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EFFICIENCY OF DEFECT SPECIFIC MAINTENANCE OF STEAM GENERATOR TUBES: THE CASE OF ODSCC

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ABSTRACT

The outside diameter stress corrosion cracking at tube support plates became the dominating ageing mechanism in steam generator tubes made of Inconel 600. A variety of maintenance approaches were developed and implemented worldwide to deal with this mechanism. Despite different philosophical and physical backgrounds implemented, all of the applied approaches satisfy the relevant regulatory requirements. For our purpose, the maintenance approach consists of: (1) inspection of tubes, (2) accepting or rejecting the defective tube and (3) plugging of rejected tubes.

The problem of selecting an optimal maintenance approach is raised in the paper. Consequently, a method comparing the efficiency of applicable maintenance approaches is proposed. The efficiency is defined by three parameters: (a) number of plugged tubes, (b) probability of steam generator tube rupture and (c) predicted accidental leak rates through the defects.

An original probabilistic model is proposed to quantify the probability of tube rupture, while procedures available in literature were used to define the accidental leak rates.

The numerical example considers the data from Krško NPP (Westinghouse 632 MWe). The maintenance approaches analyzed include: (i) no repair at all, (ii) traditional defect depth (40%) based maintenance, (iii) alternate plugging criterion (bobbin coil voltage as defined by EPRI and U.S. NRC) and (iv) combined traditional and alternate approach.

Advantages of the defect specific approaches (iii) and (iv) over the traditional one (defect depth) are clearly shown. A brief discussion on the optimization of safe life of steam generator is given.

1 INTRODUCTION

Tubes in steam generators (SG) are exposed to thermal and mechanical loads combined by aggressive environmental conditions. Rather severe corrosion damage results in tubes made of Inconel 600, which may affect the integrity of degraded tubes. The SG tubes represent more than one half of the reactor coolant pressure boundary. Consequently, excessive degradation of tubes might imply reduced reliability and safety of the entire plant [1]. Two potential failure modes of degraded tubing are of particular concern:

- single or multiple tube rupture and
- excessive leaking of the reactor coolant to the secondary side.

The appropriate level of plant reliability and safety is maintained by periodic maintenance. This usually starts with inspection of tubes. Tubes with defects which exceed certain allowable size are then repaired (e.g., sleeved) or removed from service (e.g., plugged). Traditionally, the allowable defect size (also termed plugging criterion) is defined in terms of tube wall thickness and is usually about 40% [2], [3]. This approach is termed generic maintenance approach.

The extent and morphology of the recent types of corrosion damage (Primary Water Stress Corrosion Cracking-PWSCC and Outside Diameter Stress Corrosion Cracking-ODSCC) required more specific treatment. Basically, the conservativities inherent in the development of the generic plugging criterion were replaced by dedicated inspection and implementation of the defect specific failure models. This lead to the development and implementation of the defect specific SG maintenance approaches. In particular, the plugging criterion for PWSCC in expansion transitions was defined in terms of the length of axial crack, while the ODSCC (at tube support plates only) criterion relies directly on the signal amplitude obtained from a bobbin coil eddy current inspection. A review on the development work and underlying assumptions can be found in [1] and [4].

The analyses addressing the change in plant reliability and safety due to the implementation of the defect specific maintenance are rather scarce and at present limited to the axial PWSCC in expansion transitions (e.g., [5], [6] and [7]). Those analyses were based on probabilistic fracture mechanics techniques and clearly showed the advantage of the defect specific approaches over the traditional ones. In other words, the defect specific approaches were shown to achieve lower probabilities of tube rupture with fewer tubes plugged.

In this paper we propose a method which evaluates the efficiency of the defect specific maintenance approaches in the case of ODSCC at tube support plates. The efficiency is defined by degree of defense (or safety) against failure modes during most unfavorable hypothetical accidental conditions:

- probability of (single or multiple) tube rupture;
- the maximum expected leak rate and
- number of plugged tubes (which is more a question of economics than safety).

Basically, we closely follow the methodology developed by EPRI [8] for ODSCC at tube support plate intersections. Additionally, an original probabilistic model is proposed to quantify the probability of tube rupture.

