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Safety and availability of steam generator tubes affected by secondary side corrosion

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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 world-wide to enable safe and reliable plant operation with affected tubes. Despite different philosophical and physical backgrounds involved, all applied approaches satisfy relevant regulatory requirements. The main goal in this followe paper is to quantify the degree of safety which is achieved through the implementation of selected maintenance approaches. A method is proposed which measures the operational safety and availability through three efficiency parameters: probability of steam generator tube rupture; predicted accidental leak rates through the defects in the tub e bundle; and number of plugged tubes. An original probabilistic model quantifies the probability of tube rupture, while procedures available in literature were used to evaluate the accidental leak rates. A numerical example is based on data from the Krško NPP (PWR 623 MWe). The maintenance strategies analyzed are: (a) traditional defect depth (40%) plugging criterion; (b) alternate plugging criterion (bobbin coil voltage as defined by EPRI and US NRC); (c) combination of traditional and alternate plugging criteria; and (d) no plugging at all. Advantages of the defect specific approaches (b) and (c) over the traditional one (a) are clearly shown. The efficiency of the traditional approach (a) is shown to be comparable to the no plugging at all approach (d). Finally, a sensitivity analysis aimed at ranking of the input parameters is presented. Uncertain failure models are shown to be the major contributor to the scatter of obtained results. © 1998 Elsevier Science S.A. All rights reserved.

1. Introduction

The steam generators (SG) tubes represent the majority of the reactor coolant pressure boundary. Tubes in SG are exposed to thermal and mechanical loads combined by aggressive environmental conditions. Rather sever corrosion damage results in tubes made of Inconel 600. Excessive degradation of tubes might lead to failure of tubes and therefore implies reduced availability and safety of the entire plant (MacDonald et al., 1995). 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.

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The appropriate degree of plant availability 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 was required for defects deeper than 40% of the tube wall thickness (Clark and Kurtz, 1998; ASME, 1998). This repair criterion—with slight variations in the value—was used until recently on a world-wide basis as a generic repair criterion regardless of the defect morphology (MacDonald et al., 1995).

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 conservatism inherent in the generic repair criteria ~~were~~ was reduced through dedicated inspection and defect specific failure models. This was the basis for defect specific repair criteria. For example, the plugging criterion for PWSCC in expansion transitions was defined as allowable length of an axial crack, while the ODSCC (at tube support plates only) criterion limits the signal amplitude obtained from a bobbin coil Eddy Current inspection. A review on the development work and underlying assumptions can be found for example in (MacDonald et al., 1995; US NRC 1993).

The analyses addressing the change in plant availability and safety due to the implementation of the defect specific maintenance are rather scarce and at present limited to the axial PWECC in expansion transition (Mavko and Cizelj, 1992; Cizelj et al., 1996b, 1994). 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.

PWSCC →

In this paper, an original method addressing the degree of safety and availability of different defect specific maintenance approaches in case of ODSCC at tube support plates is proposed. The degree of safety is defined by degree of defense against failure models during most unfavorable hypothetical accidental conditions and through the number of repaired tubes required to achieve this defense level. The analysis is based on an original method which is explained in some detail in the next section.

A realistic numerical example illustrates the performance of the method. The data obtained from inservice inspections of steam generator tubes in the Slovene NPP at Krško (Westinghouse 2-loop PWR) ~~(NPP Krško, 1997)~~ are analyzed. δ The degrees of safety obtained by four different maintenance options 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 show the relative importance of input parameters.

2. Mathematical model

Safety and availability of degraded tubing clearly depend~~s~~ on the degree of defense against potential failure modes. δ This can be described using:

- the probability of single or multiple tube rupture;
- the maximum expected primary to secondary leak rate through tubing under postulated limiting accidental conditions;
- number of plugged/repaired tubes. ⊥ OR

All of the above parameters strongly depend on the distribution and size of defects.

