



## New method to compare efficiency of SG tube maintenance approaches

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### ABSTRACT

The problem of selecting the most efficient steam generator tubes maintenance approach is addressed in the paper. An original method is proposed which quantifies the maintenance efficiency through three parameters: (a) probability of steam generator tube rupture, (b) predicted accidental leak rates through the defects in the tube bundle and (c) number of plugged tubes. Advantages of the defect specific approach over the traditional one are clearly shown. Some hints on the optimization of safe life of steam generator are also given.

### 1 INTRODUCTION

Excessive degradation of tubes made of Inconel 600 might lead to failure of tubes and therefore implies reduced reliability and safety of the entire plant [1]. Two potential failure modes of degraded tubing are of particular concern: (1) single or multiple tube rupture and (2) excessive leaking of the reactor coolant to the secondary side.

The appropriate level of plant reliability and safety is maintained by periodic inspection of tubes, which is followed by repair (e.g., sleeving) or removal from service (e.g., plugging) of tubes with excessive degradation. The excessive and acceptable degradation are delineated through repair criteria. Traditionally, repair criteria was set to defect depth of 40% of the tube wall thickness [2], [3]. This repair criterion-with slight variations in the value-was used until recently on a worldwide basis as a generic repair criterion regardless of the defect morphology [1].

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 generic repair criteria were reduced through dedicated inspection and defect specific failure models [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]). Those analyses were based on probabilistic fracture mechanics techniques and clearly showed the advantage of the defect specific approaches over the traditional ones.

In this paper, an original method addressing the efficiency of different defect specific maintenance approaches in the case of ODSCC at tube support plates is described. The efficiency is defined by degree of defense against failure modes during most unfavorable

hypothetical accidental conditions and through the number of repaired tubes required to achieve this defense level. The method is based on an original procedure which is explained in some details in the next section.

A realistic numerical example is provided to illustrate the performance of the method. The data obtained from inservice inspections of steam generator tubes in Slovene NPP at Krško (Westinghouse 2-loop PWR) are analyzed. The efficiency of three different maintenance approaches are analyzed and discussed. The results of the numerical example clearly show the advantages of the defect specific approaches.

Furthermore, results of sensitivity analysis of input parameters are presented in this paper. The relative importance of input parameters is discussed in some detail at the end of the paper.

## 2 MATHEMATICAL MODEL

Safety and reliability of degraded tubing clearly depend on the level of defense against potential failure modes. This was used as a basis to define efficiency of maintenance strategy. The efficiency is described by:

- probability of (single or multiple) tube rupture and
- the maximum expected leak rate through tubing under postulated limiting accidental conditions.

The third important parameter considered is number of plugged (or repaired) tubes. Reasoning and computation behind each of the three parameters mentioned is explained in some detail below.

### 2.1 Probability of tube rupture

Let us assume an infinite population of steam generator tubes, each containing exactly one defect. Further, let random variables  $x_1, x_2, \dots, x_n$  with density functions  $f_1(x_1), f_2(x_2), \dots, f_n(x_n)$  describe the statistically independent parameters defining load and resistance of damaged tubes. The probability of failure  $P_f$  in this population is defined - following the traditional methods of probabilistic fracture mechanics - by:

$$P_f = \int_{g(x_1, x_2, \dots, x_n) \leq 0} f_1(x_1) f_2(x_2) \dots f_n(x_n) dx_1 dx_2 \dots dx_n \quad (1)$$

The failure of the tube is defined in terms of failure function  $g(x_1, x_2, \dots, x_n)$ , which is by definition negative for all failure states.

We are concerned with the rupture of the tube which is essentially caused when the pressure load on the tube exceeds the limiting pressure difference the tube can sustain. The failure function is thus defined by:

$$g(\Delta p_{ACC}, \Delta p_B, a) = \Delta p_{ACC} - \Delta p_B(a) \quad (2)$$

$\Delta p_{ACC}$  denotes the pressure load acting during a postulated limiting accident (e.g., Steam Line Break).  $\Delta p_B$  represents the maximum pressure difference the tube containing a defect of a given size  $a$  can sustain.  $\Delta p_B$  is sometimes also termed burst pressure of the tube.

