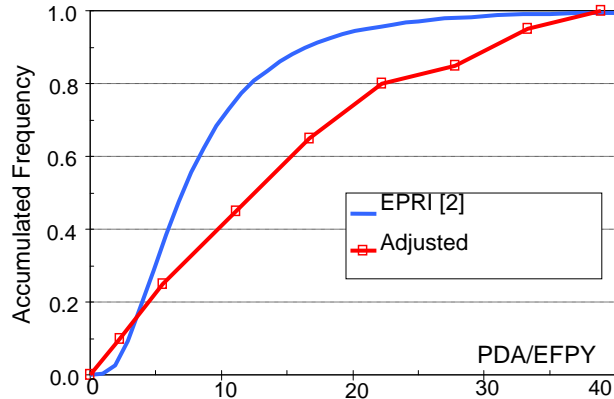


Figure 2: Crack growth rate distribution for OD Circ TTS defects.

		P7	P8	P9	P10	P11	P12	P12a	P13	P14	P14a	P15a
EPFY		4.28	4.89	5.97	6.50	7.50	8.26	8.81	9.26	10.04	10.48	11.05
OD Circ TTS	SG 1	12	14	85	24	105	87	126	42	72	41	45
	SG 2	3	3	56	38	60	65	134	30	49	25	42
OD Axial 01H	SG 1	---	---	---	37	65	167	160	43	94	23	64
	SG 2	---	---	---	7	22	24	51	17	15	10	15

Table 4: Number of repaired tubes per outage.

Slope, α	Scale, β	Setback, t_o	
1.9	25	-4.2	OD circ TTS
1	36	0	OD axial 01H

Table 5: Weibull three-parameter distribution (SG 1).

Operational history. The length of each cycle was already presented in table 2. As mentioned, all OD axial 01H indications are repaired at detection. The uncertainties related with the used technique were presented in table 3. (The operational cycle is about 0.6 EPFY.)

Probability of detection, PoD . As mentioned in the previous case, for the circumferential cracks, there is no specific function for OD axial 01H in Angra 1. So, using the program [3] in an iterative process, it was assumed a PoD log-logistic distribution for each outage from the P9. The process ended when the predicted values compared with the measured ones. The obtained parameters A and B (*plus-point* probes) for the distributions are presented in table 6 while the $PoDs$ can be seen graphically in figure 3.

Crack length distribution. The accumulated frequency of the measured defect lengths in the P15a outage is represented by a log-normal function with an average (\ln) and a standard deviation (σ_{\ln}), respectively: -1.029 and 0.36. These values were already adjusted to reproduce the measured values in the P10 to P15a outages.

Crack growth rate. The growth rate between the last two outages was adjusted, as for the PoD, using the OPCON program in an iterative process. The results are shown in figure 4. As in the previous case (OD circ TTS) the adopted crack growth rate is bigger than the EPRI [2] values shown also in figure 4.

	P9-P10-P11	P12	P12a-P13-P14	P14a	P15a
A	28.5	16.4	53.51	53.51	53.51
B	-15.5	-9.3	-32.37	-31.5	-31.5

Table 6: Parameters for the log-logistic distributions - OD axial 01H.

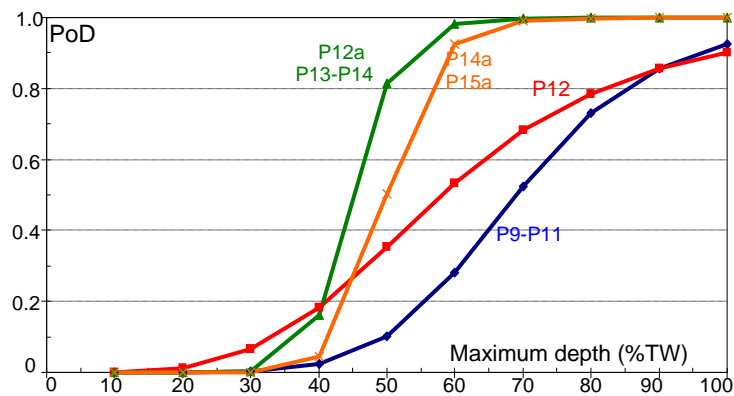


Figure 3. *PoD* – Axial defects at 01H plate - OD axial 01H.