The main result is the efficiency of defect specific maintenance as compared to the generic maintenance in terms of: (1) tube rupture probability, (2) expected accidental primary to secondary leak rate and (3) number of plugged tubes. These three parameters also represent a basis for the optimization of safe steam generator life time. The results of the numerical example clearly show the advantages of the defect specific approaches.

2 COMMENTS ON THE MODELING

A brief description of the calculation procedure is given below. The main body of the calculations follows the methodology defined for the alternate voltage criteria by EPRI (for details see [8], [9] and references therein), which is very briefly given below in order to explain the developments leading to the present analysis.

2.1 Probability of tube rupture

The probability of failure P_f in probabilistic fracture mechanics is usually defined by:

$$P_f = \int_{g(x_1,\, x_2,\, \ldots,\, x_n) \le 0} f_1(x_1)\, f_2(x_2)\, \ldots\, f_n(x_n)\; dx_1\; dx_2 \ldots dx_n \qquad (1)$$

The statistically independent basic variables and their probability densities, n in number, are denoted by $x_1, x_2, \ldots, x_n$ and $f_1(x_1), f_2(x_2), \ldots, f_n(x_n)$. The failure is defined in terms of failure function $g(\cdot)$, which is by definition negative for all failure states.

The failure function in the case of ODSCC specific maintenance can be defined simply as:

$$g(\Delta p_{SLB},\, \Delta p_{EOC}) = \Delta p_{SLB} - \Delta p_{EOC} \qquad (2)$$

Δp_{SLB} denotes the pressure difference obtained from the limiting accidental state such as Steam Line Break (SLB). Δp_{EOC} represents the burst pressure of the tube containing a defect at the end of inspection cycle (EOC). A tube is therefore considered to be failed (ruptured) when its burst pressure becomes less than the highest expected accidental pressured difference (e.g., at SLB). Δp_{EOC} is obtained from the correlation between burst pressure and bobbin coil signal amplitude [8] as a function of the End of Cycle defect size. This in turn is obtained by a stochastic combination of basic variables describing:

- distribution of defects at the beginning of inspection cycle (BOC). The plugging criterion may be included here by imposing appropriate upper limit to the distribution function;
- defect progression until the end of inspection cycle (EOC);
- uncertainties inherent to the Eddy Current Technique (ECT) measurement variability.

The calculation of Δp_{EOC} accounts also for uncertainties inherent to the correlation between burst pressure and bobbin coil signal amplitude.

The value of P_f (eq. (1)) was obtained using the First and Second Order reliability methods as implemented in the ZERBERUS code [7], [10]. These fast numerical methods were accurately implemented instead of the computationaly very intensive Direct Monte Carlo simulations, which are acceptable to the NRC [9].

P_f represents the fraction of failed tubes in the population of all defective tubes. The observed steam generator is then represented as a random sample of N defects. The probability of having i tubes failed $p(i)$ then follows from the Poisson distribution:

$$p(i) = \frac{\left(N \cdot P_f\right)^i}{i!} \exp\left(-N \cdot P_f\right) \qquad (3)$$

Thus, appropriate choice of i enables the calculation of single and multiple tube rupture probabilities.

2.2 Maximum expected leak rate

The estimation of the maximum expected leak rate at the end of operating cycle (EOC) under accidental conditions strictly follows the procedure outlined in [8] and [12].

2.3 Number of plugged tubes

Suppose that inspection of the tubes revealed N defects. Distribution of defect sizes (in terms of bobbin coil signal amplitudes) is denoted by $f(V_{BOC})$. Imposing a plugging criterion with value of PC (in Volts), the number of plugged tubes N_{PLG} can be obtained from the relation:

$$\frac{N_{PLG}}{N} = \frac{\int_{PC}^{\infty} f\left(V_{BOC}\right) dV_{BOC}}{\int_{0}^{\infty} f\left(V_{BOC}\right) dV_{BOC}} \qquad (4)$$

3 NUMERICAL EXAMPLE

The data used in the following numerical example was obtained during regular inspections of SG tubes in the Slovenian NPP at Krško performed in 1993 and 1994. Detailed description of data used is given in [12] and [11].