ODSCC defects are usually seen as rather complex networks of cracks. A simple and measurable formulation of defect size  $a$  in the sense of crack lengths in fracture mechanics is therefore not yet achieved. However, the state-of-the-art applications rely on experimentally

determined correlation between the defect size  $a$  and burst pressure  $\Delta p_B$  [6]:

$$\Delta p_B(a) = A + B \cdot \log_{10}(a) + \varepsilon \quad (3)$$

$A$  and  $B$  are coefficients obtained from the regression analysis [6].  $\varepsilon$  represents a zero-mean random error of the regression model. Defect size  $a$  in this regression model is referred to bobbin coil signal amplitude (voltage) and is explained in some detail in section 2.4.

The value of  $P_f$  (eq. (1)) was obtained using the First and Second Order reliability methods as implemented in the ZERBERUS code [8]. These fast numerical methods were accurately implemented [10] instead of the computationally very intensive Direct Monte Carlo simulations, which are acceptable to the NRC [7].

$P_f$  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  $p(i)$  is assumed to follow the Poisson distribution:

$$p(i) = \frac{(N \cdot P_f)^i}{i!} \cdot \exp(-N \cdot P_f) \quad (4)$$

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

## 2.2 Maximum expected leak rate

The prediction of leak rates through complex networks of cracks is rather uncertain, even for defects with well defined morphologies. A relative simple and robust model which relies on experimental analysis of a sample of tubes including those pulled from operating steam generators was developed and proposed by EPRI [6]. This is a two step model which considers: (1) probability that a defect of given size will leak, and (2) conditional leak rate (for defects that do leak).

The probability of leaking is determined for given size of defect  $a$ :

$$P(a) = \frac{1}{1 + e^{-[q_0 + q_1 \cdot \log_{10}(a) + \varepsilon]}} \quad (5)$$

The parameters  $q_0$  and  $q_1$  were obtained by regression analysis of measured values [6]. The uncertainty of the regression is accounted for in parameter  $\varepsilon$ . The measure of uncertainty  $\varepsilon$  is a random variable which describes the scatter around the regression curve (logit function).

For subpopulation of leakers, the individual leak rate  $Q$  can be obtained for a given defect size  $a$ :

$$\log_{10}(Q) = A + B \cdot \log_{10}(a) + \varepsilon \quad (6)$$

The parameters of the regression model ( $A$ ,  $B$ , and  $\varepsilon$ ) were obtained from measured values [6]. The uncertainty of the regression model is quantified by  $A$ ,  $B$ , and  $\varepsilon$ . Correlated random variables  $A$  and  $B$  denote the intercept and slope of the regression line.  $\varepsilon$  denotes the scatter around the regression line.

The total leak rate through the entire steam generator  $Q_T$  is essentially a sum of all individual leak rates  $Q$ . To characterize its statistical properties, numerical methods such as Monte Carlo simulation may be used. This usually involves substantial computational efforts.

The CPU time may be reduced by using approximate methods. In the present analysis a method proposed by EPRI [6] was used to estimate the total leak rate  $Q_T$ . The whole sample of defects in the observed SG is divided in classes of small size (e.g., 0.1V). The total leak rate  $Q_T|_{95\%}$  is then given at 95% probability level (with 95% confidence) as:

$$Q_T|_{95\%} = \sum_{i=1}^{N_b} [P(a_i) \cdot Q(a_i)]_{961|1000} \cdot n_i \quad (7)$$

The subscript 961 | 1000 means that 1000 values of  $[P(a_i) \cdot Q(a_i)]$  are generated using Monte Carlo simulation and sorted in ascending order. The 961<sup>st</sup> value of this ordered set is chosen as a representative value for the entire class of defects.  $n_i$  in eq. (7) depicts the number of defects in  $i$ -th bin and  $N_b$  number of classes.