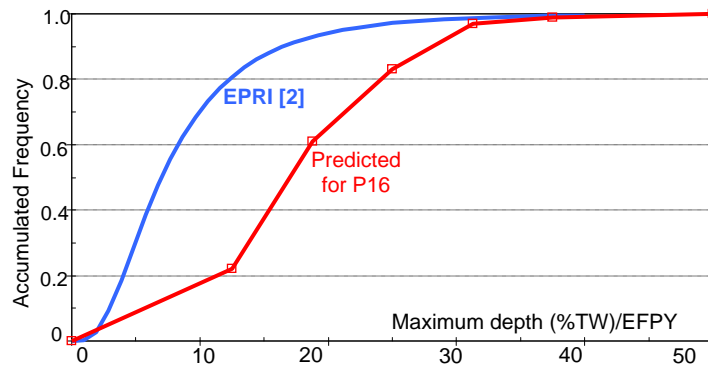


Figure 4. Crack growth rate distribution for OD axial 01H defects.

5 RESULTS

5.1 Outside Circumferential Defects at the Tubesheet - OD circ TTS

In the *multi-cycle* analysis it is necessary to validate the predicted results, in terms of the defect 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 with the detected ones found in the outages P12a to P15a. This is done in figure 5, 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 6 shows this comparison in terms of PDA. One can notice the predicted values are very near the measured ones assuring the goodness of the predictions (and of the analyses results).

Once the predicted data are validated the quantity and size of the defect predicted until the next outage (P16) are consistent and useful for the integrity and leakage analysis purpose. The final results of these analyses for the OD circ TTS defects are presented in table 6 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.

5.2 Outside Axial Defects in 01H Plate - OD axial 01H

As per circumferential defects, it is necessary to validate the predictions to assure their conservativeness. Figure 7 compares the number of detected defects with the predicted ones, for each outage from P10 to P15a. Again, the predictions are near the observed values and show a conservative bias assuring good values to perform the analyses for the P16.

The other comparison is between the defects accumulated frequency with the one obtained in the most recent inspection/outage. Figure 8 shows this comparison in terms of the maximum depth. Again, the predicted values are very near the measured ones. So, it is assured the goodness and conservativeness of the predictions and analyses results for the next outage.

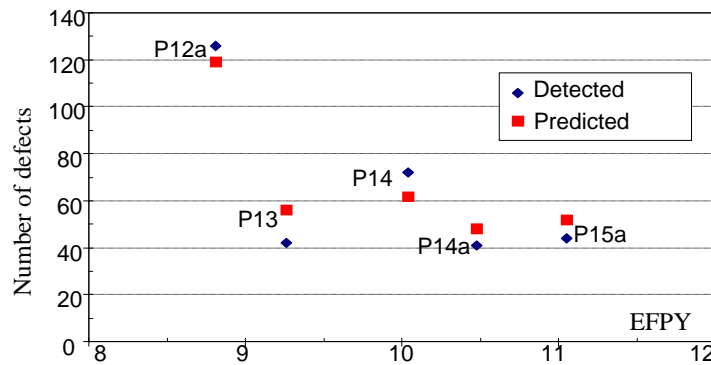


Figure 5. Number of detected X predicted defects - OD circ TTS.

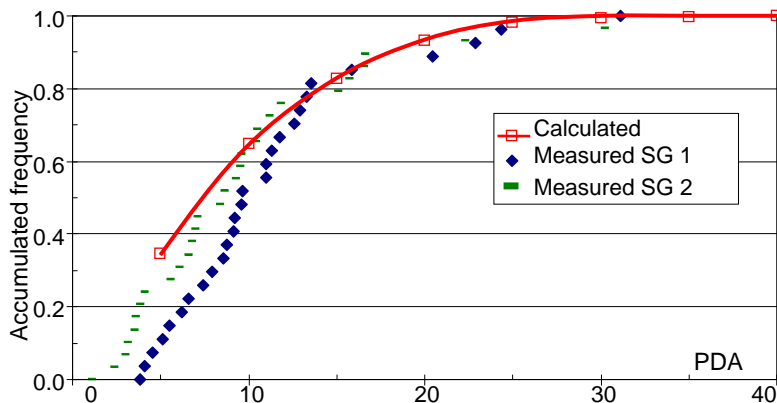


Figure 6. PDA predicted X measured in the P15a - OD circ TTS.

