Proceedings of COBEM 2009
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20th International Congress of Mechanical Engineering
November 15-20, 2009, Gramado, RS, Brazil

STATISTICAL METHODS TO ASSESS THE STRUCTURAL INTEGRITY OF STEAM GENERATOR TUBING - ANGRA 1 PRACTICAL EXAMPLE

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Abstract. Typically, in a Nuclear Power Plant there are about 5000 tubes per steam generator (SG) and all tubes should be 100% inspected. In general, they are examined using an eddy current test 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 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 when a defect should have its burst accumulated probability of failure Pr $\leq$ 5% to avoid 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 an example of a tube structural integrity and leaking assessment performed for the most common degradation, in its 2008 outage, using the multi-cycle approach along with a discussion of the obtained results using industry available correlations. 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. 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.

Keywords *Structural Integrity, Steam Generator, Nuclear Power Plant, Statistical Approach*

1. INTRODUCTION

The steam generators (SG) tube bundle 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* 97-06, as presented in the report *Steam Generator Program Guidelines* [NEI 2001] and the EPRI report *Steam Generator Integrity Assessment Guidelines* [EPRI 2006]. All tube degradations found in the tube 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 (structural integrity) 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 described through its application to the Angra 1 SG tube bundle for a period of 0.60 Effective Full Power Years (EFPY). The amount of repaired tubes in Angra 1 is greater than the usual in similar plants that have already replaced their SG however they are still working, within the structural and leaking parameters of safety.

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% [EPRI 2006]. Probabilistic or deterministic models are allowed and all existing degradation types should be considered. When 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. 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 (ID axial TTS), axial ODSCC in the tubesheet(OD axial TTS) and the wearing in the anti-vibration bars (AVB). (Usually, the primary water flows inside the tubes and the secondary water flows outside.)

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 (OD axial TSP) and circumferential ODSCC in the tube support plates (OD circ TSP).

The analyses using the probabilistic approach were performed using the OPCON program [Aptech 2002] 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.

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), the tubes geometric dimensions and material properties.

3. INTEGRITY AND LEAKAGE ANALYSES

3.1. Performance Criteria and Historical Data

Three *performance criteria* should be verified [NEI 2001]:

. *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 then the value defined in the plant accident analysis which means 1.0 gpm – gallon per minute - per Steam Generator, in Angra 1.

. *Leakage Requirement in normal condition* – the primary-to-secondary leakage can not be greater then the value defined in the plant operational procedure which is 75 gpd – gallon per day (~284 lpd – litre per day) in Angra 1.

So, to assess these requirements it is necessary to perform a tube integrity analysis in normal and in accident conditions. Both criteria are fulfilled if the analyses show that each requirement is met with a probability of 0.95 with 50% of confidence [EPRI 2006]. 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 on detection. The exceptions are those tubes with PWSCC axial defects in the tubesheet (ID axial TTS) or within the 2" (~5mm) 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.

Previously to the analyses, a defect prioritization should be adopted (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 should be recorded. Table 1 shows the history of repairs for the last outages for some of the analyzed defects in the Angra 1 NPP Steam Generator tubing operational assessment.

Table 1: Historical of repairs per outage (P*xx*) and type of degradation/defect.

Outage	P10	P11	P12	P12A	P13	P14	P14a	P15a	Defect
EFPY	6.50	7.50	8.26	8.81	9.26	10.04	10.48	11.05	
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	
SG 1	4	5	12	5	3	15	23	61	OD circ TSP
SG 2	8	6	11	2	2	14	15	79	

3.2. Basic Equations – Burst and Leaking

The burst pressure and the leaking rate of a tube with a given defect can be obtained from the literature [Aptech 2002, Aptech 2000, EPRI, 2001]. 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), and P_O, eq. (3), if the defect is outside (OD) and it is the minimum value between P, and P_i, eq. (4) 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 Degraded 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 ^{o}F, ~343 ºC), L and d_{ef} are the defect length and the defect effective (or average or structural) depth.

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

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

$$P_o = \left(\frac{R_o^2 - R_i^2}{R_i^2}\right)\left(1 - \frac{PDA}{100}\right)\left(\frac{S_y + S_u}{2}\right) \qquad \text{(circ. external)} \qquad (3)$$

$$P_i = \frac{P_o R_i^2}{R_i^2 + (R_o^2 - R_i^2)\frac{PDA}{100}} \qquad \text{(circ. internal)} \qquad (4)$$

The leaking for the axial and the circumferential defects is given by eq. (5), (6) and (7) [EPRI, 2001]. 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, in^2 and psi (in the English unit system) or m, m^2 and Pa (in the SI system). 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, …, Cn are available in [EPRI 2001] only for the English system of units.

