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CAN WE SIMULATE THE DEVELOPMENT OF ODSCC DEFECTS IN STEAM GENERATOR TUBES?

Leon Cizelj, Marko Kovač, Tomaž Dvoršek
"Jožef Stefan" Institute, Ljubljana, Slovenia
Leon.Cizelj@ijs.si

ABSTRACT

The qualitative and quantitative aspects of degradation mechanisms causing early retirement of SG tubing are not yet explained to the level allowing for accurate predictions of future behavior. On the other hand, a large amount of data related to tube degradation, inspection, repair, and plant operation have been collected during recent years. It allows for reasonably accurate quantitative predictions, based on statistical analysis of past events and assumption of reasonably constant operating conditions.

A computational algorithm was developed to simulate life cycle of ODSCC defects: initiation, growth, measurement, and repair. The main feature of the algorithm is the possibility to address some important changes in the operating parameters, especially those related to the conditions during the plant shutdown. The algorithm can be used to get better insight into the background of SG aging and to predict the future populations of defects, as shown in a realistic numerical example.

1 INTRODUCTION

The qualitative and quantitative aspects of degradation mechanisms causing early retirement of SG tubing are not yet explained to the level allowing for accurate predictions of, for example, impact of changed operating conditions on the initiation and growth of ODSCC (Outside Diameter Stress Corrosion Cracking) defects [1]. On the other hand, a large amount of data related to tube degradation, inspection, repair, and plant operating parameters have been collected during recent years ([2], [3] and [4]). It allows for reasonably accurate quantitative predictions, based on statistical analysis of past events and assumption of reasonably constant operating conditions.

A computational algorithm was developed to simulate life cycle of ODSCC defects as a stochastic process. Currently, the life cycle is composed of four stochastic subprocesses: initiation, growth, measurement, and repair. The main feature of the algorithm is the possibility to address some important changes in the operating parameters, especially those related to the conditions during the plant shutdown. The algorithm can be used to get better insight into the background of SG aging and to predict the future populations of defects.

Numerical example explains the input data for the algorithm, which was obtained from past plant data and compares the predictions with results of the recent in-service inspection. Some comments on the possible future behavior are given.

2 MATHEMATICAL MODEL

2.1 Life Cycle of Defects

Let m_{i+1} denote the size of a randomly selected defect. $i+1$ indicates, that the particular defect was sized during the $(i+1)^{th}$ inspection. Its measured size is assumed to depend entirely on the history of the defect:

$$m_{i+1} = \begin{cases} m_i + g_i, m_i > 0 \\ n_{i+1}, m_i = 0 \\ 0, if \begin{Bmatrix} m_i + g_i \\ n_{i+1} \end{Bmatrix} exceed\ repair\ criteria \end{cases} \qquad (1)$$

m_i represents the size of the same defect at inspection i and g_i represents its growth between inspections i and $i+1$. n_{i+1} accounts for the new defects, which are detected and sized for the first time during the inspection $i+1$. Both g_i and n_{i+1} may heavily depend on the operational conditions (see Section 2.4).

The size of the defect is set to 0, if its current size exceeds the repair criteria. The repair criteria used in the analysis are consistent with repair criteria used in field.

Simulation of the life cycle over more than two inspections is straightforward and requires only successive applications of eq. **(1)**.

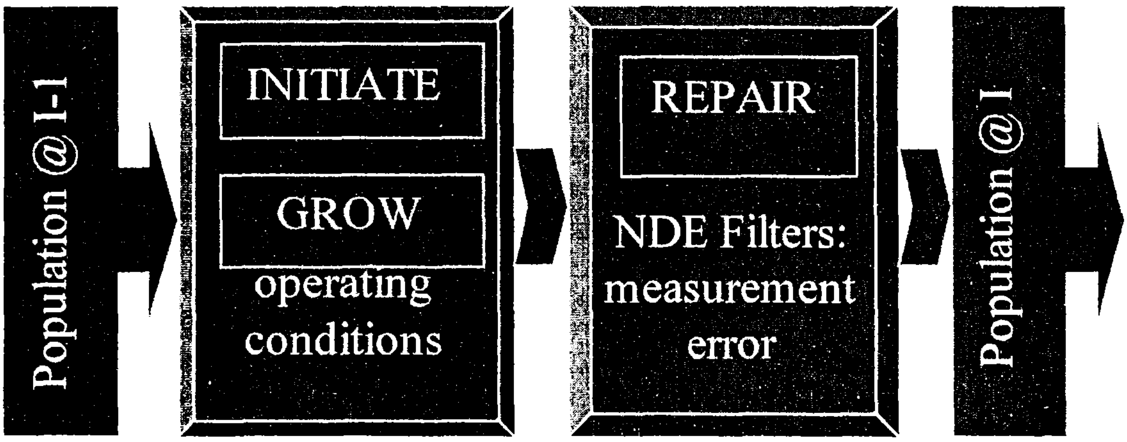

Figure 1 **Schematic view of the algorithm simulating the life cycle of defects**

2.2 Defect growth

The defect growth as observed from the results of in-service inspections is depicted in **Figure 2**, which is discussed in some more detail in Section 2.3. Two conclusions however are relevant for our discussion here:

- A significant fraction of defects experience negative growth;
- The negative growth seems to be limited by approx. 50% of the defect size before growth.