Figure 9 shows the maximum depth accumulated distribution of defects predicted for the current outage (P15a), after 11.05 EPFY, compared with the predictions for the next outage

(P16), when the plant will have 11.65 EFPY. Due to the short period between these outages the curves show little difference. The figure shows, also, an exercise done supposing the next outage with 12.05 EFPY which means the plant running at full power for a year. In this case we can notice a difference in the curves.

As the predicted data are validated for the previous outages are validated the predictions for the next outage (P16) are consistent and the integrity and leakage analysis results are reliable. These results for the OD axial 01H defects are presented in table 6 as probability of burst in normal operation condition and leakage rate in accident condition, both calculated at 95% probability. As in the previous case, both values are far below the allowable ones.

5.3 Results for OD Axial in the Freespan

The tubes with this type of defect 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: (1) from the *PoD* associated with the used technique (usually, in this tube region, the bobbin coil is used) and (2) based on the defects detected in the last inspections. For this case the limits are met if the point defined by the defect dimensions, length and effective depth, (L, d_{ef}), is below the curves like those shown in figure 10 (burst) or figure 11 (leakage), obtained with the technique uncertainties. All defects of this type were found to meet the limits (burst probability < 5% at $3\Delta P_{NOP}$ and probability of leakage < 5% at P_{SLB}).

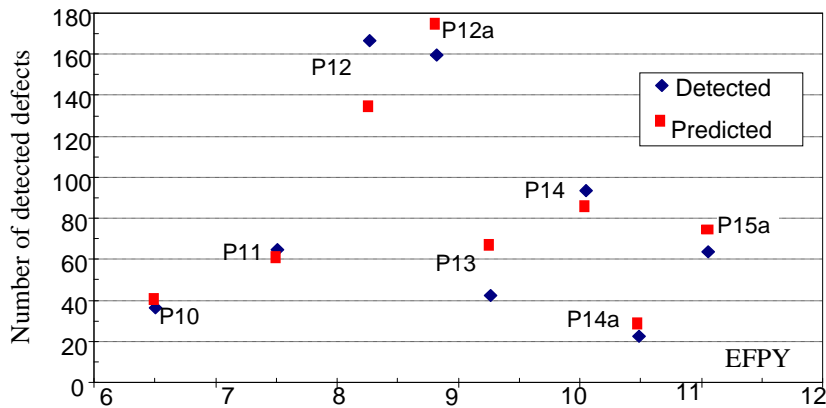


Figure 7. Number of detected X predicted OD Axial 01H defects.

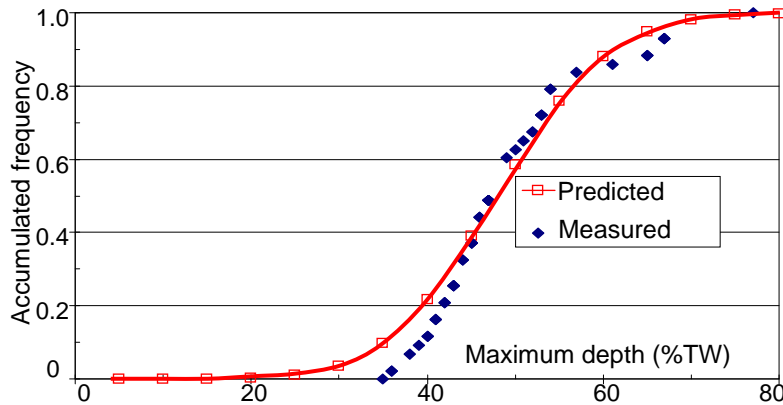


Figure 8. OD Axial 01H Results (maximum depth, measured X predicted).

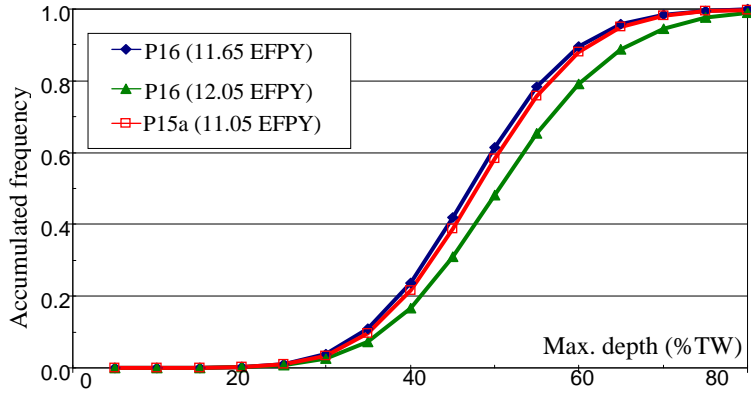


Figure 9 – OD Axial 01H Maximum depth predicted for P16.

