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Probabilistic evaluation of leak rates through multiple defects – the case of nuclear steam generators

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ABSTRACT

A probabilistic approach aimed at prediction of the probability of excessive leakage through flaws in tubes is proposed in the paper. The excessive leakage is assumed to occur when *the sum of all individual leak rates through degraded tubes exceeds the predefined acceptable value.* Additionally, a brief description of some estimators used in the field to obtain conservative estimates of the 95th percentile (e.g., upper limit) of the total leak rate is given.

The conservatism of those estimators is quantified through failure probability in the two numerical examples.

The leak rates through the individual flaws were evaluated using models developed by EPRI for assessment of Outside Diameter Stress Corrosion Cracks (ODSCC) in tubes of steam generators in nuclear power plants assuming postulated hypothetical accidental conditions. The distributions of flaw sizes are based on inspection data obtained from Slovene and Belgian plants with 3/4 inch tubes made of Alloy 600 Mill Annealed. The numerical examples analyze the behavior of the model for both small and large flaw sizes. The results include:

- prediction and discussion of the probability of excessive leakage;
- the conservatism of approximate estimators;
- 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 estimators and models used to estimate the leak rates through individual defects are given.

KEYWORDS

Leak rate, through-wall flaw, probabilistic model

NOMENCLATURE

BOC	Beginning of cycle
EOC	End of Cycle
LBB	Leak before Break
ODSCC	Outside diameter stress corrosion cracking
SG	Steam generator
b_0, b_1	Parameters of the regression model
$f_i(\bullet)$	Probability density function of variable $\bullet$
$g(\bullet)$	Failure function
n	Number of defect
l	Random umber of leaking defects $l \le n$
Δp_i	Pressure difference
P_i	Probability of leak
$P(\bullet)$	Probability of event $\bullet$
$Q_i, Q(\bullet)$	Individual leak rate (indices may vary)
Q_{MAX}	Acceptable leak rate
Q_T	Total leak rate
ΔT_i	Temperature difference
V_i	Defect characteristics (e.g., size)
z	Parameter of the regression model
ε	Parameter of the regression model
η_0 , η_1	Parameters of the regression model
σ_η	Parameters of the regression model

1. INTRODUCTION

Through-wall flaws in ductile pressurized components (e.g., pressure vessels, piping etc.) may at appropriate conditions lead to detectable leaks long before the structural integrity of the component is challenged (e.g., Roos 1999). Through-wall leaks should in most cases be treated as a reliable call for a corrective action (repair or replacement). However, in some specific cases continued operation with controlled leaks within the safety, legal, economical or other constraints might be acceptable.

The Alloy 600 mill annealed (MA) steam generator tubes in pressurized water reactors may serve as a good example of allowable continued operation with limited leakage. Steam generator tubes represent a major fraction of the reactor coolant pressure boundary surface area and are susceptible to corrosion damage, which may have detrimental consequences to the plant safety and reliability (Shah and MacDonald 1993). Two potential failure modes of the tubes have received special attention: (i) single or multiple tube rupture and (ii) excessive primary-to-secondary leakage 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, which were developed to maintain a suitable level of plant safety and reliability (see (Banic et al. 1996) and (Shah and MacDonald 1993) for more details). This topic will not be pursued further here. It will merely be noted that some of the maintenance strategies justified sufficient margin also for the tubes with through-wall flaws. Consequently, several through-wall flaws may remain in operation and potentially contribute to the total primary-to-secondary leak rate. Cases with up to 2000 flaws within a single steam generator (typically, in the order of 5000 tubes of about 20 mm in diameter and 1 mm wall thickness) have been reported to operate successfully (Cuvelliez and Roussel 1997). Quantification of the expected leak rate and demonstration of the available safety margin against the associated radiological consequences was required in such cases (Nuclear Regulatory Commission 1995).

The quantification of the total leak rate through a single component (for example steam generator) essentially requires summation of leak rates through individual through-wall flaws. The information about the number and other relevant characteristics of the individual flaws is in practical situations obtained from non-destructive examinations with significant data scatter inherent to the method. In addition, the empirical correlations and the uncertainties attached to the leak rate model are also significant sources of variability in the calculated leak rate even through well-defined individual defects. Our goal is therefore to estimate a sum of a random number of random variables.

