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Probabilistic Assessment of Excessive Leakage through Steam Generator Tubes Degraded by Secondary Side Corrosion

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ABSTRACT

A probabilistic approach aiming at prediction of the probability of excessive leakage through degraded steam generator (SG) tubes is proposed in the paper. The excessive leakage is assumed to occur during postulated hypothetical accidental conditions when *the sum of all individual leak rates through degraded tubes exceeds the predefined acceptable value.* The leak rates through the individual defects were evaluated using models developed by EPRI for assessment of Outside Diameter Stress Corrosion Cracking (ODSCC) at the tube support plate intersections.

Additionally, a brief description of procedures which are used in the field to obtain conservative estimates of the total leak rate during accidental conditions is given. The conservativity of those methods is quantified through failure probability in the numerical examples.

Two numerical examples are provided. They are based on inspection data obtained from Slovene and Belgian plants with 3 / 4 inch tubes made of Inconel 600 M.A. The numerical examples analyze the behavior of the model for both small (<3V) and large defect sizes (>10V). The discussion of results includes:

- prediction and discussion of the probability of excessive leakage;
- the conservativity of approximate summation procedures used in the field to obtain conservative estimates of the total leak rate during accidental conditions;
- some comments on the sensitivity of the probability of excessive leakage to the major uncertainties inherent to data and models used.

As a conclusion, some suggestions to improve both the efficiency of the numerical procedures and models used to estimate the leak rates through individual defects are given.

1. INTRODUCTION

The steam generator tubes in nuclear power plants with pressurized water reactors comprise most of the reactor coolant pressure boundary. The tubes made of Inconel 600 are susceptible to corrosion damage. This may have detrimental consequences on the plant safety and reliability (Shah and MacDonald, 1993). Two potential failure modes of the tubes are of special concern: (i) single or multiple tube rupture and (ii) excessive leak of the reactor coolant to the secondary side without tube rupture (Banic et al., 1996).

A sufficient safety margin against tube rupture used to be the basis for a variety of maintenance strategies developed to maintain suitable level of plant safety and reliability. Originally, the defects not deeper than 40% of the tube wall thickness were allowed (The American Society of Mechanical Engineers, 1986). Therefore, all tubes with through-wall defects were assumed to be removed from operation (e.g., plugged) or repaired (e.g., sleeved). This essentially precluded the second failure mode (excessive leaks).

Recently, the defect specific maintenance and fitness-for-service criteria for degraded steam generator tubes are being implemented on a worldwide basis (Banic et al., 1996; Shah and MacDonald, 1993). An important consequence of such approach is that through-wall defects in tubes may remain in operation. This requires the quantification of the expected leak rates and a demonstration of the available safety margin (Nuclear Regulatory Commission, 1995).

The second failure mode may represent a concern in the case where several through-wall defects remain in operation. A particular example is the application of dedicated plugging criteria to defects recognized as Outside Diameter Stress Corrosion Cracking -ODSCC - at the tube support plate intersections (Nuclear Regulatory Commission, 1993).

The state-of-the-art modeling of leak rates through individual ODSCC defects is based on regression analysis of experimentally determined leak rates and defects sizes (Nuclear Regulatory Commission, 1993; Electric Power Research Institute, 1993). This is, of course, connected with relatively large uncertainties. An estimation of the total leak rate through one steam generator is then obtained by summing all the individual leak rates. Thus, we are dealing with a problem of a sum of a random number of random variables.

For the field use, EPRI (Electric Power Research Institute, 1993) proposed a relatively simple summation procedure aiming at determining a deterministic estimate of the (e.g., 95%) upper limit of the total leak rate (short description is given in Section 2.4.1 hereafter). Some improvements to the EPRI summation method were proposed (Cuvelliez and Roussel, 1997) aiming at reducing its conservativity. An assessment of the probability of exceeding predefined maximum total leak rate rather than estimating a single limiting value was not yet attempted.

In this paper, a completely probabilistic approach is proposed, aiming at predicting the probability of excessive leaks, i.e. the *probability that the sum of individual leak rates exceeds the allowable leak rate* (given pressure difference and the distribution of defects in the steam generator). The probabilistic approach proposed here is based on the analogy with probabilistic models estimating the tube burst probability of tubes with axial through wall cracks (Cizelj et al., 1996). Similar probabilistic methods have already been successfully implemented to the assessment of structural integrity of ODSCC defects (Cizelj et al., 1996; Cizelj et al., 1997).

The probabilistic approach is further supported by the fact that the number of defects within one single steam generator can easily reach up to 2000 (Cuvelliez and Roussel, 1997). Samples of this size are relatively rare and may be considered as a good approximation of the population. On the other hand, the regression models which are used to define the individual leak rates (Nuclear Regulatory Commission, 1993) are already probabilistic in their nature. As a consequence, the probabilistic analysis can be carried out without significant additional investments in data acquisition and computational efforts. Thus, a probabilistic approach seams to be naturally suited for assessing leak rates through the steam generator tubing affected by ODSCC.

Two realistic cases differing in the size and number of defects are provided to illustrate the performance of the proposed approach. ODSCC defects in the 3/4 inch tubes of presently replaced Belgian Doel-4 and Slovenian Krško steam generators are addressed.

2. MODELING OF THE LEAK RATES

The ODSCC defects at tube support plates are usually seen as complex networks of cracks. The network is initiated at the outside surface of the tube and then slowly branches through the wall thickness. The prediction of leak rates through such networks is rather uncertain, even for defects with well defined morphologies. More detailed discussion of sources of uncertainty is given elsewhere (Electric Power Research Institute, 1993).