2.1. Probability of tube rupture

Let us assume an infinite population of steam generator tubes, each containing exactly one defect. Furthermore, let random variables x_1, $x_2,\ldots,x_n$ with density functions $f_1(x_1)$, $f_2(x_2),\ldots,f_n(x_n)$ 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:

$$P_f = \int_{g(x_1,x_2,\ldots,x_n)\le 0} f_1(x_1)f_2(x_2)\ldots f_n(x_n) \times \mathrm{d}x_1\,\mathrm{d}x_2\ldots\mathrm{d}x_n \qquad (1)$$

The failure of the tube is defined in terms of a failure function $g(x_1, x_2,\ldots,x_n)$, 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 the tube can sustain. The failure function is thus defined by:

$$g(\Delta p_{\mathrm{ACC}}, \Delta p_{\mathrm{B}}, a) = \Delta p_{\mathrm{ACC}} - \Delta p_{\mathrm{B}}(a) \qquad (2)$$

∀statement → Δp_{ACC} denotes the pressure load acting during a postulated limiting accident (e.g. Steam Line Break). Δp_{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 (e.g. the crack length 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 Δp_{B} (Steam Generator Degradation Specific Management (Draft), 1993):

$$\Delta p_{\mathrm{B}}(a) = A + B \cdot \log_{10}(a) + \varepsilon \qquad (3)$$

A and B are proprietary coefficients obtained from the regression analysis. At present they are treated as constants. ε represents a zero-mean random error of the regression model. Defect size a in this regression model is referred to as 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 (FORM, SORM) as implemented in the ZERBERUS code (Cizelj et al., 1994; Cizelj, 1991). These fast numerical methods were accurately implemented (Dvoršek, 1996; Cizelj, 1995) instead of the computationally very intensive Direct Monte Carlo simulations, which are acceptable to the NRC (US NRC, 1995).

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 on N defects. The probability of having i tubes failed $p(i)$ is assumed to follow the Poisson distribution:

$$p(i) = \frac{(N \cdot P_{\mathrm{f}})^i}{i!} \cdot \exp(-N \cdot P_{\mathrm{f}}) \qquad (4)$$

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

2.2. Maximum expected leak rate

The ODSCC defects at tube support plates are usually seen as complex networks of cracks. The prediction of leak rates through such complex networks of cracks is rather uncertain, even for defects with well defined morphologies. However, the state-of-the-art methods used to detect defects are not capable of describing crack morphologies at present (Steam Generator Degradation Specific Management (Draft), 1993). Therefore, empirical methods are used to support the prediction of leak rates through defects.

A relative simple and robust model which relies on experimental analysis of the sample of tubes including those pulled from operating steam generators was developed and proposed by EPRI (Steam Generator Degradation Specific Management (Draft), 1993). This is a two step model which considers: (1) the probability that a defect of given size a will leak; and (2) conditional leak rate (for defects that do leak).

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

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

The parameters q_0 and q_1 were obtained by regression analysis of measured values (Steam Generator Degradation Specific Management (Draft), 1993). The uncertainty of the regression is accounted for in parameter ε. The measure of uncertainty ε is a zero-mean normal random variable which describes the scatter around the regression curve (logit function).

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

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

The parameters of the regression model (A, B, and ε) were obtained from measured values (Steam Generator Degradation Specific Management (Draft), 1993). Correlated random variables A and B denote the intercept and slope of the regression line. ε denotes the scatter around the regression line. Again, defect size a in this regression model is referred to as bobbin coil signal amplitude which is explained in some detail in Section 2.4.

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 the 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 (Steam Generator Degradation Specific Management (Draft), 1993) was used to estimate the total leak rate Q_T. The whole sample of defects in the observed SG is divided in to classes of small size (e.g. 0.1 V). The total leak rate $Q_T|_{95\%}$ is then given at 95% probability level (with 95% confidence) as:

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

The subscript 961|1000 means that 1000 values of $[P(a_i) \cdot Q(a_i)]$ are generated using Monte Carlo simulation and are sorted in ascending order. The 961st 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 ith class and N_b number of classes. →

However, Eq. (7) defines the representative leak rate by averaging the contributions of 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 (Cizelj et al., 1996c).

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:

$$\frac{N_{PLG}}{N} = \frac{\int_{PC}^{\infty} f(a) \cdot da}{\int_{0}^{\infty} f(a) \cdot da} \tag{8}$$

2.4. Defect size

The field inspection of ODSCC defects are performed by bobbin coils (Eddy Current Technique (ECT)). 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. Establishing further relationship between measured amplitude of the signal and physical size (e.g. length of the cracks) is of out of the scope of this paper. ←

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

$$a(t) = a_0 + a_\varepsilon + \int_0^t \frac{da}{dt} \tag{9}$$

where a_0 represents the defect size at the beginning of the inspection cycle (BOC), a_ε uncertainties inherent to the 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) the beginning (BOC) and (2) the end of the cycle (EOC) between two consecutive inspections, which includes stochastic combination of BOC defect size and predicted defect growth. At present, the growth of the crack network is assumed to be described by a 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 (Cizelj, 1995).