Appropriate probabilistic method has already been proposed by the authors (Cizelj et al, 1998), aiming at predicting the probability of excessive leaks in SG tubes, i.e. the *probability that the sum of individual leak rates exceeds the allowable leak rate* (given operating conditions and the distribution of defects in the steam generator). It was based on the analogy with probabilistic models estimating the tube burst probability of tubes (Cizelj, Dvoršek, and Mavko 1996), (Cizelj, Mavko, and Vencelj 1996). In this paper, the probabilistic approach is revisited and generalized towards other potential applications. Some estimators of the 95th percentile of the total leak rate are also formulated and their properties discussed.

Two realistic examples differing in the size and number of defects are provided to illustrate the performance of the proposed probabilistic approach and estimators of the 95th percentile. Input data represents the outside diameter stress corrosion cracks in the 3/4 inch Alloy 600 MA tubes of already replaced Belgian Doel-4 and Slovenian Krško steam generators are addressed.

2. PROBABILITY OF EXCESSIVE LEAKAGE

2.1. *Main assumptions*

Throughout this section we will assume the existence of a two-state model, which for each defect characterized by V_i estimates conditional individual leak rate Q_i:

$$Q_i = \begin{cases} Q(V_i, \Delta p_i, \Delta T_i, \ldots) & \text{if} \quad P_i > 0 \\ 0 & \text{if} \quad P_i = 0 \end{cases}, \qquad (1)$$

and probability P_i that this particular defect will leak ($Q_i > 0$):

$$P_i = P(V_i, \Delta p_i, \Delta T_i, \ldots) \qquad (2)$$

The essential parameters in eqs. (1) and (2) include, but may not be limited to the defect characteristics denoted by V_i (e.g., defect size, roughness, complexity of the leak path etc.) and variables describing the fluid conditions such as pressure difference Δp_i and temperature difference ΔT_i. Their respective stochastic properties are described with the probability density functions $f_i(V_i)$, $f_i(\Delta p_i)$ and $f_i(\Delta T_i)$. With eqs. (1) and (2) it is now possible to derive the probability density function of the conditional individual leak rate $f_i(Q_i)$.

It is beyond the scope of this paper to discuss further details on the leak rate modeling. The reader is referred to other papers in this issue and to Section 3 for the particular empirical models employed in Section 5.

The total leak rate Q_T through n defects is then obtained as sum of individual contributions from a random number of l leakers and $n-l$ leak tight defects:

$$Q_T = \sum_{i=1}^{n} Q_i = \sum_{i=1}^{l} Q_i\Big|_{P_i > 0} + \sum_{j=1}^{n-l} Q_j\Big|_{P_j = 0}$$

$$\text{where } Q_j\Big|_{P_j = 0} = 0 \qquad (3)$$

The discrimination between leaking and leak tight defects is made according to the rule in eq. (2). Some additional useful and reasonable assumptions were used:

- all individual leak rates Q_i are members of the same population. This assumption requires for example that the same degradation mechanism is responsible for the development of all defects considered.

- individual leak rates are statistically independent. This is fulfilled in fluid systems where any change in the energy stored in the system caused by the total leak rate is negligible as compared to the same system without leaks. The pressure, temperature and mass flow rates in such system shall therefore not depend on the total leak rate.

2.2. *Probabilistic model*

It is reasonable to expect that continued operation with controlled leak rates be limited by an acceptable leak rate Q_{MAX}. Its value may be governed by safety, legal, economical or other constraints and may be either constant or a stochastic variable.

It is then useful to define that the event "failure" takes place whenever "*the total leak rate Q_T exceeds the allowable leak rate Q_{MAX}*". Recall that the total leak rate Q_T is simply the sum of all individual leak rates Q_i (eq (3)). The failure probability P_f is then given by:

$$P_f = P(Q_T \geq Q_{\mathrm{MAX}}) = P\left(\sum_{i=1}^{n} Q_i \geq Q_{\mathrm{MAX}}\right) \tag{4}$$

The individual leak rate through a single defect has already been described as a random variable, denoted by Q_i (eq.(1)) with probability density function $f_i(Q_i)$.