To eliminate the temperature dependence from theses expressions the leakage is given in gpm at 70ºF (~20 ºC). 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 (~20 ºC).

$$Q_{RT} = C_1 AP^{0.5}\left[1 - e^{f_1(A/L)}\right], \quad f_1(a/L) = C_2\left(A/L\right)^{0.5} - C_3\left(A/L\right) \qquad (5)$$

$$Q_{NOP} = AP^{\left(1 - C_4 e^{\left(C_5 A^{C_6}\right)}\right)}\left[C_7 - C_8 e^{\left(-C_9 (A/L)^{C_{10}}\right)}\right] \qquad (6)$$

$$Q_{SLB} = AP^{C_{11}}\left[C_{12} - C_{13} 6e^{f_2(A/L)}\right], \quad f_2(A/L) = C_{14}\left(A/L\right)^{C_{15}} - C_{16}\left(A/L\right) \qquad (7)$$

3.3. 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 Condition Monitoring

(CM) or Operational Assessment (OA) curves [EPRI 2001]. The SL is obtained using the nominal values of the parameters (material properties, defect size, etc.). 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 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. (8.a) and (8.b) where L and 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. For Angra 1 specific case the relation is $D/d_{ef} \approx 1.3$ [Angra 2007].

The performance criteria presented in the eq. (8.a) and (8.b) should be verified at the end of cycle [NEI 2001].

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

$$D_{EOC} = D_{ECT} + D_{ERR} + cg \times t_o < SL \text{ or } CM/OA \text{ curves} \qquad \text{(b)} \qquad (8)$$

3.4. Multi-Cycle Probabilistic Analysis

For a given defect, the NEI requirements [NEI 2001] 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* (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). Details of the Monte Carlo method application, as well typical tube defects and relative burst equations, can be seen in Miranda et alli [2007]. 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 bellow the specified limit in the accident condition.

To perform the analyses, the adopted program, OPCON [Aptech 2002], 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 ones.

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 bellow $3\Delta P_{NOP}$ (or $1.4\Delta P_{SLB}$) and the total 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. (5) to (7). Again the Monte Carlo method is used to obtain a total leaking distribution for each SG and the 95/50 associated value.

4. INPUT DATA FOR THE INTEGRITY AND LEAKING ANALYSES

To exemplify a typical multi-cycle analyses the OD axial 01H defect will be assessed for a period of operation of 0.6 EFPY, between P15A and P16. The input generic data are presented firstly, followed by the specific data needed for the analysis.

4.1. Generic Input data

These data include 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 used in the ECT to detect the defect. All data as well as all literature about these analyses are in the English units and, so, these units are used all around this work with the SI units given only as reference.

The tubes in the Angra 1 SGs have an external diameter $D_o = 0.75$ in (~19 mm) and a thickness t = 0,043 in (~1.1 mm). The number of tubes per SG is N = 4674. The tube material is the alloy Inconel 600 with Young's modulus E = $28.45\ 10^6$ psi (~196 GPa), $(S_y+S_u)_{max} = 160000$ psi (~1420 MPa), $(S_y+S_u)_{min} = 121400$ psi (~837 MPa), $\mu_{Sy+Su} = 146605$

psi (~1010 MPa) and σ_{Sy+Su} = 6226 psi (~43 MPa). μ and σ are, respectively, the mean and the standard deviation of the (S_y+S_u) values taken at 650 °F (~343 ºC).

The SG normal conditions are: internal tube pressure Pi = 2250 psi (~15.5 MPa), external pressure P_e = 920 psi (~6.3 MPa), differential pressure ΔP_{NOP} = 1330 psi (~9.2 MPa), so $3.\Delta P_{NOP} \approx 4000$ psi (~27.6 MPa). The primary to secondary leaking limit is Q_{NOP} = 0.052 gpm (75 gpd or ~284 lpd). The accident conditions are: differential pressure ΔP_{SLB} = 2560 psi (~17.6 MPa), primary to secondary leaking limit Q_{SLB} = 1.0 gpm or ~3.8 lpm).

For most of the cases the EPRI specifications [EPRI/ETSS] 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 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. Table 2 presents the values for the chosen inspection techniques (ETSS) and the associated uncertainties used in the Angra 1 last outage to detect the OD Axial 01H defect. 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.

Table 2: Inspection techniques and the associated correlation used to detect OD Axial 01H.

ETSS (*probe type*)	ECT correlation parameters	$R^{2\,(1)}$
21411.1 (+*Point*)	$L=0.64L_{ECT}+0.11$; $\sigma_L = 0.177$in $D=1.116D_{ECT}-2.27$; $\sigma_D = 9.1\%$	0.73 0.84

(1) ETSS correlation coefficient. (2) The structural limit for thru-wall defects is L_{STR} = 0.43 in (11 mm) [Angra, 2007].