The comparison of the efficiency of both different maintenance strategies (defect specific and generic) is presented as a function of voltage plugging criterion. The efficiency was evaluated through

- the predicted total leak rate through one steam generator during the postulated limiting accident (SLB) at the end of cycle;
- estimated probability of tube rupture (single or multiple) at the EOC, given postulated limiting accidental conditions (FLB);

number of tubes (and distribution of defect sizes in them) which are supposed to be plugged using one or another maintenance strategy.

The maintenance approaches considered in this paper are:

- ***no plugging*** at all;
- ***traditional*** approach. All tubes with defect depths exceeding the Krško specific 45% of tube wall thickness were assumed plugged;
- ***alternate*** (or EPRI bobbin coil voltage based) approach. All tubes with defect sizes exceeding the Krško specific value of 1 V were assumed plugged;
- ***combined*** traditional and EPRI approach. All tubes with defect sizes exceeding 1 V and depths exceeding 45% of tube wall thickness were assumed plugged.

Differences in maintenance approaches were described by different distributions and numbers of defect sizes at the beginning of inspection cycle (BOC). For example, setting the alternate plugging criterion to 1.5 V simply caused setting 1.5 as an upper limit of the distribution describing the BOC defect sizes. On the other hand, the list of tubes plugged because of the traditional (45% loss of tube wall thickness) plugging criterion was available. Therefore, all plugged tubes were eliminated from the inspection results, yielding an empirical distribution of defect sizes.

3.1 Tube rupture probability

To estimate tube rupture probability a postulated Feed Line Break (FLB) accident was assumed with differential pressure of 195.6 bar (2850 psi).

In this analysis we only present the single tube rupture probabilities. As to the absolute values, they varied considerably between particular SG and inspection years. At the same time, all of them were estimated to be less than 1%, which is in agreement with U.S. NRC requirements [9]. These values are, as stated above, conditional given a postulated FLB accident. The probability of multiple tube ruptures was at least two orders of magnitude lower than for single tube rupture for all cases analyzed. Thus, the multiple tube rupture event was not considered to be of particular importance here.

The results obtained from all data sets showed similar behavior in the qualitative manner. Therefore, examples given here are considered representative. Relative probabilities of single tube ruptures are depicted in **Figure 1** and **Figure 2** (curves denoted probability of single SGTR). The values obtained by traditional (**Figure 1**) and Krško (**Figure 2**) approaches were set to 1.

The relative probability of SGTR is obtained in the following way. First, the probability of SGTR was predicted for the traditional (**Figure 1**) and Krško (**Figure 2**) maintenance approaches. Then, the probabilities of SGTR were predicted for appropriate data sets as a function of alternate plugging criterion PC. The ratio between corresponding rupture probabilities was then plotted as a function of the defect specific plugging criterion (**Figure 1**, **Figure 2**).

Those figures depict the effect of the alternate maintenance approach on the probability of single tube rupture. Setting the defect specific plugging criterion below about 1.4 V is shown to outperform the traditional and combined approach. It should be however noted that above 1.4 V the state of *not plugging at all* is approached. In both cases (**Figure 1, Figure 2**) the state of no plugging at all is only slightly more unfavorable than other maintenance approaches. Again, the conditional tube rupture probabilities were consistently less than 1%.

3.2 Maximum expected leak rate

A postulated steam line break (SLB) accident with a conservative pressure difference of 182.7 bar (2650 psi) was assumed in the analysis.

The relative (maximum expected) leak rates were estimated in the way analogous to the tube rupture probabilities. All data sets showed similar behavior in the qualitative sense. Therefore, examples given here are considered representative. Relative leak rates are depicted in **Figure 1** and **Figure 2** (curves denoted leak rate).

Again, lower leak rates are obtained by using alternate maintenance approach with PC < 1.8 V. However, the no plugging at all approach results in leak rates of the same order of magnitude. Considerable differences in the absolute total leak rates were observed between different steam generators. This is essentially caused by different *number* and *distribution* of defects included in data sets available. However, all the leak rates obtained were well below the limit for normal operation.

A practical conclusion is that such analyses should be preformed after *each* inspection of a particular steam generator.