Using the well-known estimators from statistical reliability theory (Madsen, Krenk, and Lind 1986), the failure probability P_f can be calculated by the integration of the probability content of the failure space ($Q_T > Q_{MAX}$):

$$P_f \;=\; \int\limits_{g(Q_1,Q_2,\ldots,Q_n)\leq 0} \prod_{i=1}^{n} \left(f(Q_i)\ dQ_i \right) \tag{5}$$

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

$$g(Q_1, Q_2, \ldots, Q_n) = Q_{\mathrm{MAX}} - \sum_{i=1}^{n} Q_i \tag{6}$$

2.3. *Numerical solution*

For the purpose of this paper, eq (5) was solved using direct Monte Carlo simulation. Only the leakers (recall eq (2)) need to be considered in the simulation. A reasonably reliable estimate of failure probability in the order of 10^{-2} required about 1000 simulations.

3. MODELING OF THE LEAK RATES

The example pursued in this paper is application of repair criteria dedicated to defects recognized as Outside Diameter Stress Corrosion Cracking -ODSCC - at the tube support plate intersections (Nuclear Regulatory Commission 1993), which were detected in the Alloy 600 MA steam generator tubes in nuclear power plants with pressurized water reactors worldwide (Shah and MacDonald 1993).

The state-of-the-art modeling of leak rates through individual ODSCC defects is based on regression analysis of experimentally determined leak rates as a function of flaw size (Nuclear Regulatory Commission 1993) (Electric Power Research Institute 1993) at selected thermodynamical conditions representing loading during a hypothetical design basis accident (e.g., Δp_i and ΔT_i are assumed constant and identical for all defects!). This is, of course, connected with relatively large uncertainties.

This section briefly summarizes the main characteristics of the defects followed by the discussion on the defect size, probability of leak given the defect size and conditional leak rates through individual defects.

3.1. ODSCC defects in SG tubes

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 in the chemically aggressive crevice between the tube and tube support plate 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 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 typical for ODSCC, cannot 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) that is further detailed in Sections 3.3 and 3.4.

3.2. Size of an ODSCC defect

The field inspections of ODSCC defects are performed by bobbin coil probes (eddy current technique). The result of the inspection, which is assumed to indicate 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 leak rate data from the steam generator tubes. Some of the tubes analysed were pulled from operating steam generators, other defects were grown in the laboratory conditions. The defect sizes were measured with appropriate bobbin coil method prior to the measurement of leak rates. It is important to note that a well-defined calibration estimator should be used together with the bobbin coil eddy current technique in order to comply with the model outlined in this Section.

In operation, 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).

3.3. *Probability of leak through a defect*

The probability of leaking $P_i = P(V_i)$ is determined given the size of the defect V_i:

$$P_i = P(V_i) = \frac{1}{1-\exp\left[-\left(\eta_0 + \eta_1 \log(V_i)\right) + z\sigma_\eta\right]} \qquad (7)$$

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 (7) is rather simple. It namely splits the population of all defects in two parts: (1) those that exhibit measurable leaks and (2) those, which remain leak-tight. As an example, consider an infinite number of defects of size V_i. Then, a fraction of $P(V_i)$ is expected to leak while the rest $1-P(V_i)$ 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.

3.4. *Leak rate through an individual defect*

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

$$\log(Q_i) = b_0 + b_1 \log(V_i) + \varepsilon \qquad (8)$$

The parameters of the regression model (b_0, b_1 and ε) 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 ε. Correlated random variables b_0 and b_1 denote the intercept and slope of the regression line. ε denotes the scatter around the regression line.

4. Estimators of the total leak rate (95th percentile)

For the field use, EPRI (Electric Power Research Institute 1993) proposed a relatively simple estimator aiming at a deterministic estimate of the 95th percentile (e.g., upper limit) of the total leak rate with the property:

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

The EPRI estimator and two additional estimators proposed by (Cuvelliez and Roussel 1997) are described below. Further discussion of their properties is given in the section of numerical examples.

