THE RELATIVE IMPACT OF SIZING ERRORS ON STEAM GENERATOR TUBE FAILURE PROBABILITY

L.Cizelj, T.Dvoršek

ABSTRACT

The Outside Diameter Stress Corrosion Cracking (ODSCC) at tube support plates is currently the major degradation mechanism affecting the steam generator tubes made of Inconel 600. This caused development and licensing of degradation specific maintenance approaches, which addressed two main failure modes of the degraded piping:

- Tube rupture and
- Excessive leakage through degraded tubes.

A methodology aiming at assessing the efficiency of a given set of possible maintenance approaches has already been proposed by the authors. It pointed out better performance of the degradation specific over generic approaches in (1) lower probability of single and multiple steam generator tube rupture (SGTR), (2) lower estimated accidental leak rates and (3) less tubes plugged.

A sensitivity analysis was also performed pointing out the relative contributions of uncertain input parameters to the tube rupture probabilities. The dominant contribution was assigned to the uncertainties inherent to the regression models used to correlate the defect size and tube burst pressure.

The uncertainties, which can be estimated from the in-service inspections, are further analysed in this paper. The defect growth was found to have significant and to some extent unrealistic impact on the probability of single tube rupture. Since the defect growth estimates were based on the past inspection records they strongly depend on the sizing errors. Therefore, an attempt was made to filter out the sizing errors and to arrive at more realistic estimates of the defect growth.

The impact of different assumptions regarding sizing errors on the tube rupture probability was studied using a realistic numerical example. The data used is obtained from a series of inspection results from Krško NPP with 2 Westinghouse D-4 steam generators. The results obtained are considered useful in safety assessment and maintenance of affected steam generators.

"Jožef Stefan" Institute, Jamova 39, SI-1000 Ljubljana, Slovenia
E-mail: leon.cizelj@ijs.si, tomaz.dvorsek@ijs.si
http://www2.ijs.si/~cizelj/index.html, http://www2ijs.si/~dvorsek/index.html

THE RELATIVE IMPACT OF SIZING ERRORS ON STEAM GENERATOR TUBE FAILURE PROBABILITY

L.Cizelj, T.Dvoršek

1 INTRODUCTION

The steam generator (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 severe 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. Two potential failure modes of degraded tubing are of particular concern [1], [2]:

- single or multiple steam generator tube rupture (SGTR) and
- excessive leaking of the reactor coolant to the secondary side.

The probabilistic methods aimed at estimating the SGTR probabilities are given elsewhere for axial cracks in expansion transitions (e.g., [3], [4]) and for Outside Diameter Stress Corrosion Cracking (ODSCC) at Tube Support Plates (TSP; e.g., [5], [6] and [7]). The methods assessing probability of excessive leakage through ODSCC at tube support plates are addressed in [8], [9] and [10].

The failure probabilities calculated for both potential failure modes of the ODSCC at TSP have been found to be very sensitive [5] to the regression models used to describe correlation between burst pressures (leak rates) at given defect size. Considerable sensitivity to the statistical interpretation of inspection results (e.g., distribution of defect sizes and defect growth) was also studied, leading to the conclusion that current models of defect growth tend to significantly overestimate the field observations [11].

Especially approximation of defect growths was found to be a rather sophisticated problem [11]. Since the defect growth is derived from two consecutive measurements of defect size, the accumulated sizing error tends to dominate the growth distribution. The main goal of this paper is to explore and quantify the impact of sizing errors on the estimated probability of single tube rupture. The sizing errors are removed from both the distributions of defect sizes and defect growths.

A realistic numerical example illustrates the effects of different assumptions on sizing errors with the help of data obtained from a series of 100% in-service inspections of steam generator tubes in the Slovene NPP at Krško (Westinghouse 2-loop PWR).

2 MODELING CONSIDERATIONS

2.1 Probability of SGTR

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

$$P_f = \int_{g(x_1,x_2,...,x_n)\leq 0} f_1(x_1)f_2(x_2)...f_n(x_n)dx_1dx_2...dx_n \qquad \textbf{Eq. 1}$$

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

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

$$g(\Delta p_{ACC}, \Delta p_B, a) = \Delta p_{ACC} - \Delta p_B(a) \qquad \textbf{Eq. 2}$$

Δp_{ACC} denotes the pressure load acting during a postulated limiting accident (e.g., Steam Line Break). Δp_B represents the maximum pressure which the tube containing a defect of a given size a can sustain. 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 (as for example 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 [12]:

$$\Delta p_B(a) = A + B \cdot \log_{10}(a) + \varepsilon \qquad \textbf{Eq. 3}$$

A and B are proprietary coefficients obtained from the regression analysis [12]. 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 bobbin coil signal amplitude (voltage) and is explained in some detail elsewhere [5], [11].