However, eq. (3) averages representative leak rates over leakers and non-leakers. This is reasonable given a large number of defects of approximately the same size or for defects with  $P(a) \approx 1$ . Otherwise it may lead to an underestimation of  $Q_T$  [11].

### 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  $f(a)$ . Imposing a plugging criterion with value of  $PC$  (in Volts), the number of plugged tubes  $N_{PLG}$  can be obtained from the relation:

$$\frac{N_{PLG}}{N} = \frac{\int_0^{\infty} f(a) \cdot da}{\int_0^{\infty} f(a) \cdot da} \quad (8)$$

### 2.4 Defect size

The field inspections of ODSCC defects are performed by bobbin coils (eddy current technique). The result of the inspection which is assumed to represent the defect size is the amplitude of the signal (measured in Volts) obtained from the bobbin coil.

The defect size is generally a time dependent variable. Defect size  $a$  at the time  $t$  is defined by:

$$a(t) = a_0 + a_e + \int_0^t \frac{da}{dt} \quad (9)$$

where  $a_0$  represents defect size at the beginning of inspection cycle (BOC),  $a_e$  uncertainties inherent to the Eddy Current Technique (ECT) measurement variability, and third term defect growth in time  $t$ .

In this analysis, two points in time are of special concern and essentially define the value of defect size: (1) beginning (BOC) and (2) end of the cycle (EOC) between two consecutive inspections, which includes stochastic combination of BOC defect size and defect growth. At the present, the growth of the crack network is assumed to be described by the voltage increase between two successive inspections of the defects. For the purpose of the present analysis, defect growth was predicted from the statistical analysis of consecutive inspections [9].

### 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 [9] (Figure 1).

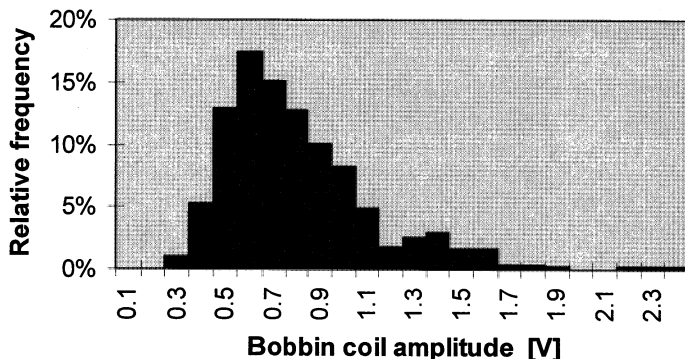


Figure 1 Distribution of defect sizes

The maintenance approaches considered in this numerical example are:

- *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 certain bobbin coil voltage (e.g., 1 V) were assumed plugged;
- *no plugging at all*;

Differences in maintenance approaches were described by different distributions and numbers of defect sizes at the beginning of inspection cycle.

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

- estimated probability of tube rupture (single or multiple) at the end of cycle (EOC), given postulated limiting accidental conditions (FLB);
- the predicted total leak rate through one steam generator during the postulated limiting accident (SLB) at the end of cycle;
- number of tubes (and distribution of defect sizes in them) which are supposed to be plugged using one or another maintenance strategy.

The comparison of the efficiencies of different maintenance approaches is defined in a manner of relative values of efficiency parameters. The relative curves (e.g. for leak rate) are obtained in the following way. First, the leak rate was predicted for the traditional maintenance approach. Then, the leak rates were predicted for appropriate data sets as a function of alternate plugging criterion PC. The ratio between corresponding leak rates was then plotted as a function of the defect specific plugging criterion.

To estimate tube rupture probability a postulated Feed Line Break (FLB) accident was assumed with differential pressure of 195.6 bar (2850 psi). The absolute values of tube rupture probabilities varied considerably between particular SG. These values are, as stated above, conditional given a postulated FLB accident. All of them were estimated to be less than 1%, which is in agreement with U.S. NRC requirements [7].