3.3 Number of plugged tubes

The relative number of plugged tubes is obtained by dividing number of tubes scheduled by plugging by different maintenance approaches. This is analogous with probability of tube rupture and leak rates. Representative examples are depicted in **Figure 1** and **Figure 2** (curve denoted number of plugged tubes). The relative number of plugged tubes seems to be the most sensitive to the changes in plugging criterion.

It is probably important to stress that with PC ≥ 1 V, a significant savings in tube plugging may be achieved by allowing for a rather small increase in probability in tube rupture and expected accidental leak rate. In the cases analyzed, the no plugging at all approach would still keep the conditional probability of tube rupture below 1% and expected accidental (SLB) leak rate below the limits valid for normal operation.

We should stress here again that the above results strongly depend on the particular steam generator analyzed. This results can therefore not be generalized either to another steam generators or other inspection results of the same steam generators.

3.4 Toward the optimization of SG life time

The general behavior of all three curves in **Figure 1** and **Figure 2** was already explained in above discussion. We shall now examine the general efficiency of particular maintenance approaches. The general efficiency is of course based on the joint consideration of the three efficiency parameters discussed above.

It is obvious (**Figure 1** and **Figure 2**) that it is possible to achieve lower SGTR probabilities and expected accidental leak rates by application of lower values of alternate plugging criteria. This in turn obviously increases the number of plugged tubes. Now, let us examine the two separate cases: (1) alternate vs. traditional approach (**Figure 1**) and (2) alternate vs. combined approach (**Figure 2**).

Alternate vs. traditional approach. In shadowed region in **Figure 1**, the alternate approach completely outperforms the traditional one. In this region, lower likelihood of tube bursting and excessive leakage is obtained with fewer tubes plugged. This is also the region where the present values of the defect specific criteria reside (about 1V for 3/4" tubes [9]). This is an obvious candidate for a definition of an optimal maintenance approach.

Between 1.3 and 2.1V, the SGTR probability is raised to its asymptotic level (given the defect population), while there can still be significant reduction in expected leak rates as compared to the traditional approach. This region may be very useful if we are more interested in preventing excessive leak rates (without tube rupture) than the tube rupture event. It should be however noted here that this effect could very well be caused only by the uncertainties in the correlations defining tube bursting and individual leak rates. Some more detailed physical modeling may be therefore required to clarify this effect.