The value of P_f (eq. (1)) was obtained using the Direct Monte Carlo simulations and represents the fraction of failed tubes in the population of all defective tubes. The observed steam generator is then represented as a random sample of N defects. The probability of having i tubes failed $p(i)$ is assumed to follow the Poisson distribution:

$$p(i) = \frac{(N \cdot P_f)^i}{i!} \cdot \exp(-N \cdot P_f) \qquad \textbf{Eq. 4}$$

Appropriate choice of i enables the calculation of single and multiple tube rupture probabilities.

2.2 Sizing Errors

2.2.1 Bases

Let us assume that the ***measured defect size m*** is a random variable. Further, assume that the measured defect size m_i observed at the particular point in time i is related to the ***apparent defect size*** a_i through the ***sizing error*** e_i:

$$m_i = a_i + e_i \qquad \textbf{Eq. 5}$$

Index i denotes measured defect sizes observed at different points in time (e.g., at regular inspections).

Eq. 5 can be rewritten in terms of probability density functions as (e.g., Ref. [14]):

$$f_M(m) = \int_{-\infty}^{\infty} f_{M|A}(m|a) \cdot f_A(a) \cdot da \qquad \textbf{Eq. 6}$$

with $f_{M|A}(m|a)$ being the conditional probability density of measured defect sizes m given the apparent defect size a. $f_A(a)$ represents the probability density of apparent defect sizes.

Solution of Eq. 6 unfortunately requires subjective judgement of types of distributions for:

- $f_{M|A}(m|a)$ (conditional probability density of measured defect sizes m given the apparent defect size a) *and*
- $f_A(a)$ (the probability density of apparent defect sizes).

The optimal parameters of both chosen distributions can then be determined using standard fitting procedures such as maximum likelihood method or minimisation of chi-squared. For the purpose of this analysis, the maximum likelihood method was utilised.

A similar reasoning can be used to describe the measured defect growth Δm which is estimated from two consecutive sizings of measured defect sizes:

$$\Delta m_{i+1} = m_{i+1} - m_i = (a_{i+1} + e_{i+1}) - (a_i + e_i) = \Delta a_{i+1} + \Delta e_{i+1} \qquad \textbf{Eq. 7}$$

For the purpose of the present analysis, the $f_{M|A}(m|a)$ is assumed to be a normal distribution with parameters:

- Mean equals to apparent defect size (a and Δa) + bias (where applicable, see Subsection 2.2.2);
- Standard deviation is a constant value (defect growth) or value proportional to the apparent defect size. The second model is consistent with models used for routine analysis of reliability of tubes affected by ODSCC in Krško NPP [13].

2.2.2 Discussion

Subjective selection of distributions (describing $f_{M|A}(m|a)$ and $f_A(a)$ in eq. 6) is a widely accepted statistical procedure. Particular selections however deserve some comments and links to the field of practice, where feasible.

The sizing errors in the traditional sense can not be defined here. We can merely deal with a process, which would be probably better characterised as a repeatability of sizing. This is caused by the fact that the amplitude of the signal obtained from bobbin probe is directly used as the value representing measured defect size. A good example where the sizing errors in the traditional sense are present would be sizing of crack lengths in SG tubes. In this case, the measured defect size is obtained by using correlation between the electromagnetic state of the probe and crack length. Nevertheless, we consistently use the term ***sizing errors*** to generalise the discussion to other existing conventions about defect sizes.

A direct consequence of such definition of measured defect size is that it is very hard to support the presence of any systematic sizing errors (or bias) in the measurements. Using again the example of sizing the axial crack lengths; the uncertain correlation between the measured and reported parameters would be the major source of systematic sizing errors (bias, e.g., consistent overestimation of the apparent crack length).

On the other hand, the data on the measured defect growth (obtained from the inspection results using Eq. 7) can easily catch a bias. For example, a slight improvement in the inspection procedure, which may lead to a slightly (but consistently) different interpretation of signal amplitudes in consecutive inspections, is an obvious source of bias. For the purpose of the present analysis, a possible shift in the mean value of the measured growth is assumed. The amount of shift is then determined by the maximum likelihood procedure when fitting eq. 6 to the field data.