The extent of information which can be obtained from the state-of-the-art inspection methods may also represent a serious constraint. For ODSCC in particular, the eddy current technique is believed to have a reasonably good detection capabilities (Harris, 1996)**.** On the other hand, the information about crack morphology obtained from the inspections is currently limited to length and orientation of single cracks. The networks of cracks which are tipical for ODSCC can not yet be accurately described.

Thus, a relatively 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 (Electric Power Research Institute, 1993). This is a two step model which considers:

- probability that a defect of given size will leak;
- conditional leak rate (for defects that do leak).

EPRI leak rate model is assumed to be the state-of-the-art technology and is explained in some detail below.

It is however our intention to propose a general solution. Thus, any other leak rate models may be easily incorporated in the proposed approach when they become available.

2.1. Size of an ODSCC defect

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. As a very general reference, the signal amplitude indicates the volume of the lost material in the sense that its value depends on the crack length, crack depth and crack opening.

The models described below are based on experimentally determined leaks from the steam generator tubes. Some of the tubes analysed were pulled from operating steam generators. The defect sizes were measured with appropriate bobbin coil method prior to the examination of leak rates. It is important to note that a well defined calibration procedure should be used together with the bobbin coil eddy current technique in order to comply with the model outlined in this Section.

The defect size is generally a time dependent variable. 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 (EOC) of the cycle between two consecutive inspections. Thus, the prediction of the EOC defects sizes includes stochastic combination of BOC defect sizes and defect growth.

At present, the growth of the crack network is assumed to be described by the voltage increase between two successive inspections of the ODSCC defects. For the purpose of the present analysis, it may be predicted from the statistical analysis of results of consecutive inspections (Cizelj et al., 1995).

2.2. *Probability of leak through a defect*

The probability of leaking $P(V)$ is determined given the size of the defect V:

$$P(V) = \frac{1}{1 - \exp\left[-\left(\eta_0 + \eta_1 \log(V)\right) + z\sigma_\eta\right]} \qquad (1)$$

The parameters η_0 and η_1 were obtained by regression analysis of measured values (Electric Power Research Institute, 1993). The uncertainty of the regression is accounted for in parameters z and σ_η. The measure of uncertainty $z\,\sigma_\eta$ is a random variable which describes the scatter around the regression curve (logit function).

The physical interpretation of eq (1) is rather simple. It namely splits the population of all defects in two parts: (1) those which exhibit measurable leaks and (2) those which remain leak-tight. As an example, consider an infinite number of defects of size V. Then, a fraction of $P(V)$ is expected to leak while the rest (1-$P(V)$) will not leak. It is however beyond the scope of this paper to enter the physical reasons for leak tightness of a significant number of defects.

2.3. *Leak rate through an individual defect*

For the subpopulation of leakers, the individual leak rate Q_i can be obtained given the defect size V_i:

$$\log(Q_i) = b_0 + b_1 \log(V_i) + e \qquad (2)$$

The parameters of the regression model (b_0, b_1 and e) were obtained from measured values and are given elsewhere (Electric Power Research Institute, 1993). The uncertainty of the regression model is quantified by b_0, b_1 and e. Correlated random variables b_0 and b_1 denote the intercept and slope of the regression line. e denotes the scatter around the regression line.

The individual leak rate Q_i is therefore a random variable.

2.4. *Total leak rate through all defects in SG*

The leak rate through the entire steam generator Q_T is a sum of all leak rates through individual defects Q_i:

$$Q_T = \sum_{i=1}^{l} Q_i \qquad (3)$$

l represents the random number (eq (1)) of defects exhibiting a leak. Q_T is a random variable. Its statistical properties may be characterized by numerical methods such as Monte Carlo simulation. This usually involves substantial computational efforts. For the reliable estimation of the 99% percentile of the Q_T, the computational efforts are expected to be of the order of 1000 l simulations of eqs (1) and (2).

Some special summation procedures have been proposed to give reliable estimates of Q_T (at say, 95% probability level) with smaller computational efforts. They are summarized below.

2.4.1. EPRI 95%/95% Summation Procedure

The whole sample of defects in the observed SG is divided in classes of size 0.1 V. The number of defects in class j [j-0.1 V, j V] is denoted by m_j. A representative individual leak rate for the particular defect size is then as:

$$Q_j \big|_{95\%} \approx \left[P(V_j)\, Q(V_j) \right]_{961|1000} \tag{4}$$

The subscript 961|1000 means that 1000 values of [$P(V)$ $Q(V)$] are generated using Monte Carlo simulation (see eqs (1) and (2)) and finally sorted in ascending order. The 961st value of this ordered set is chosen as a representative value for the entire class of defects. This is assumed to yield an estimate of the 95% limit with 95% confidence (Electric Power Research Institute, 1993).

Eq (4) essentialy averages the leak rates over both leakers and non-leakers. This approach is reasonable given a large number of defects of approximately the same size or samples with $P(V)\approx 1$. On the other hand, use of eq (4) may lead to an underestimation of Q_T when applied to small samples or even individual leaks (m_j =1) with $P(V)<<1$. This is indeed the case in some practical applications as illustrated in the numerical examples.

The total leak rate through the steam generator Q_T is given by summing contributions from all n_{class} classes:

$$Q_T \big|_{95\%} \approx \sum_{j=1}^{n_{class}} m_j \left[P(V_j) Q(V_j) \right]_{961|1000} \tag{5}$$

The computational effort involved in evaluation of eq (5) is simply given by 1000 n_{class} evaluations of eqs (1) and (2) followed by 1000 n_{class} sorts to obtain the 961st value.