4.1. *EPRI 95%/95% Estimator*

The whole sample of defects detected and sized by the non-destructive examination is divided in classes of size 0.1 V. The number of defects in class k [k-0.1 V, k V] is denoted by m_k. A representative individual leak rate for the particular defect size is then defined as:

$$Q_k \Big|_{95\%} \approx \lfloor P(V_k)\, Q\ (V_k) \rfloor_{961|1000} \tag{10}$$

The subscript 961|1000 means that 1000 values of $\lfloor P\ (V_k)\, Q\ (V_k) \rfloor$ are generated using Monte Carlo simulation (see eqs (7) and (8)) 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 (10) essentially 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 $P(V_k) \approx 1$. On the other hand, use of eq (10) may lead to an underestimation of Q_T when applied to small samples or even individual leaks (m_k =1) with $P(V_k) << 1$. 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:

$$Q_T \Big|_{95\%} \approx \sum_{j=1}^{n_{class}} m_j \left[P(V_j) Q(V_j)\right]_{961|1000} \tag{11}$$

The computational effort involved in evaluation of eq (11) is simply given by 1000 n_{class} evaluations of eqs (7) and (8) followed by 1000 n_{class} sorts to obtain the 961st value.

4.2. *AVN Estimators*

The AVN estimators (Cuvelliez and Roussel 1997) are aiming at extending the statistical analysis further than the determination of the 95th percentiles of individual leak rates (EPRI, eq (11)). 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.

4.2.1. AVN estimator #1

Assume that the defects are divided in small classes as in the EPRI estimator (eq. (11)). 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:

$$Q_T \Big|_{95\%} \approx \left[\sum_{k=1}^{n_{class}} P(V_k) Q\ (V_k) m_k \right]_{961|1000} \qquad (12)$$

The estimate of 95% limit of the total leak rate is the major difference as compared to the EPRI estimator. The practical consequence of this difference is that eq. (12) would always yield lower or at least equal estimates of Q_T than eq. (11), which can be explained by the Chebishev inequality. In other words, the AVN#1 estimator uses less conservative way to estimate the 95% limit of the Q_T than the EPRI estimator.

The computational effort is reduced with respect to EPRI estimator (eq (11)). Although there are 1000 n_{class} individual leak rate calculations, there is only one sorting of results (EPRI requires n_{class} sorts).

4.2.2. The AVN estimator #2

This estimator 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:

$$Q_T \Big|_{95\%} \approx \left[\sum_{i=1}^{n} P(V_j) Q(V_j) \right]_{961|1000} \qquad (13)$$

The AVN estimator #2 (eq (13)) is essentially the limit of the AVN estimator #1 (eq (12)) given $n_{class} \to n$. 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 estimators. Using individual data points rather using the upper limits of data classes as representative defect sizes causes this particular reduction of conservatism.

The computational effort required by the AVN #2 estimator is larger than by EPRI and AVN#1 estimators and is proportional to 1000 n .

5. NUMERICAL EXAMPLES

Two numerical examples were chosen to illustrate the performance of the proposed probabilistic approach and estimators of the 95th percentile of the total leak rate. They are based on the inspection data obtained from Slovenian Krško and Belgian Doel-4 steam generator tubes (3/4 inch tubes made of Alloy-600 Mill Annealed).

5.1. Krško

5.1.1. 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 consistently leads 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 detected 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 (11)) 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 (7) and (8)). The absolute maximum total leak rate (lower right cell of Table 1) always exceeded the 95% upper limit predicted by the EPRI estimator (eq (11)) by a few orders of magnitude.

Based on results in Table 1, the value of 25 l/h was chosen to be representative for the EPRI estimator (eq (11)) for comparison with probabilistic calculations. Representative values for both AVN estimators were chosen in an analogous way to be: 20 l/h for AVN #1 (eq (12)) and 15 l/h for AVN #2 (eq (13)).

5.1.2. 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 (7) and (8)) and postulated hypothetical accidental conditions - steam line break. A distribution of leakers as obtained from the Monte Carlo simulations (eq (7)) is depicted in Table 1. Although this is not clearly seen, larger defects tend to leak more frequently which is in accordance with eq (7).