3 NUMERICAL EXAMPLE

The data presented in the following is obtained from 5 consecutive inspections of SG # 2 in Krško nuclear power plant. The SG # 2 was chosen because it exhibits more severe development of ODSCC at tube support plate intersections than SG # 1. The operational parameters of all operational periods observed are virtually the same, which to some extent simplified the analysis and presentation of the data.

In the present analysis, the tubes plugged or sleeved during the observed period are conservatively treated as left in service without any repair. This leads to modelling of larger number and larger sizes of defects left in operation and therefore also to more conservative estimates of SGTR probabilities.

All estimates of single tube rupture probabilities are conditional given the occurrence of feed line break (or steam line break) as the initiating event.

3.1 Data

3.1.1 Measured defect sizes

Measured defect sizes as obtained from 5 consecutive (100%) bobbin coil inspections of one steam generator are shown in Figure 1. The distribution remained fairly stable over the years in most cases analysed in this paper. The tail of the measured sizes obtained during In-Service Inspection (ISI) 5 is getting fat as compared to the older data. The lognormal distribution was considered to provide reasonable fit.

We should note here that the number of defect sizes detected has grown from 261 in the first to over 2000 in the last inspection. Although the change in the number of tubes does not directly influence the calculation of failure probability (eq. 1), it significantly influences the single SGTR probability (eq. 4).

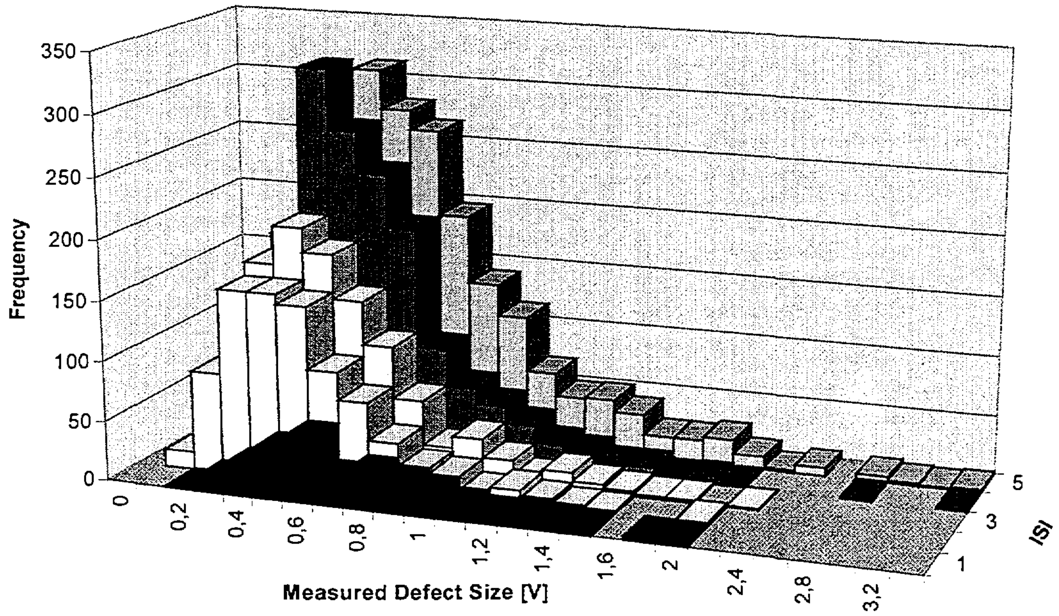

Figure 1 Measured Defect Sizes

3.1.2 Measured Defect Growth

Measured defect growths depicted in Figure 2 were obtained directly from each pair of two consecutive measurements available. The number of available data points grew from 80 in the first inspection to over 1300 in the last. Reasonably stable distribution of positive growths was observed over all years, tending to get a more fat distribution tail in ISI 5.

Only the data points exhibiting positive growth (see Figure 2) were used to directly fit the distributions of measured defect growth, which is consistent with routine analyses of Krško ODSCC [13]. Reasonable fits were provided by either lognormal or gamma distributions. Lognormal distributions were used in subsequent calculations since they are well known to cause larger failure probabilities than gamma distribution (e.g., [4]).