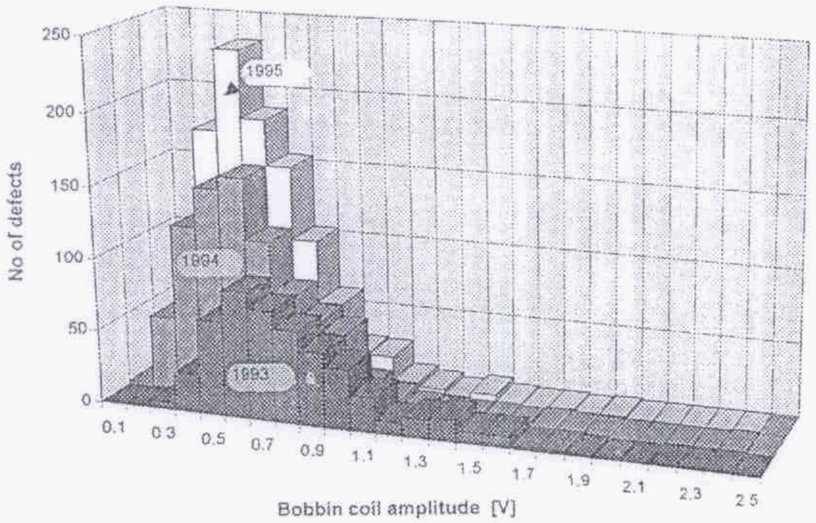

Fig. 1. Distribution of defect sizes (SG # 1).

3. Numerical example

3.1. Input data description

The data used in the numerical example were obtained during regular annual inspections of tubes of SG # 1 at the Slovenian NPP at Krško performed in 1993, 1994, and 1995 (Fig. 1).

It is interesting to point out that the distribution of defect sizes remained virtually unchanged over those years. However, the number of detected defects has increased from 492 in 1993 to 1048 in 1995 in SG # 1.

The defect growth (Eq. (9)) is based on a plant specific analysis of changes in bobbin coil voltage amplitudes observed in consecutive inspections. Generally, different growth rates were observed and implemented in this analysis for each SG and each operational cycle. Detailed description of defect growth observations and modeling is give in Dvoršek, 1996 and Cizelj, 1995. The measurement errors (Eq. (9)) were also estimated from plant specific study which is given in Inetec, 1996.

3.2. Assumptions for maintenance approaches

The comparison of the degree of safety of defect specific and generic maintenance strategies is presented as a function of alternate plugging criterion. The degree of safety 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, give postulated limiting n 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 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;
- combined traditional and EPRI approach. All tubes with defect sizes exceeding 1 V and depths exceeding 45% of tube wall thickness were assumed plugged.
- no plugging at all;

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

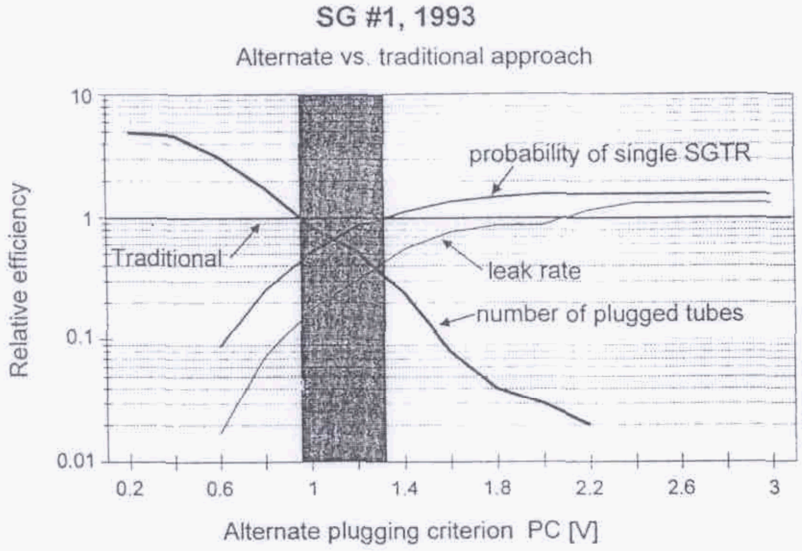

Fig. 2. Comparison of traditional and alternate maintenance approaches (1993).