In this analysis we present only the single tube rupture probabilities. The probability of multiple tube rupture 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. Relative probability of single tube rupture is depicted in Figure 2 (curve denoted probability of single SGTR).

A postulated steam line break (SLB) accident with a conservative pressure difference of 182.7 bar (2650 psi) was assumed in the analysis of leak rate. Considerable differences in the absolute total leak rates were observed between particular SG. 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 Plant Technical Specification limit for normal operation (40 l/h). Relative leak rate is depicted in Figure 2 (curve denoted leak rate).

The relative number of plugged tubes is obtained by dividing number of tubes scheduled for plugging by different maintenance approaches (curve denoted number of plugged tubes in Figure 2). The relative number of plugged tubes seems to be more sensitive to the changes in plugging criterion than tube rupture probability and leak rate.

### 3.1 *Toward the optimization of SG life time*

The general level of safety is of course based on the joint consideration of the three parameters discussed above. Now, let us compare traditional, alternate and no plugging at all approach (Figure 2).

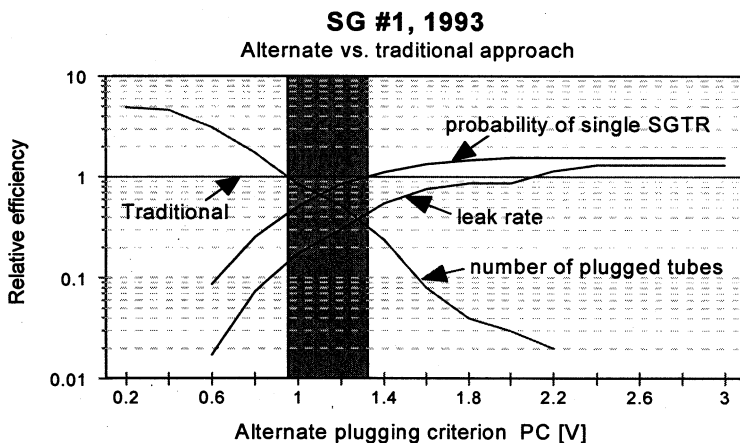


Figure 2 Comparison of traditional and alternate plugging approach

In shadowed region in Figure 2, 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 [7]). This is an obvious candidate for a definition of an optimal maintenance approach.

Between 1.3 and 2.1 V, 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. In this region we are already approaching the no plugging at all state.

The performance of no plugging at all approach is comparable both to traditional and above 1.3 V also to alternate approach. 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.

We should stress here 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. A practical conclusion is that such analyses should be performed after each inspection of a particular steam generator.

### 3.2 *Sensitivity analysis*

To evaluate the relative importance of input parameters of above discussed models a sensitivity analysis was performed. The sensitivity factors for tube rupture probability are obtained directly from First Order Reliability Method calculation. Thus, the sensitivity factors simply denote the degree of the change imposed to the tube rupture probability by the magnitude of the scatter of particular random variable. Consistent method was used in the case of Monte Carlo simulation of leak rates.

The sensitivity analysis addresses the following parameters: defect size, defect growth, uncertainty of regression model, and measurement error. The analysis clearly shows that uncertainties of regression models dominate regardless of the value of the alternate plugging criterion.

The uncertainty of the regression model strongly depends on the sample size used in the regression analysis [6]. Larger samples would therefore reduce both the uncertainty of the regressions and calculated failure probabilities or leak rates. This would require further expensive experimental work [6].

## 4 CONCLUSIONS

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

The procedure used in the comparison essentially follows the probabilistic fracture mechanics approach already implemented in the case of primary water stress corrosion cracking. It was appropriately modified to accommodate the present analysis.

The level of safety 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, we found that the defect specific approaches 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 traditional 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.

Sensitivity analyses show that the scatter of regression models represent the dominant contributor to the leak rate and tube rupture probability. Thus, an additional topic which should get closer attention in the future is more accurate and/or physics-based modeling of the tube rupture conditions and individual leak rates.

## 5 ACKNOWLEDGMENTS

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