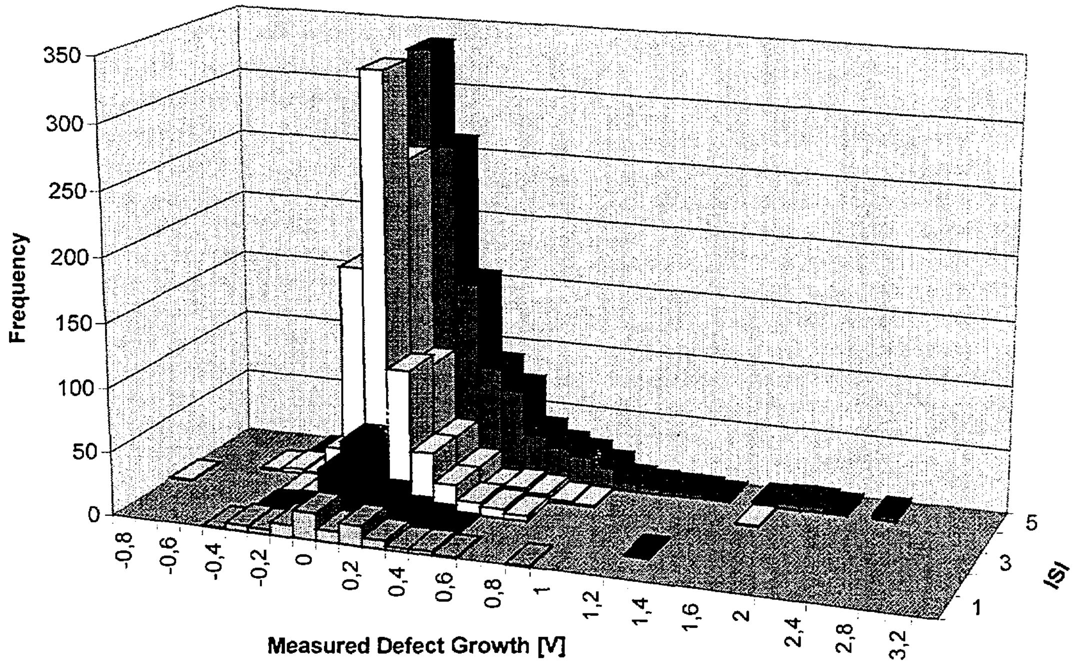

Figure 2 Measured Defect Growth

3.2 Results

3.2.1 Apparent defect sizes

The lognormal distribution was assumed to describe the apparent defect sizes. The sizing errors were assumed to be normally distributed with zero mean (without bias or systematic errors), while the standard deviation was assumed proportional to the apparent defect size (for example, 20% of a). The parameters of the lognormal distribution and the value of standard deviation were determined by the maximum likelihood procedure.

The quality of fits (Eq. 6) was monitored using the χ^2 test. The significance levels obtained varied from 0,01 to nearly 98%, depending on the particular year under investigation. While interpreting the meaning of the χ^2 test results we shall recall that Eq. 6 does not represent a standard fitting problem: the quality of fit here is significantly affected also by the "arbitrary" selection of the sizing error model. Thus, all fits were considered reasonable and accepted.

A sample comparison of cumulative distributions of apparent and measured defect sizes is given in Figure 3.