2.4.2. AVN Summation Procedures

The AVN summation procedures (Cuvelliez and Roussel, 1997) are aiming at extending the statistical analysis further than the determination of the 95-percentiles of individual leak rates (EPRI, eq **(5)**). In order to do that, the total leak rate is considered as a random variable and the upper limit of the total leak rate is determined from its probability distribution.

The AVN procedure #1 assumes that the defects are divided in small classes as in the EPRI summation procedure. Then, the 95% limit of the total leak rate is defined from the set of calculated total leak rates rather than from a set of class limits:

$$Q_T \big|_{95\%} \approx \left[\sum_{ji=1}^{n_{class}} P(V_j) Q(V_j) m_j \right]_{961|1000} \tag{6}$$

The estimate of 95% limit of the total leak rate is the major difference as compared to the EPRI summation procedure. The practical consequence of this difference is that eq. (6) would always yield lower or at least equal estimates of Q_T than eq. (5), which can be explained by the Chebishev inequality.

In other words, the AVN#1 procedure uses less conservative way to estimate the 95% limit of the Q_T than the EPRI procedure.

The computational effort is reduced with respect to EPRI procedure (eq **(5)**). Although there are 1000 n_{class} individual leak rate calculations, there is only one sorting of results (EPRI requires n_{class} sorts).

The AVN procedure #2 excludes grouping of defects in voltage classes (m_j =1). Each individual leak rate is considered as a random variable and the total leak rate is then the sum of these individual leak rates over the whole set of n defects:

$$Q_T \Big|_{95\%} \approx \left[\sum_{i=1}^{n} P(V_j) Q(V_j) \right]_{961|1000} \tag{7}$$

The AVN procedure #2 (eq (7)) is essentially the limit of the AVN procedure #1 (eq (6)) given $n_{class} \rightarrow n$. A consequence of interest in this analysis is again consistently lower estimate of the Q_T obtained by AVN#2 than by both AVN#1 and EPRI procedures. This particular reduction of conservativitiy is caused by using individual data points rather using the upper limits of data classes as representative defect sizes.

The computational effort required by AVN #2 procedure is larger than by EPRI and AVN#1 procedures and is proportional to 1000 n.

3. PROBABILITY OF EXCESSIVE LEAKAGE

3.1. Modeling Considerations

Let us define the failure of a steam generator by the event "*total leak rate Q_T exceeds allowable leak rate Q_{MAX}*". Recall that the total leak rate Q_T is simply a sum of all individual leak rates Q_i (eq **(3)**).The failure probability P_f is then given by:

$$P_f = P\left(Q_T \geq Q_{\text{MAX}}\right) = P\left(\sum_{i=1}^{n} Q_i \geq Q_{\text{MAX}} \right) \tag{8}$$

Q_{MAX} may be any value, which is considered acceptable. In fact, the intention of the summation procedures outlined above (EPRI - eq **(5)**, AVN #1 - eq **(6)** and AVN #2 - eq **(7)**) was to estimate the 95th percentile of Q_T which satisfies the following condition:

$$P_f = P\left(\sum_{i=1}^{n} Q_i \geq Q_T \right) \leq 5\% \tag{9}$$

The individual leak rate through a single defect has already been described as a random variable, denoted by Q_i (eq (2)) with probability density function $f_i(Q_i)$. For example, the probability density function $f_i(Q_i)$ can be estimated from the distributions of defect sizes using eqs (1), (2) and Monte Carlo simulation.

Some additional useful and reasonable assumptions were used :

- all individual leak rates are members of the same population. This assumption requires for example that the same degradation mechanism is responsible for the development of the defects.
- individual leak rates are statistically independent. For example, if a tube is affected at several locations, then the leak rate through individual defects should be small compared to the flow rate through the tube.

Using the well-known procedures from statistical reliability theory (Madsen et al., 1986), the failure probability P_f can be calculated by the integration of the probability content of the failure space (Q_T>Q_{MAX}):

$$P_f = \int_{g(Q_1,Q_2,...,Q_n)\leq 0} \prod_{i=1}^{n} \left(f(Q_i)\ dQ_i \right) \tag{10}$$

$g(Q_1, Q_2, \ldots, Q_n)$ represents the failure function, which is by definition positive in the safe space and negative in the failure space ($Q_T > Q_{\mathrm{MAX}}$). Therefore, it is given here as:

$$g(Q_1, Q_2, \ldots, Q_n) = Q_{\mathrm{MAX}} - \sum_{i=1}^{n} Q_i \tag{11}$$

For the purpose of this analysis, the predefined and fixed value of Q_{MAX} was assumed. This is however not a limitation of the method. Appropriate probability density of Q_{MAX} may be obtained for example from meteorological conditions around the plant.

3.2. Numerical simulation

For the purpose of this analysis, eq (10) was solved using direct Monte Carlo simulation. Implementation of more computationally efficient numerical methods is currently underway.

In fact, the simulations used to estimate the probability of excessive leak rates are very similar to those used in summation procedures (Sections 2.4.1 and 2.4.2). The major differences however are:

- The probabilistic approach is seeking the probability of exceeding certain predefined leak rate rather than some limiting value of leak rate. In general, this would require a different computational approach. However, in the particular example addressed in this paper, this is more a different interpretation of the data and results.
- probabilistic simulations explicitly split the populations of leakers and non-leakers, which is not the case with summation procedures outlined in Sections 2.4.1 and 2.4.2.