The results of the three estimators are visualized by vertical lines at appropriate values of total leak rates (Figure 2). Thus, for EPRI estimator, 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 estimators #1 and #2 tend to 5 and 11%, respectively.

The main conclusion is that the EPRI estimator 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 estimators give underestimated 95th percentiles of total leak rate, which is consistent with discussion in Sections 4.1 and 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 3.3 and 3.4).

5.2. Doel-4

5.2.1. 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 repair 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.

In addition, Figure 3 gives the sample distribution of defects, which exhibit leak (eq (7)). 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 (7).

Table 2 was generated to illustrate the numerical stability of the EPRI estimator (eq. (11)) 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 estimator 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 estimators, respectively.

5.2.2. 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 (7)) 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.

Again, the results of all three estimators 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 estimators 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 estimator seems to be realistic (leading to failure probability of 6%) while the AVN estimators lead to failure probabilities exceeding 10% (AVN#1 11%, AVN#2 16%).

5.3. Estimators vs. Probabilistic Approach

The main differences between the probabilistic approach and estimators are discussed here:

- Probabilistic approach explicitly splits the population of defects on leakers and non-leakers (eq. (7)), while estimators average the leak rates over both leakers and non-leakers (eq. (10)). The error of eq. (10) is rather serious underestimate of total leak rates (at 95% probability level) for small defects where the probability of leak (eq. (7)) 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 between estimators (Section 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 conservativisms accumulated in EPRI estimator seem to be appropriate to compensate the underestimates caused by averaging of leaks over both leakers and non-leakers (eq. (7)) for small defect sizes (Krško Case). On the other hand, the least conservative AVN #2 estimator 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 approach is recommended because it is not sensitive on the defect size and the inherent assumptions of the estimator used.

5.4. 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 (7) and (8)). 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. (8))

which is followed by the probability of leak (eq (7)). 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.

6. 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 estimators, which were developed to determine conservative predictions of total leak rates, outlined and verified against the probabilistic approach. The probabilistic approach gives a reliable measure of their conservativity.

In particular, two numerical examples based on data from Slovenian Krško and Belgian Doel-4 power plants were studied. It was shown that the existing estimators are conservative for large defect sizes (>10V), but not 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 estimators.

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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TABLES

Table 1 Selected statistical parameters of total leak rates obtained by EPRI estimator (eq **(11)**) - Krško steam generator

Total leak rate based on eq (11)	**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

Table 2 Selected statistical parameters of total leak rates obtained by EPRI estimator (eq. (11) - 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