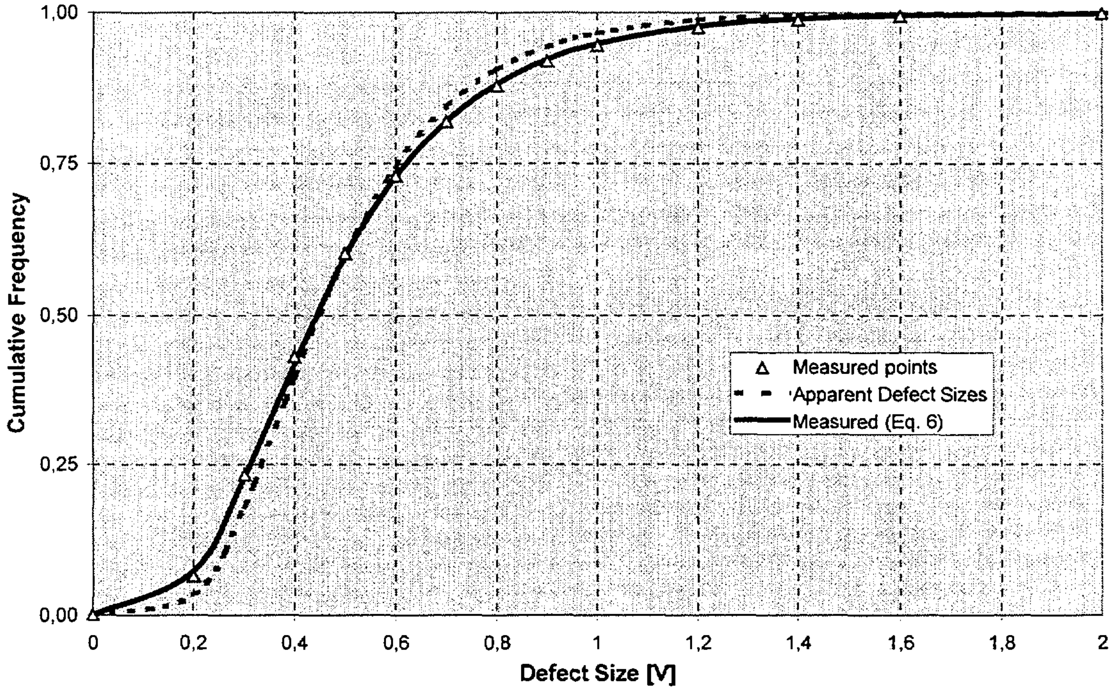

Figure 3 Comparison of distributions of apparent and measured defect sizes (a sample)

3.2.2 Apparent defect growth

A lognormal distribution was again assumed to describe adequately the apparent defect growth. The sizing errors were assumed to be normally distributed with zero mean (without bias or systematic errors). The parameters of the logonormal distribution and the value of standard deviation were determined by the maximum likelihood procedure.

In some cases (e.g., Figure 4) it was not possible to fit satisfactory the model to the field data. This was caused by the rather dominant frequencies of negative measured defect growths. Unfortunately, there is no known physical reason causing the decrease of the apparent defect sizes with time. On the other hand, a systematic decrease of measured defect sizes (and consequently also negative measured defect growth) could be caused by a systematic change in the technology of sizing.

Indeed, assumption of systematically different sizing technologies at different inspections was built in the sizing error model. Consequently, the quality of fitting improved significantly (Figure 5).

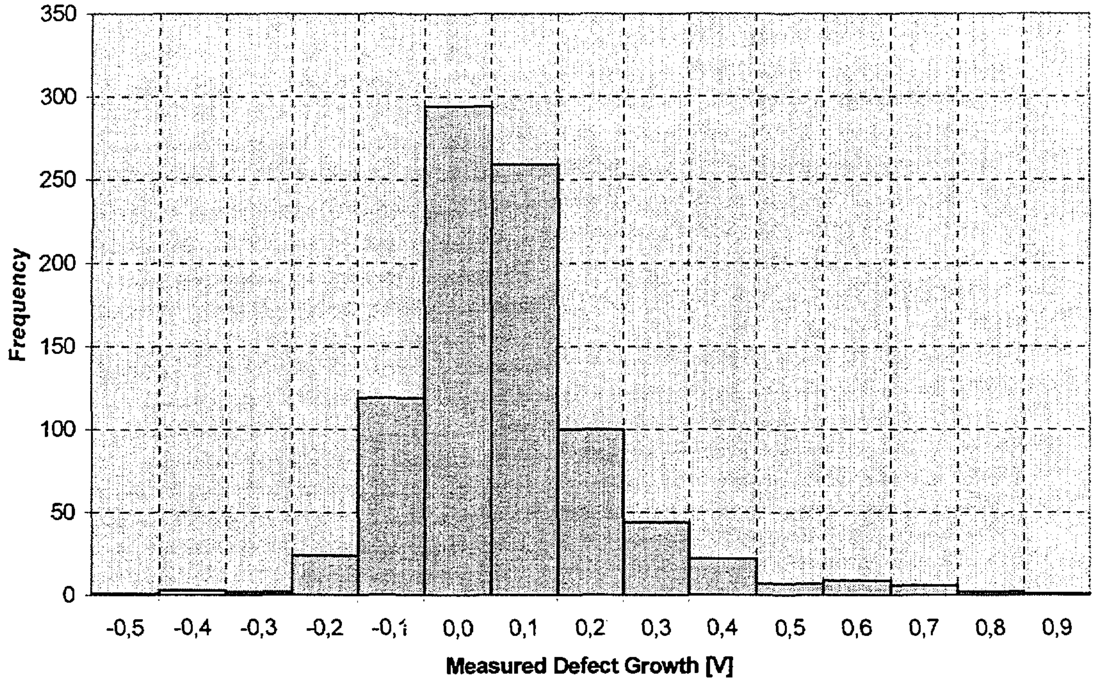

Figure 4 **Example of measured data, which can't be fitted without biased sizing errors**