We should note here that only the leakers (recall eq (1)) need to be considered in a Monte Carlo simulation. Thus, failure probability in the order of 10^{-2} needs about 1000 simulations of a rather small number of leaks. Based on results of simulations already performed, it is expected that only about 18 % of all detected defects in Doel-4 case (1% in the Krško case) will leak during hypothetical accidental conditions.

Extending the proposed probabilistic methodology to any other model which relates the size of the individual defect with the leak rate through this defect is straightforward.

4. NUMERICAL EXAMPLES

Two numerical examples were chosen to demonstrate the applicability of the probabilistic approach. They are based on the inspection data obtained from Slovenian Krško and Belgian Doel-4 steam generator tubes (3/4 inch tubes made of Inconel-600 MA).

4.1. Krško

4.1.1. Data

The distribution of defect sizes at the BOC is given in Figure 1. In the calculations, empirical and fitted lognormal distributions of defect sizes at BOC were used. The differences between failure probabilities obtained with different defect size distributions were comparable to the statistical noise of the Monte Carlo simulation. Nevertheless, the empirical distribution

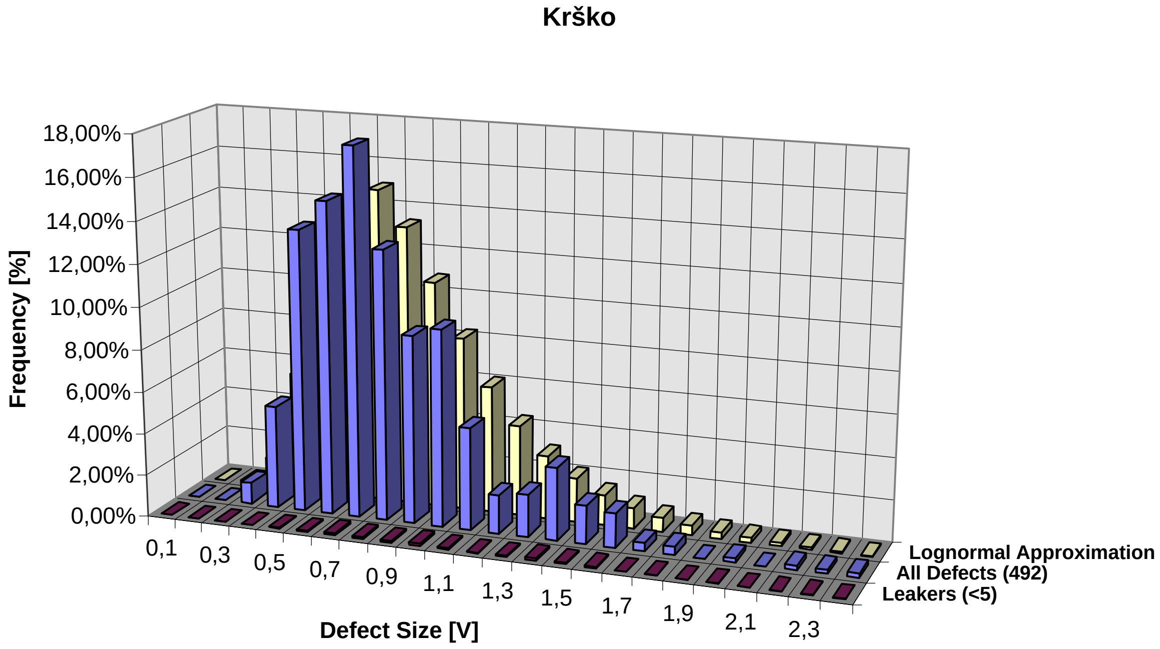

Figure 1 Distribution of BOC defect sizes-Krško plant

consistently lead to higher values of the probability of exceeding the allowable leak rate and was therefore selected as representative input data model for subsequent analysis. The total number of defects was 492.

Allowances for defect growth (with 52,6 % of defects exhibiting nonnegative growth) and measurement errors were also provided and yielded the defect size at EOC. The Krško power plant specific values were used (detailed description is given in (Cizelj et al., 1995)).

The statistical stability of the total leak rate estimate given by (eq (5)) was analyzed using Monte Carlo simulation (Table 1) and was considered reasonable. A big scatter is however observed in maxima of sums. This scatter is mainly caused by the large influence of the uncertain regression parameters in the leak rate model (eqs (1) and (2)). The absolute maximum total leak rate (lower right cell of Table 1**)** always exceeded the 95% upper limit predicted by the EPRI summation procedure (eq (5)) by a few orders of magnitude.

Table 1 Selected statistical parameters of total leak rates obtained by EPRI summation procedure (eq **(5)**) - Krško steam generator

Total leak rate based on eq (5)	**Total leak rates from 100 numerical experiments** [l/h]				
	Mean	**Median**	**Std.Dev.**	**Minimum**	**Maximum**
min (1|1000)	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$
median (501|1000)	0.35	0.35	0.01	0.32	0.37
95% (961|1000)	**23**.83	**23**.90	**1**.17	**21**.44	**26**.60
max (1000|1000)	**1,298**.24	**1,148**.14	**652**.24	**507**.68	**4,465**.07