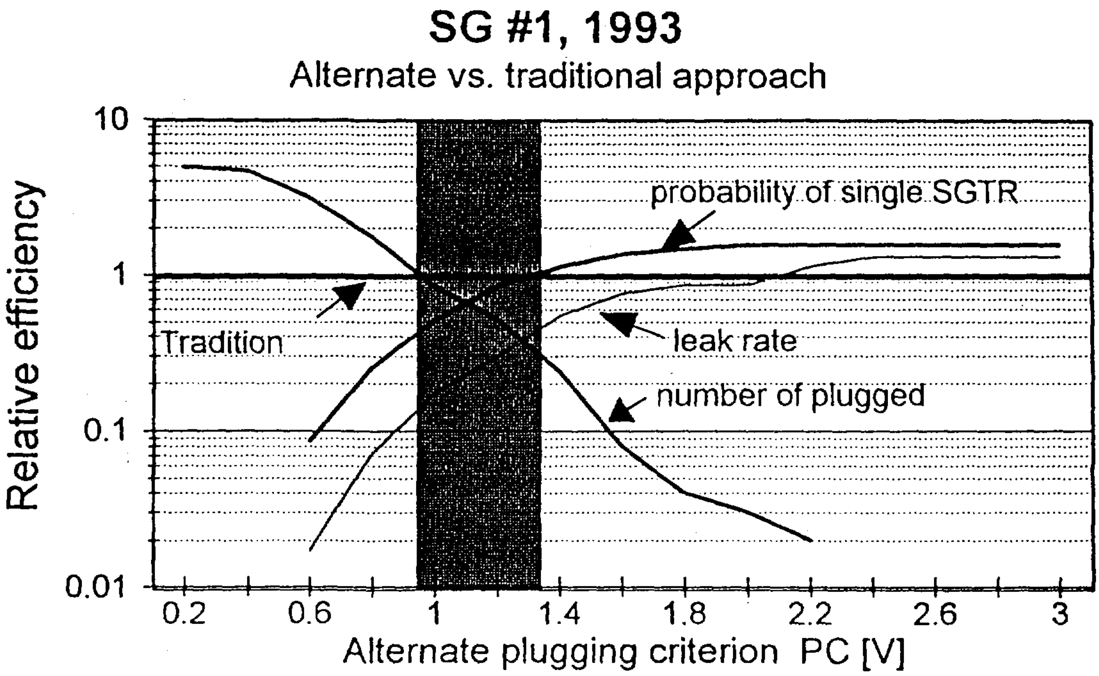

Figure 1 Comparison of traditional and alternate plugging approach

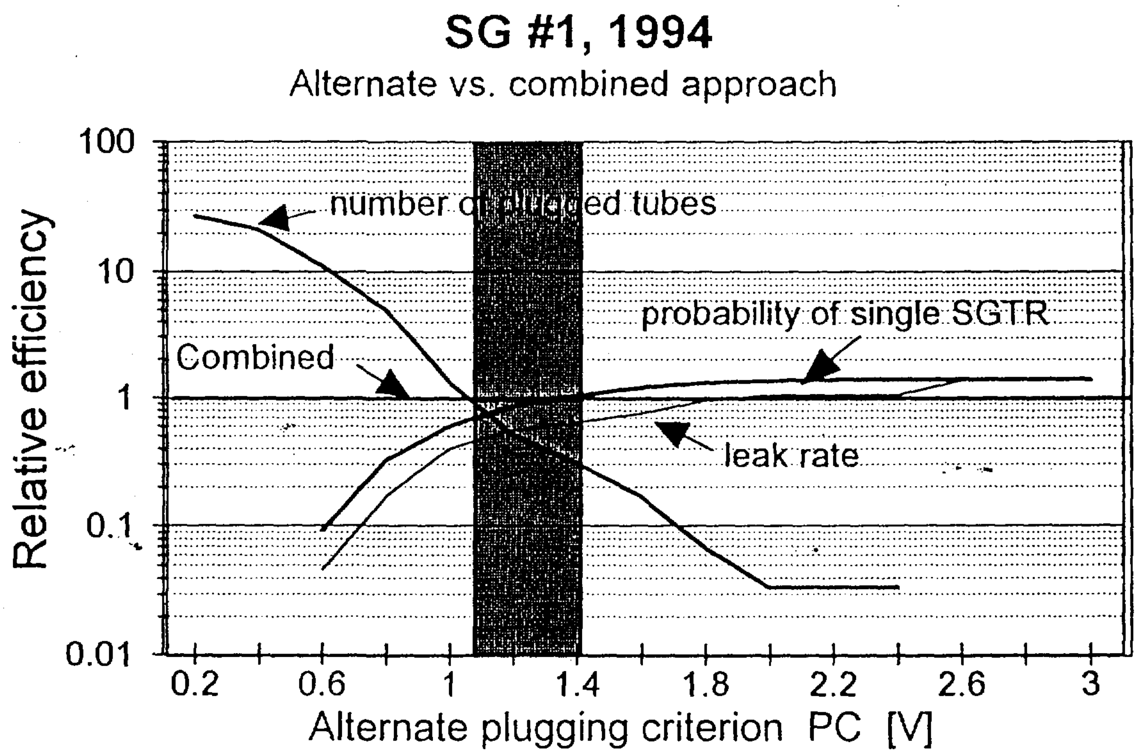

Figure 2 Comparison of combined and alternate maintenance approach

Alternate vs. combined approach. Again, the shadowed region in **Figure 2** represents the region where alternate approach completely dominates the combined approach. It should be however noted that given PC ≥ 1V, there is only one significant difference between those two approaches: number of tubes plugged. The performance of **no plugging at all** approach in this region is comparable both to combined and alternate approaches.

This leads to the conclusion that it would be useful to define a risk based plugging criterion. In simple terms, some limits should be imposed on the tube rupture probability and accidental leak rate rather than on the defect size. Then, methods outlined above could be used to define which and how many tubes should be plugged in order to satisfy the risk limits. This would of course strongly depend on a particular steam generator and operating cycle considered.