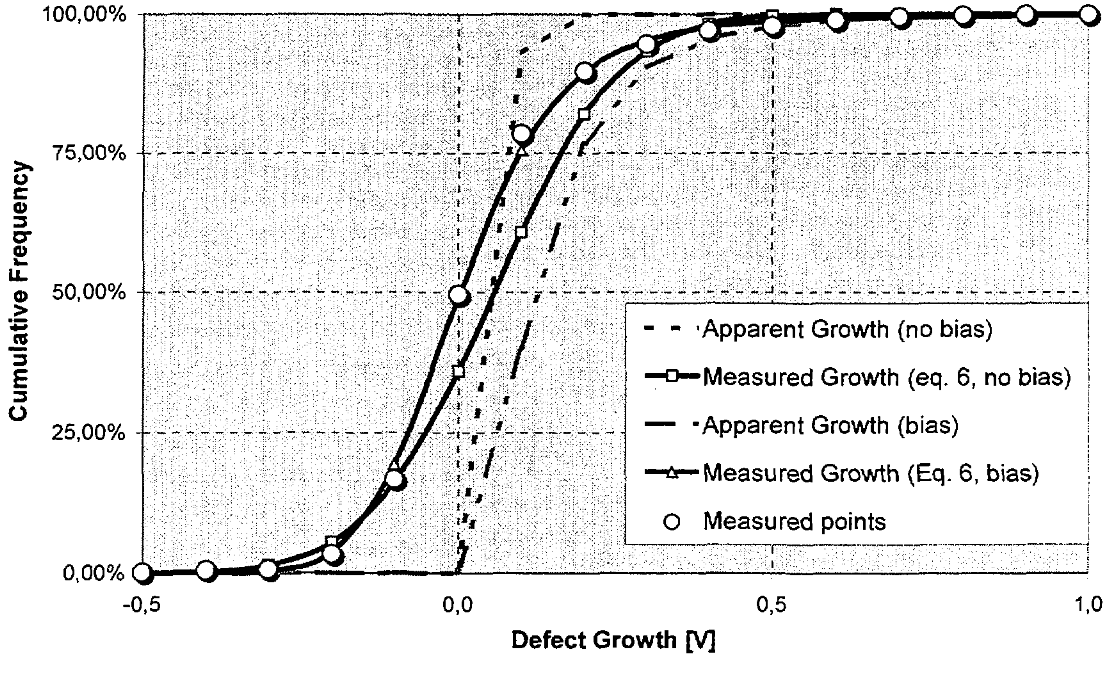

Figure 5 Comparison of distributions of apparent and measured defect growths (a sample)

Figure 5 depicts a sample comparison of measured and apparent defect growths as fitted with or without bias. Using bias generally yielded better fits.

3.2.3 Tube rupture probabilities

The tube rupture probabilities (conditional given occurrence of feed/steam line break) were evaluated using direct Monte Carlo Simulation for a set of different assumptions on the input data for the entire period of 5 inspections (years). They are depicted together with the U.S. NRC acceptable value of 1% [2] in Figure 6. The direct Monte Carlo simulation is usually considered to give exact results but may also require prohibitively long computing times. For example, the points in Figure 6 required about 4-5 hours of Sun Microsystems UltraSparc Station to get the statistical accuracy of about ± 5%.