(a_0 in Eq. (9)). 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. Therefor, all plugged tubes were eliminated from the inspection result, yielding a corresponding empirical distribution of defect sizes.

The distribution of defect sizes at the BOC strongly depends on particular SG, operational cycle, and maintenance approach.

3.3. Tube rupture probability

To estimate the 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 of the single tube rupture probability, they varied considerably between particular SG and operational cycles. At the same time, all of them were estimated to be less than 1%, which is in agreement with US NRC requirements (US NRC, 1995). These values are conditional, given a postulated FLB accident.

The estimated probability of multiple tube rupture was in all cases at least two orders of magnitude lower than for the single tube rupture probability. Thus, the multiple tube rupture event was not considered to be of particular importance at this time.

The results obtained from all data sets showed similar behaviour in the qualitative manner. Relative probabilities of single tube ruptures are depicted in Figs. 2–4 (curves denoted probability of single SGTR). The values obtained by traditional (Fig. 2) and combined (Figs. 3 and 4) maintenance approaches were set to 1 in order to allow direct comparison of both approaches.

δ

The relative probability of SGTR is obtained by firstly, predicting the probability of SGTR for the traditional (Fig. 2) and combined (Figs. 3 and 4) 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 (Figs. 2–4).

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 show to outperform the traditional and combined approach. It should

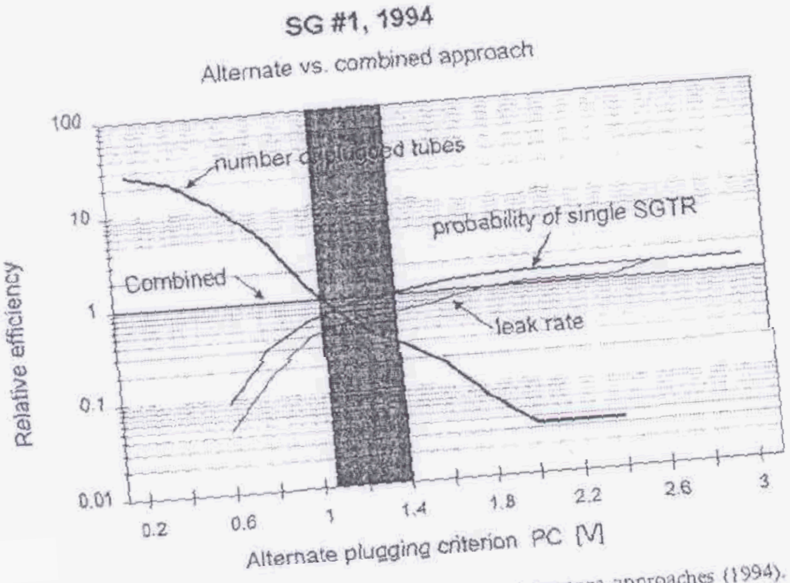

Fig. 3. Comparison of combined and alternate maintenance approaches (1994).

be however noted that above 1.4 V the state of no plugging at all is approached. In both cases (Figs. 2–4) the no plugging at all approach yields results comparable to other maintenance approaches. Again, the conditional tube rupture probabilities were consistently less than 1% (US NRC, 1995). (US NRC requirements

1.2

3.4. Maximum expected leak rate

A postulated Steam Line Break (SLB) accident with a conservative pressure difference of 182.7 bar (2650 psi) was assumed. 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. Relative leak rates are depicted in Figs. 2–4 (curves denoted leak rate).

1i

Again, lower leak rates are obtained by using an 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 total leak rates obtained were well below the limit for normal operation (40 l h^{-1}) [17]. (NPP Krško, 1997

The practical conclusion is that such an analysis should be repeated after the inspection of a particular steam generator. each

3.5. Number of plugged tubes

The relative number of plugged tubes is obtained by dividing number of tubes scheduled for plugging by different maintenance approaches. This is analogous with relative efficiencies defined by probability of tube rupture and leak rates. Representative examples are depicted in Figs. 2–4 (curve denoted number of plugged tubes). The relative number of plugged tubes seems to be more sensitive to the changes in plugging criterion than tube rupture probability and leak rate.

It is important to stress that at $PC \geq 1$ V, a significant savings in tube plugging may be achieved by allowing for a virtually negligible 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.