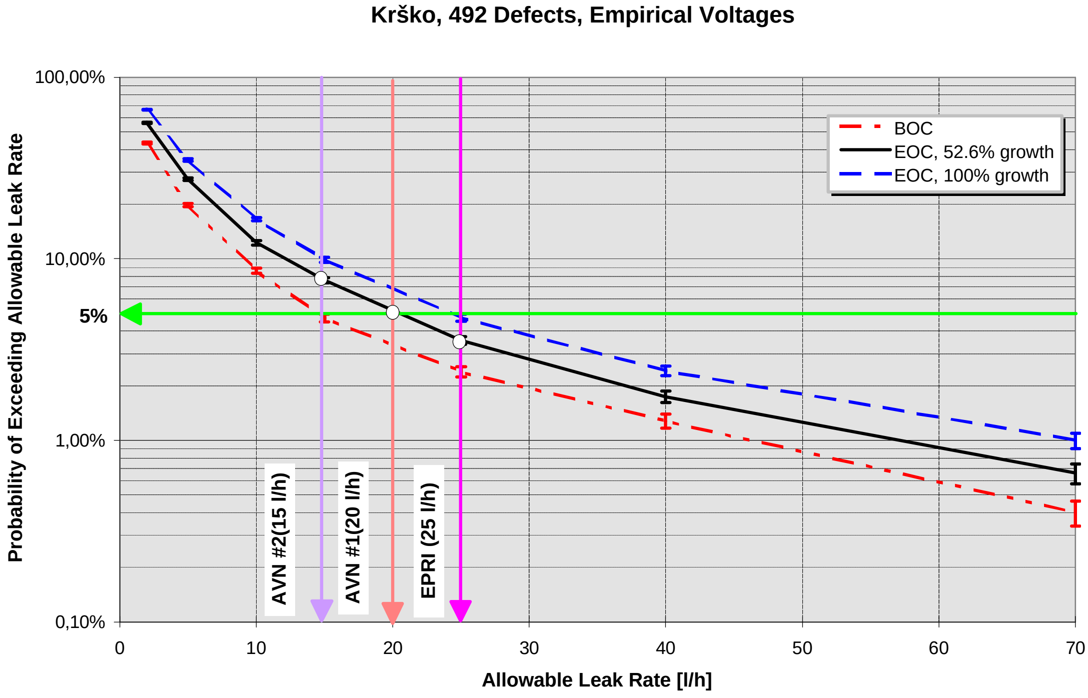

Figure 2 Probability of Exceeding Allowable Leak Rates - Krško case

Based on results in Table 1, the value of 25 l/h was chosen to be representative for EPRI summation method (eq (5)) for comparison with probabilistic calculations. Representative values for both AVN summation procedures were chosen in an analogous way to be: 20 l/h for AVN #1 (eq (6)) and 15 l/h for AVN #2 (eq (7)).

4.1.2. Results

Figure 2 depicts probability of excessive leakage as a function of allowable total leak rate. Three different curves are given to illustrate the effect of defect progression: BOC (no defect progression), EOC with 52,6% of defects exhibiting growth (which is consistent with field observations in Krško) and EOC with 100% of defects exhibiting growth. The Krško specific growth rate is used in the analysis ((Cizelj et al., 1995)) and is shown to contribute less than one order of magnitude.

The statistical standard error of Monte Carlo simulations is represented by error bars in Figure 2. It is in the order of 0.1% and is considered to have negligible influence on the quality of results presented here.

Simulations revealed that only about 5 (1%) out of 492 potential leakers would really leak given assumed model (recall eqs (1) and (2)) and postulated hypothetical accidental conditions - steam line break. A distribution of leakers as obtained from the Monte Carlo simulations (eq (1)) is depicted in Figure 1. Although this is not clearly seen, larger defects tend to leak more frequently which is in accordance with eq (1).

The results of the three summation procedures are visualized by vertical lines at appropriate values of total leak rates (Figure 2). Thus, for EPRI summation procedure, the failure probability is defined by the intersection of curves denoted by *EOC, 52,6% growth* and *EPRI (25 l/h)*. Its value is about 3.5%. The AVN procedures #1 and #2 tend to 5 and 11%, respectively.

The main conclusion is that the EPRI summation procedure yields about the 95th percentile of the total leak rate value. Thus, its should be treated as realistic and not conservative, as anticipated in (Electric Power Research Institute, 1993). Both AVN procedures give underestimated 95th percentiles of total leak rate, which is consistent with discussion in Sections 2.4.1 and 2.4.2.

The failure probability is decreasing relatively slowly with increasing allowable total leak rate. This again indicates considerable scatter in the leak rate model (Sections 2.2 and 2.3).

4.2. Doel-4

4.2.1. Data

The distribution of defect sizes from Belgian Doel-4 plant is given Figure 3. The number of defects detected is 1960 (significantly more than in Krško). Also, the defect sizes are rather large and poses a maximum of 18.9 V. It should be however noted that Belgian inspection standards differ from EPRI standards. Thus, appropriate correlation between "*Belgian*" and "*EPRI*" bobbin coil signal amplitudes was implemented to generate input data for this paper. This may be an additional source of uncertainties which was not further investigated in this paper. The presence of defects with large voltage is due to the use of a specific plugging criterion allowing defects of about 10V to remain in service. The distribution of defects shown in Figure 3 is the raw distribution as given by bobbin coil inspection. Also, a fit of lognormal distribution to the empirical distribution is depicted in Figure 3. No defect progression was considered in the calculations.