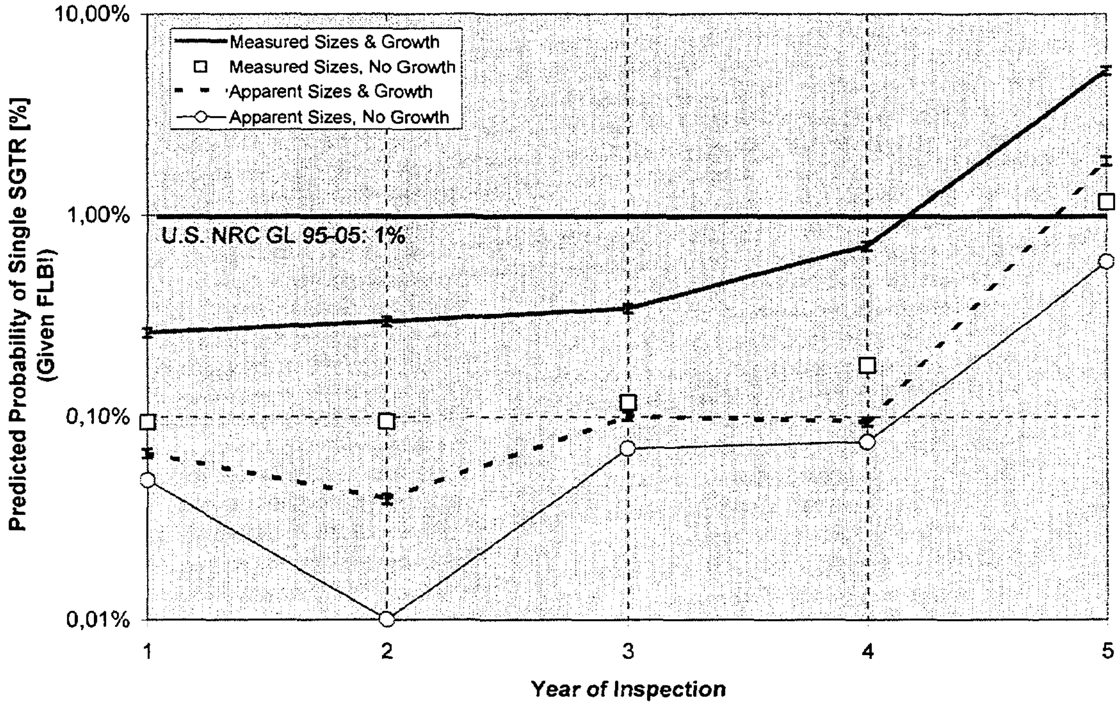

Figure 6 **Impact of sizing errors on failure probabilities**

Let us point out again that no credit was taken for tube repair (plugging and/or sleeving) while generating data for Figure 6. Any repair actions would significantly reduce the SGTR probability shown in The probabilities of multiple (>=2) tube rupture were at least two orders of magnitude lower than single tube rupture probabilities shown in Figure 6 for all cases analysed.

Direct implementation of measured defect sizes and growth to calculate the probability of SGTR consistently leads to higher probabilities of SGTR than implementation of apparent defect sizes and growths. This may attribute to up to one order of magnitude difference in the SGTR probability.

It is also clear from Figure 6 how much the sizing errors dominate the growth data. While the differences in probability of SGTR between the cases with and without growth are considerable with measured sizes & growth, they tend to be significantly smaller for apparent sizes and growths.

The results presented here show significant influence of sizing errors on the probability of SGTR and strongly support a strict implementation of apparent defect sizes and growth. Such approach would, in simple terms, eliminate most of the conservative assumptions from the analysis, which would in turn yield the best possible estimates of probability of SGTR. A consequence of practical value here would be less tubes plugged: please compare the levels of probability of SGRT for measured and apparent sizes and growths in 5th Year of Inspection (Figure 6). This difference is based entirely on the computational assumptions, but nevertheless requires significant amount of additional repair, if the allowable limits (e.g., max 1% probability of SGTR [2]) are to be observed.

4 CONCLUSIONS

The effect of sizing errors present in in-service inspections of steam generator tubes was addressed in this paper with special emphasis on the conditional probability of single steam generator tube rupture (given steam line break accident) were analysed in some detail. In particular, the sizing errors were filtered out from the inspection results, followed by the comparison of single SG tube rupture probabilities obtained using raw and filtered data on defect sizes and growth.

The numerical example considered inspection results from 5 consecutive inspections of Krško steam generator tubes. A consistent overestimate of single tube rupture probability was shown in all cases using the measured (non-filtered) defect sizes and growth. This overestimate of probability of SGTR is attributed entirely to the representation of the input data.

Use of apparent (filtered) defect sizes and defect growth is recommended for field use since this method gives best estimate values of single (and multiple) probability of SGTR by eliminating most of the conservative assumptions from the analysis. In field use, this method would result in less tubes repaired without jeopardizing safety of the steam generators.

5 ACKNOWLEDGEMENTS

This work was partially supported by the Ministry of science and technology of Slovenia and Nuclear Power Plant Krško.

6 REFERENCES

[1] U.S. NRC, **Voltage-Based Interim Plugging Criteria for Steam Generator Tubes**, Draft report NUREG-1477 (1993), Washington D.C., USA.

[2] US NRC, Generic Letter 95-05 (1995).

[3] Mavko, B., L.Cizelj: **Failure Probability of Axially Cracked Steam Generator Tubes: A Probabilistic Fracture Mechanics Model**, Nuclear Technology, Vol. 98 (1992), No. 2, pp. 171-177.

[4] Cizelj, L., B.Mavko, P.Vencelj, **Reliability of Steam Generator Tubes with Axial Cracks, Service Experience and Reliability Improvement**, Journal of Pressure Vessel Technology, Transactions of ASME, Vol. 118 (1996), No. 4, pp. 441-446.