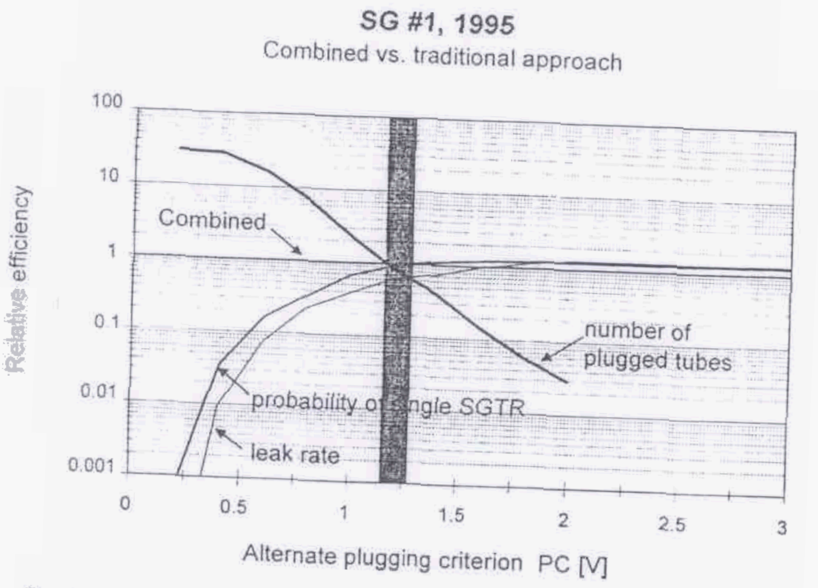

Fig. 4. Comparison of combined and alternate maintenance approaches (1995).

The above results strongly depend on the particular steam generator. These results may therefore not be generalized either to another steam generator or to other inspection results of the same steam generators.

3.6. Toward the optimization of SG life time

The general behavior of all three curves in Figs. 2–4 was already explained in above discussion. We shall now examine the general degree of safety of particular maintenance approaches. The general degree of safety is of course based on the joint consideration of the three parameters discussed above.

It is obvious (Figs. 2–4) 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 versus traditional approach (Fig. 2); and (2) alternate versus combined approach (Figs. 3 and 4).

Alternate versus traditional approach: In shadowed region in Fig. 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 (~ 1 V for 3/4 in. tubes US NRC, 1995). This is an obvious candidate for 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. 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 be the uncertainties in the correlations defining tube bursting and individual leak rates (Eqs. (3) and (6)). Some more detailed physical modeling may be therefore required to clarify this effect.

space

Alternate versus combined approach: Again, the shadowed region in Fig. 3 and Fig. 4 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

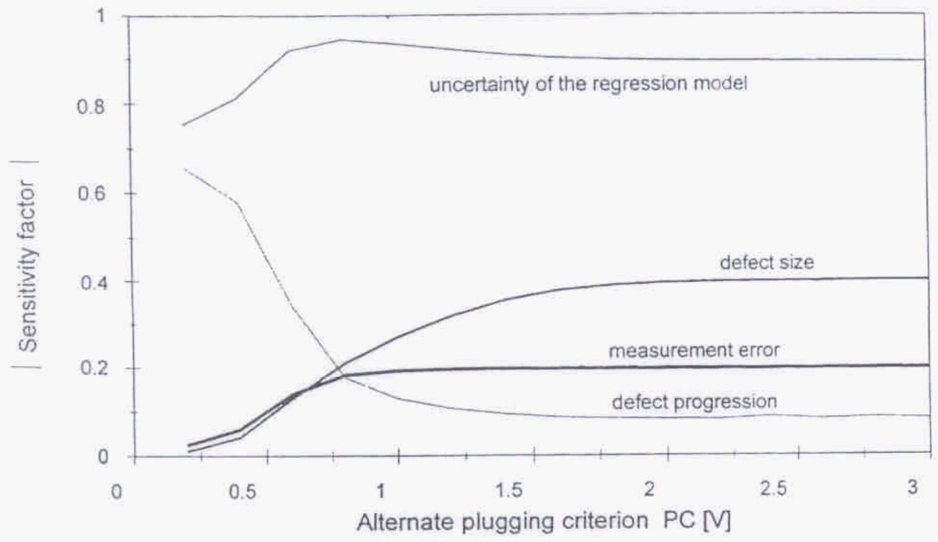

Fig. 5. Sensitivity of tube rupture probability to the scatter of basic random variables.