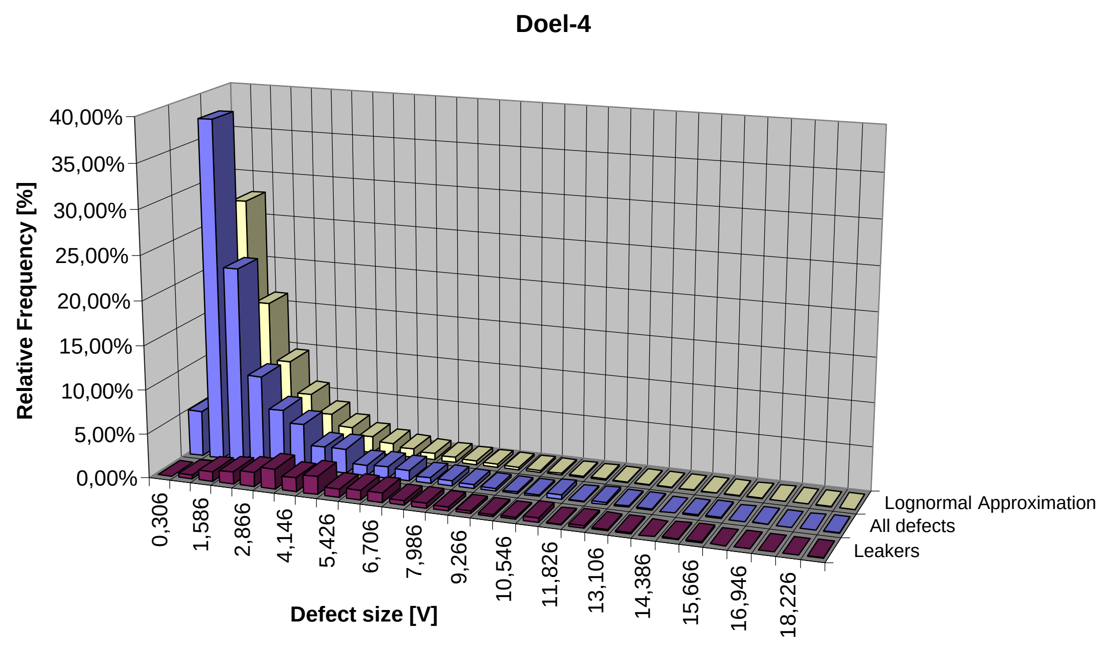

Figure 3 Distribution of BOC defect sizes - Doel-4 plant

Table 2 Selected statistical parameters of total leak rates obtained by EPRI summation procedure (eq. (5) - Doel-4 steam generator

Total leak rate based on eq (5):	**Total leak rates from 100 numerical experiments [1000 l/h]**				
	Mean	**Median**	**Std.Dev.**	**Minimum**	**Maximum**
min (1|1000)	3.1 10^{-3}	3.1 10^{-3}	0.3 10^{-3}	2.4 10^{-3}	3.9 10^{-3}
median (501|1000)	**2.**128	**2.**125	**0.**027	**2.**074	**2.**206
95% (961|1000)	**82.**044	**82.**082	**1.**938	**77.**141	**87.**184
max (1000|1000)	**3,434.**731	**3,039.**900	**1,959.**141	**2,142.**990	**19,449.**900

In addition, Figure 3 gives the sample distribution of defects which exhibit leak (eq (1)). The simulations revealed that no more than 330 (17%) would leak in this particular case. It is clearly shown in Figure 3 that defects with larger voltages tend to leak more frequently which is in accordance with eq (1).

Table 2 was generated to illustrate the numerical stability of the EPRI summation procedure (eq. (5)) for the Doel-4 data. Again, a rather stable estimate of about 80,000 l/h was obtained in 100 numerical experiments. It is however indicative that it is possible to obtain leak rates up to about 20 10^6 l/h.

A value of 80,000 l/h was chosen as representative value of EPRI summation procedure for comparison with probabilistic calculations. Similar considerations lead to the representative values of 50,000 and 45,000 l/h for AVN#1 and AVN#2 summation procedures, respectively.