[5] Dvoršek, T., L.Cizelj, B.Mavko, **Safety and Availability of Steam Generator Tubes Affected by Secondary Side Corrosion**, submitted to Nuclear Engineering and Design (1997).

[6] Dvoršek, T., **Comparison of Maintenance Strategies Applied to Steam Generator Tubes** (in Slovene), M.Sc. Thesis (1996), University of Ljubljana, Slovenia.

[7] Cizelj, L., T. Dvoršek, B. Mavko, **Efficiency of Defect Specific Maintenance of Steam Generator Tubes: The Case of ODSCC**, 15th EPRI Steam Generator NDE Workshop, EPRI Report No. TR-107161 (1996), Long Beach, CA, USA, July 29-31, 1996, pp. 9/1–9/10.

[8] Cizelj, L., B.Mavko, H.Riesch-Oppermann, **On the Probabilistic Approaches Applied to the Maintenance of Degraded Steam Generator Tubes**, CSNI-PW3 Workshop on Probabilistic Structural Integrity Analysis and its Relationship to Deterministic Analysis, NEA/CSNI/R(96) 4 (1996), Stockholm, Sweden, February 28-March 1, 1996, pp. 261-272.

[9] Cizelj, L., I.Soršek, G.Roussel, Ch.Cuvelliez, **Some Comments on the Probabilistic Modeling of Leak Rates Through Degraded SG Tubing**, 15th EPRI Steam Generator NDE Workshop, EPRI Report No. TR-107161 (1996), Long Beach, CA, USA, July 29-31, 1996, pp. 31/1-31/10.

[10] Cuvelliez, Ch., G.Roussel, **Assessment of the Leak Tightness Integrity of the Steam Generator Affected by ODSCC at Tube Support Plates**, CNRA/CNSI Workshop on Steam Generator Tube Integrity in Nuclear Power Plants, NUREG/CP-0154 (1996), Oak Brooks, Illinois, USA, October 30-November 2, 1995, pp. 385-398.

[11] Dvoršek, T., L.Cizelj, B.Mavko, **Time Dependence and Accuracy of SGTR Probability Estimates for Tubes Affected by ODSCC**, 16th EPRI Steam Generator NDE Workshop, EPRI Report No. TR-108858 (1997), Palm Beach, Fl, USA, July 21-21, 1997, pp. 21/1-21/8.

[12] **Steam Generator Degradation Specific Management** (Draft), EPRI Report No. TR-103017 (1993

[13] Cizelj, L., et al, **Safety Analysis of Krško NPP Steam Generator Tubes Damaged by Outside Diameter Stress Corrosion Cracking at Tube Support Plates**, Report No. IJS-DP-7175, Rev. 0 (1995), "J.Stefan" Institute, Ljubljana, Slovenia, proprietary.

[14] Sorenson, Harold W., **Parameter Estimation (Principles and Problems)**, Marcel Dekker, Inc. (1980).

DISCUSSION

Authors: L. Cizelj, T. Dvoršek, Jozef Stefan Institute

Paper: The Relative Impact of Sizing Errors on Steam Generator Tube Failure Probability

Questioner: R.W. Staehle

Question/Comment:

(1) I assume that the SCC you study is on the secondary side?
(2) When the cracks penetrate, would you expect a washing process that removes the chemistry that initiated and propagated the crack?

Response:

(1) Yes, that particular example dealt with secondary side SCC.
(2) That is possible. However, leak rates observed in operation and in numerical simulation are rather small. Experience with numerical simulation of leak rates shows that less than 1% of defects would leak under operating conditions. Consequently, it is not very probable to infer the effect you mentioned from the inspection results, even in case that it really happens.

Questioner: M. Clark

Question/Comment:

How does your program deal with negative growth in particular tube, is this due to random or systematic error?

Response:

Due to systematic error, the method is applicable to the populations of defect/tubes and cannot give explanation about a particular defect/tube.

On the population level, both types of errors are responsible for negative growth, whereas contributions from random and systematic errors vary significantly between different data sets (years). A typical case where systematic errors are necessary in order to explain the inspection results would be a case with more than 50% of negative growth. Such case is included in the analysis.

SESSION 3: THERMAL AND THERMALHYDRAULIC PERFORMANCE

Chair: W. Schneider, Babcock & Wilcox
Co-Chair: M. Pettigrew, Atomic Energy of Canada Limited