4.2. Specific Input data - Axial Defects - OD axial 01H

Only SG 1 will be analyzed once it has the greater number of this type of defect as shown in table 3.

Number of tubes at risk. The tube population at risk is all 4674 tubes once all tubes can be degraded by this defect.

Crack initiation. The parameters of the adopted Weibull distribution obtained after some simulations using the data from the last 5 outages are: Slope, $\alpha = 1$, Scale factor, $\beta = 36$ and *Setback* parameter, $t_o = 0$.

Operational history. The length of each cycle can be deduced from the EFPY line presented in table 1. The uncertainties related with the used technique were presented in table 2.

Probability of detection, *PoD*. There is no specific function for OD axial 01H in Angra 1. So, using the OPCON program 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 for the distributions are presented in table 4 while the *PoDs* can be seen graphically in figure 1.

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. As usual in this kind of analysis, and to be conservative, the resulting/adopted crack growth rate is bigger than the EPRI [2006] values.

5. RESULTS

The results for the *multi-cycle* probabilistic analysis performed for the OD axial 01H, the outside axial crack at the tube support plate 01H are presented.

Table 3: Number of repaired tubes per outage - OD Axial 01H.

	P7	P8	P9	P10	P11	P12	P12a	P13	P14	P14a	P15a
EFPY	4.28	4.89	5.97	6.50	7.50	8.26	8.81	9.26	10.04	10.48	11.05
SG 1	---	---	---	37	65	167	160	43	94	23	64
SG 2	---	---	---	7	22	24	51	17	15	10	15

Table 4: Parameters for the log-logistic distributions.

	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

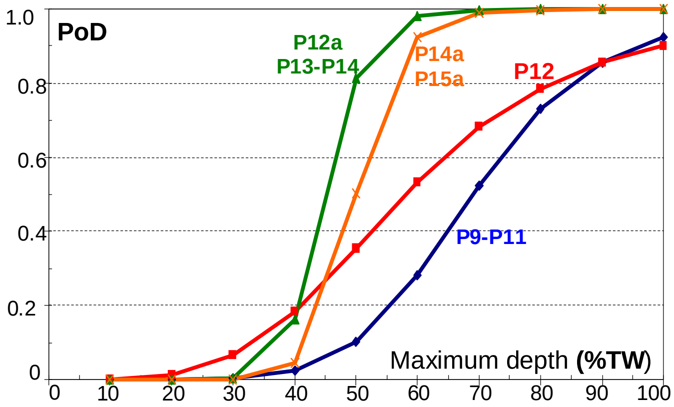

Figure 1. *PoD* – Axial defects at 01H plate - OD axial 01H.

Initially, it is necessary to validate the predictions to assure their conservativeness. Figure 2 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 defect accumulated frequencies with the one obtained in the most recent inspection/outage. Figure 3 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.

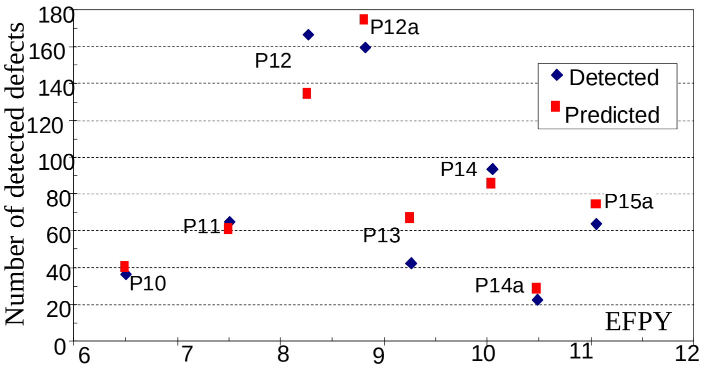

Figure 2. Number of detected X predicted OD Axial 01H defects.

Figure 4 shows the maximum depth accumulated distribution of defects predicted for the current outage (P15a), after 11.05 EFPY, 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, 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.

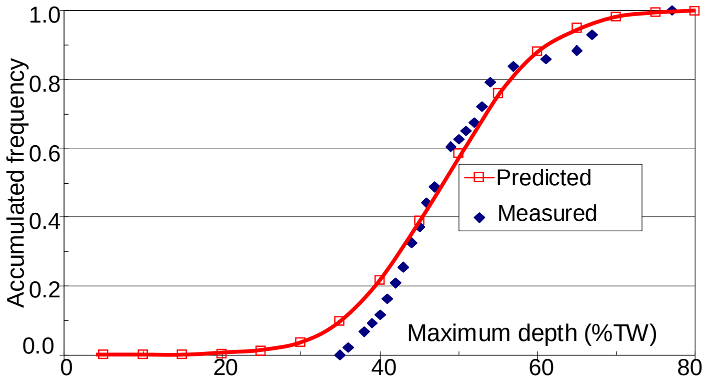

Figure 3. OD Axial 01H Results - maximum depth, measured X predicted (TW – wall thickness).