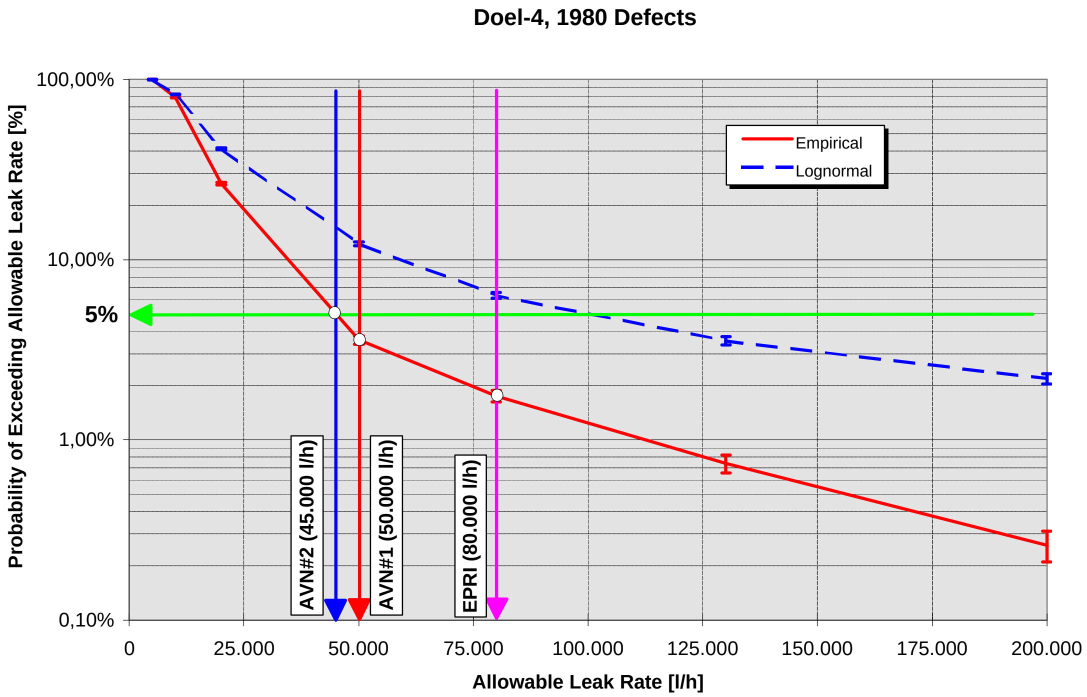

Figure 4 Probability of Exceeding Allowable Leak Rates - Krško case

4.2.2. Results

The probability of excessive leakage is depicted in Figure 4 as a function of allowable total leak rate. Results obtained by two different input distributions of defect sizes are shown. The histogram of all defects shown in Figure 3 served as the empirical distribution. On the other hand, the lognormal distribution was fitted to the raw inspection data. The rather large difference between both curves is caused by two facts:

- lognormal distribution explicitly allows for rare events. In other words, it allows for occurrences of voltage values which exceed the measured maximum of 18.9 V.
- the probability of leakage (eq (1)) is approaching 1 as the defect size is approaching 20 V. Thus, the uncertainties in the leak rate model are not dominant in this region which increases the sensitivity of the input data as compared to the Krško case.

The statistical error of Monte Carlo simulations is represented by error bars in Figure 4. It is in the order of 0.1% and is considered to have negligible influence on the quality of results presented here.

Again, the results of all three summation procedures are comparatively depicted in Figure 4**.** All of them rely on empirical distributions of the defect sizes, which suggests the comparison with probabilities of excessive leakage obtained from empirical distribution. The results of two summation procedures appear to be slightly conservative (EPRI 1.8%, AVN#1 3.5%) while AVN#2 tends to the expected 5%. On the other hand, if the lognormal distribution is used, EPRI procedure seems to be realistic (leading to failure probability of 6%) while the AVN procedures lead to failure probabilities exceeding 10% (AVN#2 11%, AVN#2 16%).

4.3. Summation methods vs. Probabilistic Approach

The main differences between the probabilistic approach and summation methods have already been summarized in Sections 2.4 and 3.2. For convenience, they are repeated here together with their impact on the simulation results:

- Probabilistic approach explicitly splits the population of defects on leakers and non-leakers (eq. (1)), while summation methods average the leak rates over both leakers and non-leakers (eq. (4)). The error of eq. (4) is rather serious underestimate of total leak rates (at 95% probability level) for small defects where the probability of leak (eq. (1)) is relatively small (e.g., Krško case). However, it levels out for relatively large defects with probabilities of leak close to 1 (Doel-4 case).
- The differences in summation methods (Section 2.4) are different estimates of the total leak rate at 95% probability level (EPRI vs AVN #1 and AVN #2) and classification of defect sizes (EPRI and AVN #1 vs AVN #2). All conservativities accumulated in EPRI summation method seem to be appropriate to compensate the underestimates caused by averaging of leaks over both leakers and non-leakers (eq. (1)) for small defect sizes (Krško Case). On the other hand, the least conservative summation method AVN #2 seems to perform well for relatively large defects with probabilities of leak close to 1 (Doel-4 case).

Based on above considerations, the use of the probabilistic approcah is recommended because it is not sensitive on:

- the defect size and
- particular assumptions used estimate the total leak rates at 95% probability level.

4.4. Sensitivity of The Results Obtained

The qualitative discussion on the sensitivity is mainly based on the significant difference in the number and size of defects analyzed in both numerical examples. In addition, some interesting observations were made during the analysis of misplaced simulations.

For rather low defect sizes (Krško case), the failure probability is most sensitive to the uncertainties in the leak rate model (eqs (1) and (2)). Those uncertainties are strong enough to generate more extremely high leak rates than large defects would do. Consequently, the probabilities of exceeding the allowable leak rate are not particularly sensitive to the different representations of defect size distributions. This leads to the conclusion that the probability of failure is mostly dominated by uncertain and correlated parameters of regression line (eq. (2)) which is followed by the probability of leak (eq (1)). Beneficial consequences of further experimental work aiming at reducing the uncertainties of the regression curves are obvious.

In the case of large defect sizes (Doel-4 case), the influence of the probability of leak is vanishing as its value approaches 1. The uncertainty in the representation of input data becomes as important as the uncertainty of the regression model.

In both cases, there is a noticeable influence of allowable total leak rate (see Figure 2 and Figure 4). The effect of the number of defects on the other hand is shown in Table 3. It is interesting to note that a factor of two change in the number of defects triggers a factor of about two and half in the corresponding failure probabilities. This may be attributed to rather small number of active and dominant leakers (from 1% in case of Krško to 17% in case of Doel-4).

Another important observation in case of Krško is that the maximum individual leak rate tends to dominate the entire sum of leak rates within the steam generator (about 5 leak rates together). Similar effect can also be observed in the Doel-4 case especially when relatively large total leak rates are observed. This leads to the implementation of extreme value statistics, which is planned in future.

5. CONCLUSIONS

A probabilistic approach aiming at prediction of the probability that a total leak rate through degraded steam generator tubes exceeds the allowable value is proposed. The approach is compatible with the current probabilistic fracture mechanics practice.