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 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. Sensitivity analysis

3.7

The absolute values of sensitivity factors are presented in Fig. 5 for tube rupture probability and Fig. 6 for leak rate, both as functions of PC value. The sensitivity factors for tube rupture probability are obtained directly from First Order Reliability Method calculation. Thus, the sensitivity factors denoted 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 (Fig. 6). An additional basic variable has been introduced here, i.e. probability of leakage. On the other hand, the sensitivity of leak rates to changes in the defect size was not addressed here. This is because only minor impact on results has been found for this basic variable in the previous analysis (Wizelj et al., 1996). ← C

The oscillations in the leak rate sensitivity factors obtained at low values of PC are mainly caused by the large scatter in the regression model (Eq. (6)). Thus, the changes of the leak rate caused by the uncertain model may be larger than those caused by deliberate change in input parameter. This effect could be filtered out by averaging over a series of calculations, which would require extensive computational effort beyond the scope of this analysis. However, the qualitative behavior of sensitivity factors is considered reasonable.

Therefore, larger uncertainty of the regression model yields larger tube rupture probabilities and expected leak rates. All other basic variables (Figs. 5 and 6) have significantly lower impact on the result. It is also intuitively clear that defect size should have important effect only at large values of PC.

The uncertainty of the regression model strongly depends on the sample size used in the regression analysis (Steam Generator Degradation Specific Management (Draft), 1993). Larger sam-

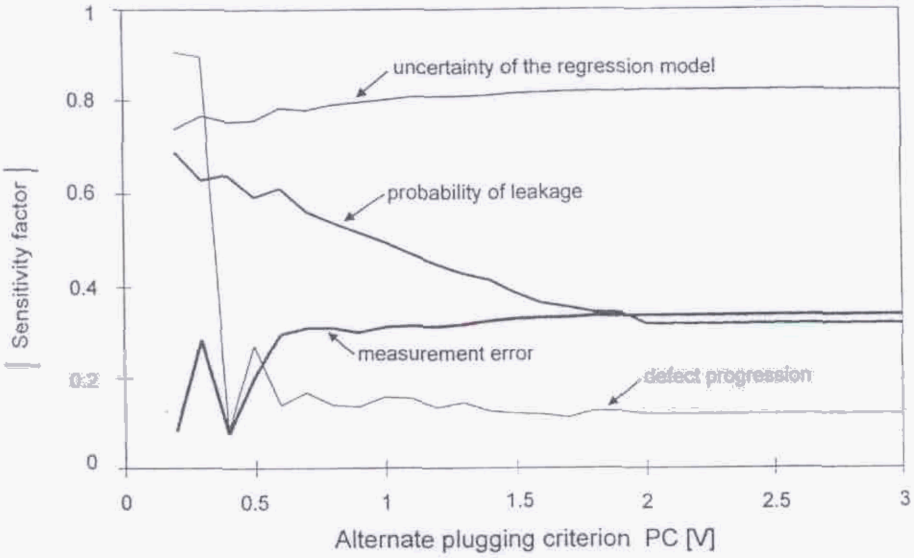

Fig. 6. Sensitivity of leak rate to the scatter of basic random variables.

ples would therefore reduce both the uncertainty of the regressions and calculated failure probabilities or leak rates. This would require further expensive experimental work (Steam Generator Degradation Specific Management (Draft), 1993).

4. Conclusions

An original method is proposed to quantify the safety and availability of different maintenance approaches for steam generator tubes affected by secondary side corrosion. In particular, the tubes affected by outside diameter stress corrosion cracking at tube support plates are taken as an example.

The quantification of safety and availability is based on three parameters: probability of tube rupture, predicted accidental leak rates and number of plugged tubes.

Four different maintenance approaches were considered in the numerical example, which was based on realistic data obtained from inservice inspections of steam generators in Krško NPP in Slovenia. Generally, better safety performance was indicated by the defect specific maintenance approaches as compared to the generic ones. Also, defect specific maintenance approaches require less tubes to be repaired in all cases analyzed.

Interesting observation is, that the no plugging at all approach, shows performance which is comparable to the traditional maintenance approaches. In all cases analyzed, the no plugging at all approach also resided within the safety limits suggested by US NRC. Therefore, it may represent a reasonable maintenance option. It may be therefore useful to define risk or performance based goals for maintenance in the future.

Sensitivity analyses show that the scatter of regression models represents the dominant contribution to the leak rate and tube rupture probability. Thus, the 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. Unlinked list AUTHOR: PLEASE CITE REFERENCES Cizelj et al., 1996a; Cuvelliez et al., 1995 IN TEXT

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