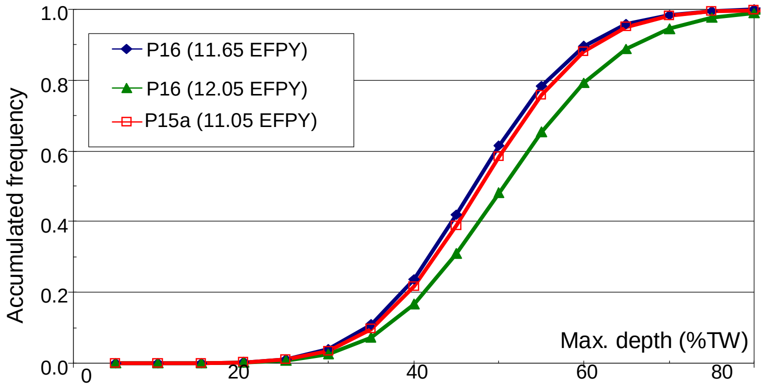

Figure 4. OD Axial 01H Maximum depth predicted for P16 (TW – wall thickness).

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

	ΔP_{SLB}	$3\Delta P_{NOP}$
Probability of burst, Pr	---	0.12%
Leakage (gpm@70oF)	<10-5	---

6. OTHER TYPES OF DEGRADATION

The tubes with OD Axial in the Freespan 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. Both analyses use the uncertainties associated with the adopted inspection technique. Usually, the limits are met if the point defined by the defect dimensions, length and effective depth, (L, d_{ef}), is below the limit curve L x d associated with 5% probability of burst at $3\Delta P_{NOP}$ or leakage at P_{SLB}. Adapting adequately the data for the adopted inspection technique and the specific crack growth rate, the same procedure can be adopted for other defects as Pitting, axial inside at a support plate (ID Axial TSP), axial inside or outside at the tubesheet (ID Axial TTS or OD Axial TTS) or the circumferential outside at the tubesheet (ID Circ TTS).

7. 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. A practical example analysis was used based on Angra 1 NPP data obtained in its last outage before the one for the SG replacement. The analysis scope was to show the NEI 97-06 [2001] safety criteria are met for the plant next operational cycle which means: the tube burst probability (in normal operational condition) as well as the leakage probability (in accident condition) are below the allowable values. This was demonstrated for all defects found in the outage, in special, for the one presented in this work.

The Angra 1 SGs are now (Jan-April 2009) being replaced for new ones. In the last five years the presented assessment methodology was use for the Angra 1 SGs tube bundle assessment. 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 (~18.9 lpd) which is far less the plant limit, 75 gpd (~284 lpd).

8. ACKNOWLEDGEMENTS

The authors would like to thanks ELETRONUCLEAR for the given support to prepare this paper.

9. REFERENCES

ANGRA, 2007. *Angra Unit 1 Steam Generator Degradation Assessment P14-A Pre-Outage Planning Report*, Westinghouse report SG-CDME-07-01 Revision 0, January 2007.
APTECH, 2000. *An Operational Assessment of Calvert Cliffs, Unit 1 Steam Generator for Cycle 15*, Aptech Engineering Service, AES 00013888-1Q-1, June 2000.
APTECH, 2002. *OPCON 3.1 Operational Assessment and Condition Monitoring of Steam Generator Tubes*, Aptech Engineering Service, 2002.
EPRI/ETSS. ECT *Examination Technique Specification Sheet*, Steam Generator Management Project, www.epriq.com.
EPRI, 2001. *Steam Generator Degradation Specific Management Flaw Handbook*, EPRI report 1001191, January 2001, Electric Power Research Institute.
EPRI, 2006. *Steam Generator Integrity Assessment Guidelines, Revision 2*, EPRI 1012987, 2006, Electric Power Research Institute.
NEI, 2001. *Steam Generator Program Guidelines, Revision1*, NEI 97-06, Nuclear Energy Institute, January 2001.
Miranda, C. A. J., Maneschy, J. E. A., Rodrigues, P. R. B., Avaliação da Integridade Estrutural de Tubos de Gerador de Vapor de Usinas Nucleares – Um Caso Prático. In: CIBIM8 - 8º Congresso Iberoamericano de Engenharia Mecânica, Cusco, 23 a 25 de Outubro de 2007.

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