Existing summation procedures which were developed to determine conservative predictions of total leak rates were tested against the probabilistic approach. The probabilistic approach gives a measure of their conservativity.

In particular, two numerical examples based on data from Slovenian Krško and Belgian Doel-4 power plants were studied. The defect sizes covered in these examples are

Table 3 Sensitivity to the number of defects

	Krško		**Doel-4**	
Fraction of defects considered	**# of defects**	**Probability of exceeding 25 l/h**	**# of defects**	**Probability of exceeding 80.000 l/h**
50% of defects	246	1.48%	980	0.44%
100% of defects	492	3.56%	1980	1.75%
200% of defects	984	9.01%	3920	4.77%

representative for the majority of operating PWR steam generators. It was shown that the existing summation procedures are conservative for large defect sizes (>10V), but not necessarily for small defect sizes (<3 V).

It is recommended to introduce probabilistic methods in the field use. This is because probabilistic methods give better insight in the problem, which includes a large number of uncertainties. On the other hand, the computational effort involved is comparable to the summation procedures.

The probability of excessive leakage is most sensitive to the probability of leakage at lower defect sizes (Krško case) and global uncertainties inherent to the applied regression models at any defect size.

The main topics suggested for the future work are implementation of extreme value statistics in order to reduce the computational effort and further experimental work aimed at reducing the uncertainties of the regression models.

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7. REFERENCES

The American Society of Mechanical Engineers, ASME Boiler and Pressure Vessel Code, Section XI, 1986.

M. J. Banic, J. Bros, L. Cizelj, P. Cornet et al., Assessment and Management of Ageing of Major Nuclear Power Plant Components Important to Safety: Steam Generator, IAEA Safety Series, International Atomic Energy Agency, Vienna, Austria, 1996, in printing

L. Cizelj, U. Aleksic, T. Dvoršek, O. Gortnar et al., Safety Analysis of Krško NPP Steam Generator Tubes Damaged by Outside Diameter Stress Corrosion Cracking at Tube Support Plates. Institut "Jožef Stefan", Ljubljana, Slovenia, 1995, IJS-DP-7175, Rev. 0, Proprietary.

L. Cizelj, T. Dvoršek and B. Mavko, Efficiency of Defect Specific Maintenance Approaches in SG Tubes, Proceedings of 15th EPRI Steam Generator NDE Workshop, Long Beach, Ca., USA, 29 July 96-31 July 96, Electric Power Research Institute, Palo Alto, Ca., USA, 1996, EPRI TR-107161, pp. 9.1-9.10.

L. Cizelj, B. Mavko and T. Dvoršek, Defect Specific Maintenance of SG Tubes-How Safe is It, Proceedings of the CNRA/CSNI Workshop on Steam Generator Tube Integrity in Nuclear Power Plants, Oak Brook, Il., USA, 30 Oct. 95-2 Nov. 95, Nuclear Regulatory Commission, Rockville, Md., USA, 1997, NUREG/CP-0154; ANL-96/14; NEA/CNRA/R (96) 1, 525-532.

L. Cizelj, B. Mavko and P. Vencelj, Reliability of Steam Generator Tubes With Axial Cracks, Journal of Pressure Vessel Technology, 118 (1996) 441-446.

C. Cuvelliez and G. Roussel, Assessment of the Leak Tightness Integrity of the Steam Generator Tubes Affected by ODSCC at the Tube Support Plates, Proceedings of the CNRA/CSNI Workshop on Steam Generator Tube Integrity in Nuclear Power Plants, Oak Brook, Il., USA, 30 Oct. 95-2 Nov. 95, Nuclear Regulatory

Commission, Rockville, Md., USA, 1997, NUREG/CP-0154; ANL-96/14; NEA/CNRA/R (96) 1, 385-398.

Electric Power Research Institute, Outside Diameter Stress Corrosion Cracking (ODSCC) of Steam Generator Tubing at Tube Support Plates-A Database for Alternate Repair Limits, Vol. 2: 3/4 Inch Diameter Tubing. Electric Power Research Institute, Palo Alto, Ca., USA, 1993, EPRI TR-100407, Rev. 1.

Electric Power Research Institute, Steam Generator Degradation Specific Management (Draft). Electric Power Research Institute, Palo Alto, Ca., USA, 1993, EPRI TR-103017.

D. D. Harris, Capabilities of Eddy Current Data Analysts to Detect and Characterize Defects in Steam Generator Tubes, Proceedings of 15th EPRI Steam Generator NDE Workshop, Long Beach, Ca., USA, 29 July 96-31 July 96, Electric Power Research Institute, 1996, EPRI TR-107161, pp. 8.1-8.8.

H. O. Madsen, S. Krenk and N. C. Lind, Methods of Structural Safety, Prentice Hall, 1986

Nuclear Regulatory Commission, Voltage-Based Interim Plugging Criteria for Steam Generator Tubes. U.S. Nuclear Regulatory Commission, Rockville, Md., USA, 1993, NUREG-1477.

Nuclear Regulatory Commission, Nuclear Regulatory Commission, Voltage-Based Repair Criteria for Westinghouse Steam Generator Tubes Affected by Outside Diameter Stress Corrosion Cracking. U.S. Nuclear Regulatory Commission, Rockville, Md., USA, 1995, NRC Generic Letter 95-05.

V. N. Shah and P. E. MacDonald, Aging and Life Extension of Major Light Water Reactor Components, Elsevier, 1993