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%

FIGURES

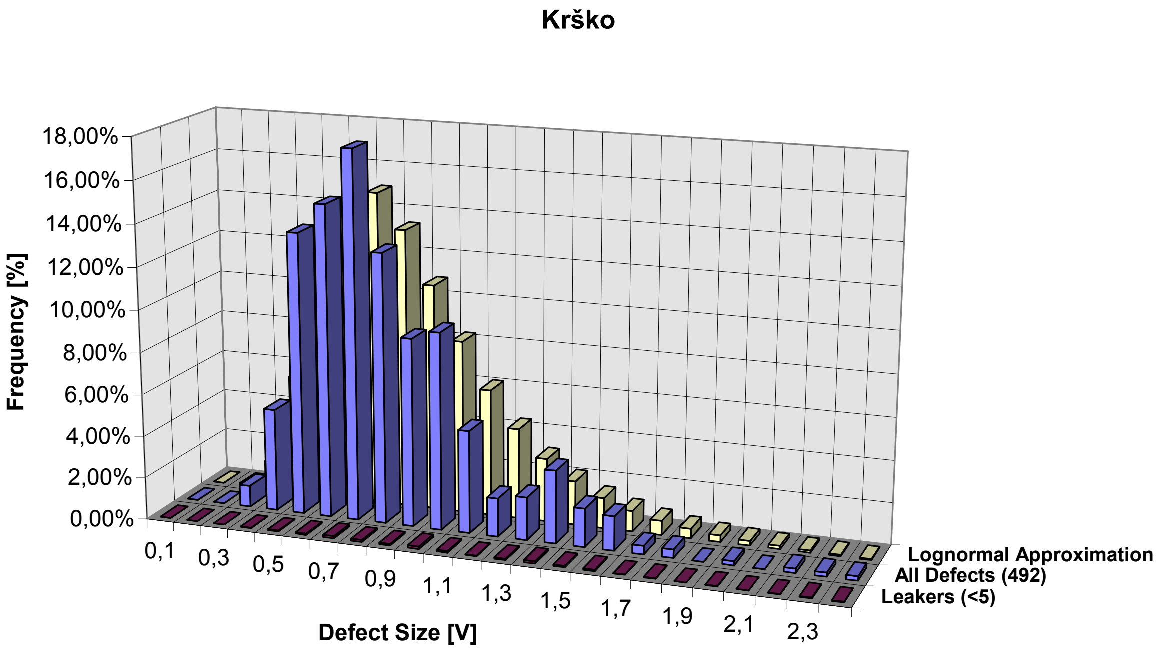

Figure 1 Distribution of BOC defect sizes-Krško plant

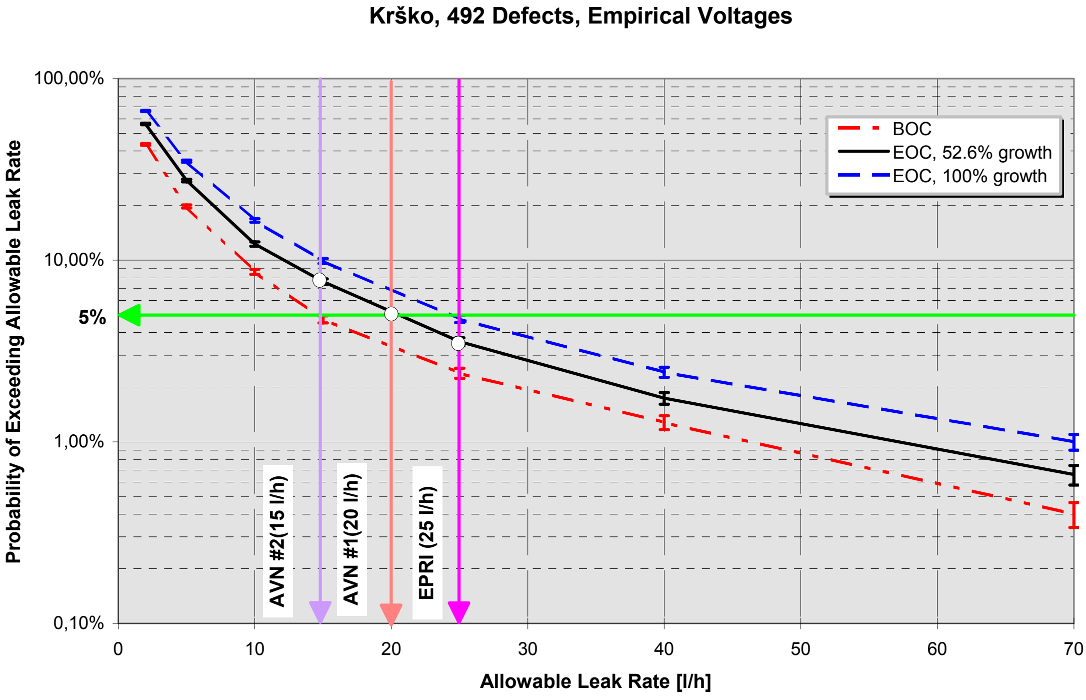

Figure 2 Probability of Exceeding Allowable Leak Rates - Krško case