3.5 Sensitivity analysis (tube rupture probability)

The absolute values of sensitivity factors are presented in **Figure 3** as a function of PC value. The sensitivity factors are obtained directly from First Order Reliability Method calculation. They simply denote the degree of the change imposed to the tube rupture probability by the magnitude of the scatter of particular random variable.

Therefore, more uncertain regression models yield larger tube rupture probabilities. All other uncertain variables (see **Figure 3**) have significantly lower impact on tube rupture probability. It is also intuitively clear that defect size should have important effect when there is no plugging.

The uncertainty of the regression model strongly depends on the sample size used in the regression analysis. Larger samples would therefore reduce both the uncertainty of the regression and calculated failure probabilities.

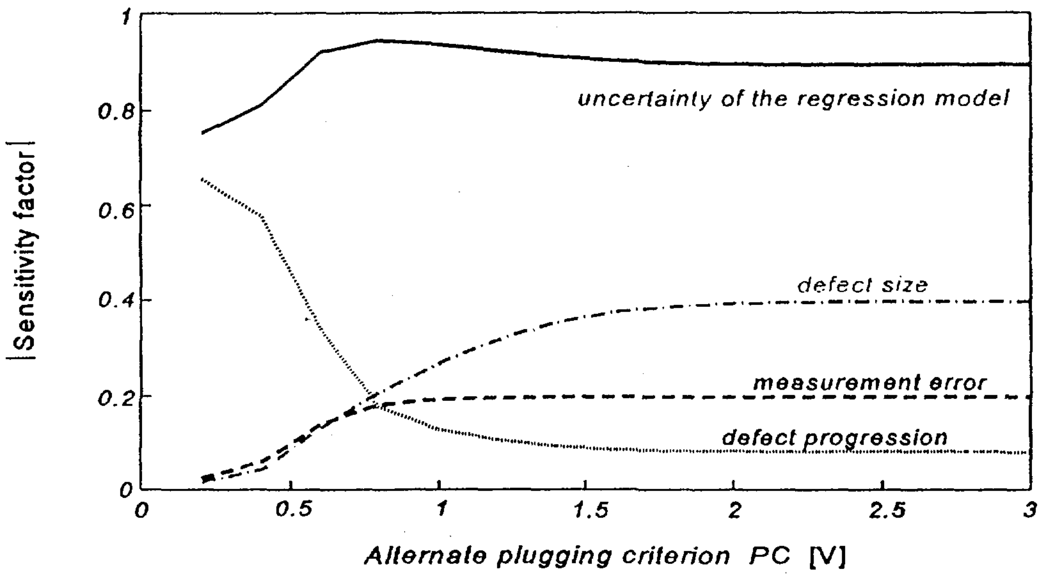

Figure 3 Sensitivity of tube rupture probability to the scatter in basic random variables

4 CONCLUSIONS

The efficiency of the defect specific maintenance approaches for steam generator tubes were studied based on the comparison with the traditional approach allowing for 45% of the tube wall loss. Three different approaches applicable for the ODSCC under tube support plates were taken as examples.

Three parameters were defined as a measure of the efficiency: (1) number of plugged tubes, (2) probability of single tube rupture (given hypothetical accidental conditions) and (3) predicted accidental leak rate through damaged steam generator tubing.

The methods used in the comparison essentially follow the probabilistic fracture mechanics approach already implemented in the case of primary water stress corrosion cracking. They were appropriately modified to accommodate the present analysis.

The efficiency of the defect specific plugging criterion was found to depend strongly on the number and distribution of the defects in the steam generator tubing and value of the criterion implemented. However, in all cases analyzed we found that the defect specific approaches can outperform the traditional one with respect to all of the parameters compared.

It is also interesting that for the distributions of defects analyzed, approach with no plugging also represents a reasonable option. The tube rupture probabilities and accidental leak rates obtained by no plugging at all are namely comparable to those obtained by alternate approach. It may be therefore useful to define risk-based plugging criteria in the future. This should be aimed at minimizing the tube plugging given acceptable level of SG safety and reliability.

An additional topic which should get closer attention in the future is more accurate and/or physics-based modeling of the individual leak rates.

5 ACKNOWLEDGMENTS

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