	ΔP_{SLB}	$3\Delta P_{NOP}$	GV1
Probability of burst, Pr	---	$<10^{-5}$	OD Circ
Leakage (gpm@70°F)	$<10^{-5}$	---	TTS
Probability of burst, Pr	---	0.12%	OD Axial
Leakage (gpm@70oF)	$<10^{-5}$	---	01H

Table 6. Final results - SG 1 Accumulated Probabilities for Burst & Leakage (OD Circ TTS & OD Axial 01H).

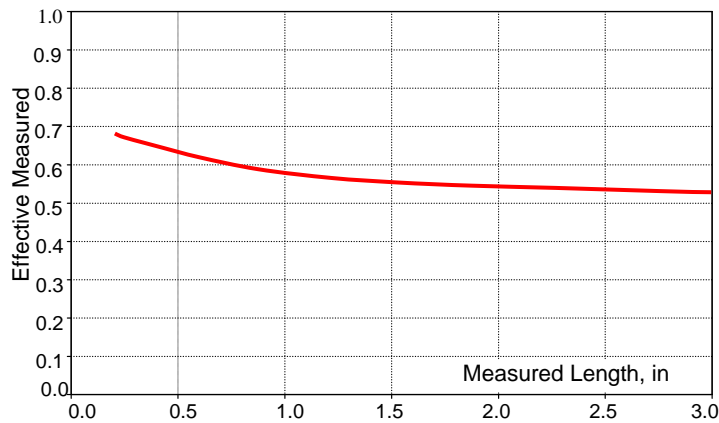


Figure 10. CM Limit for Burst at $3\Delta P_{NOP}$ (5% Burst Probability) –OD Axial in the Freespan.

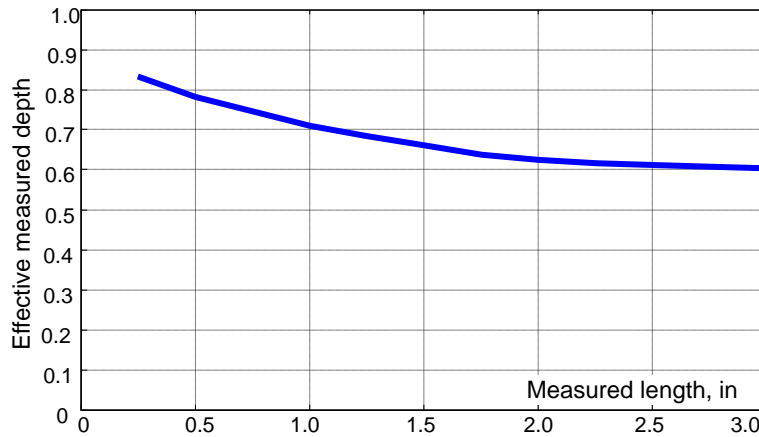


Figure 11. CM Limit for Leakage at P_{SLB} (5% leak probability) – OD Axial in the Freespan.

5.4 Other Types of degradation

Other defects as Pitting, axial inside at a support plate, axial inside or outside at the tubesheet or the circumferential outside at the tubesheet can be verified like the previous OD axial in the freespan. For each defect, the data should be adequately adapted for the adopted inspection technique (ETSS) and crack growth.

6 CONCLUSIONS

This work presented, in a very 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. Practical examples were used in the analysis based on Angra 1 NPP data obtained in its last outage. The analyses scope was 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. This was demonstrated for all defects found in the outage, in special, for those presented in this work.

In the last five years the presented assessment methodology was used for the Angra 1 SGs tubing assessment. The SGs are now being replaced for a new ones. It showed it goodness with its adherence to the observed results as well as the observed leaking rate, in its very last cycle, of about 5 gpd which is far less the limit (75 gpd).

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