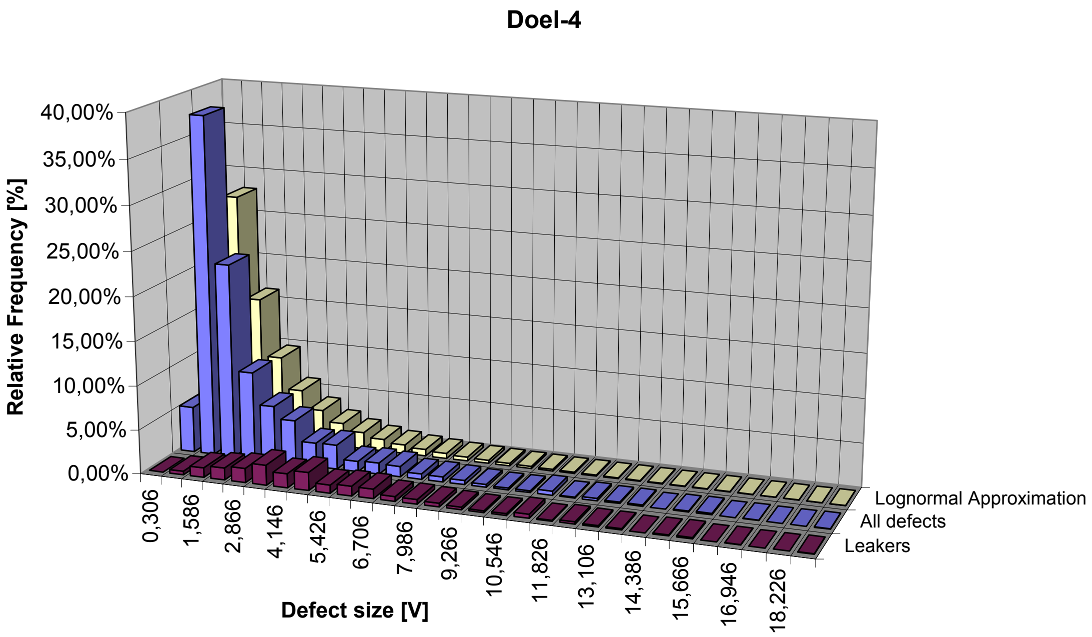

Figure 3 Distribution of BOC defect sizes - Doel-4 plant

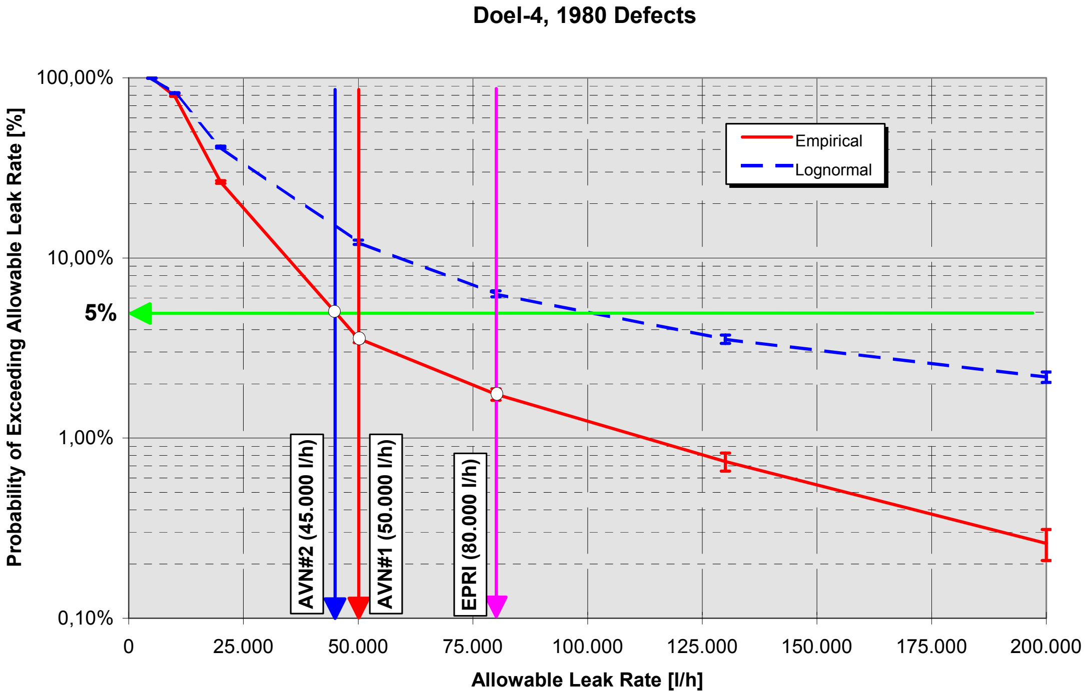

Figure 4 Probability of Exceeding Allowable Leak Rates - Krško case