Since there is no known physical reason for negative growths, it is assumed here that the negative growth is caused by the measurement error. The observed defect size m is therefore composed from the "real" defect size a and measurement error e:

$$m_{i+1} = m_i + g_i \Rightarrow a_{i+1} + e_{i+1} = a_i + e_i + g_i \qquad (2)$$

Since the same inspection equipment was used during recent inspections, we may assume that the measurement error does not change with inspections:

$$e_{i+1} \approx e_i \Rightarrow (a_{i+1} - a_i) = \Delta a_{i+1} = g_i + 2 \cdot e_i \qquad (3)$$

Solved for g and rewritten in terms of marginal and conditional probability densities, eq. **(3)** yields:

$$f_G(g) = \int_{-\infty}^{\infty} f_{G|\Delta A}(g|\Delta a) \cdot f_{\Delta A}(\Delta a) \cdot d\Delta a \qquad (4)$$

$f_G(g)$ represents the marginal probability density of measured (observed) defect growths, $f_{G|\Delta A}(g|\Delta a)$ conditional probability density of measured (observed) defect growths given a real growth of Δa (acould also be termed measurement error!) and $f_A(a)$ the marginal probability density of real defect growths.

Solution of eq. **(4)** for $f_{\Delta A}(\Delta a)$ is needed to obtain the estimate of defect growth without the noisy measurement errors. This represents a rather challenging inverse numerical problem. A subjective choice of densities $f_{G|\Delta A}(g|\Delta a)$ and $f_{\Delta A}(\Delta a)$ represents an additional challenge and, of course, potential source of uncertainties.

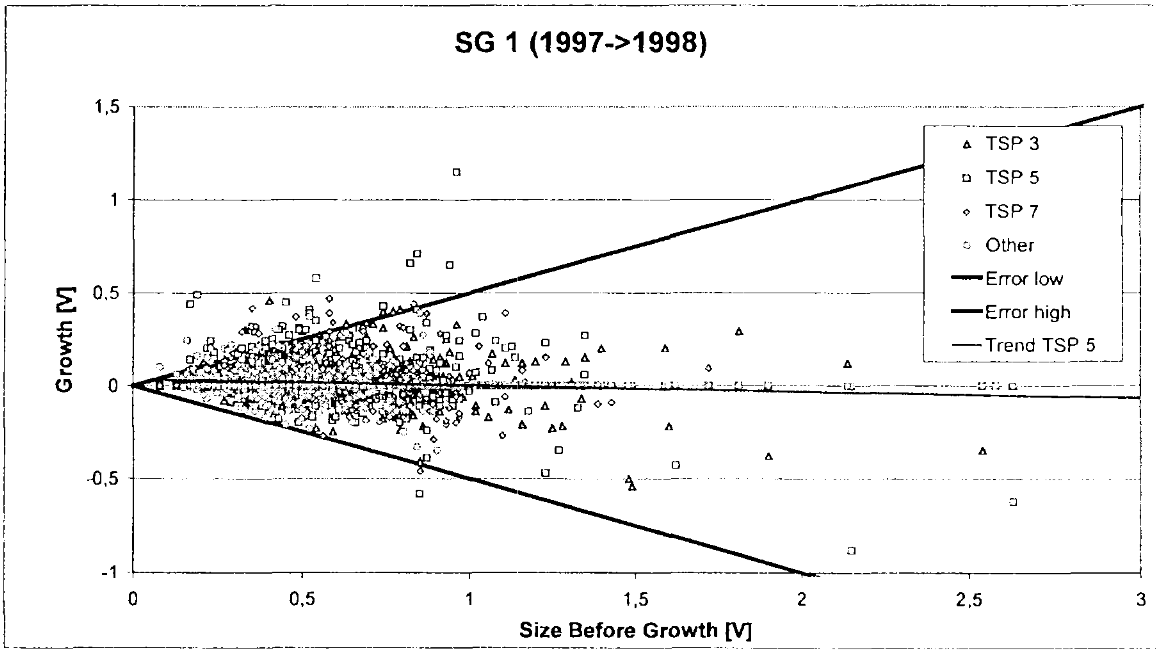

Figure 2 Defect growth as function of defect size before growth (sample)

2.3 Measurement Error

A typical example of observed defect growths is given in **Figure 2**. The growth of about 2000 defects is plotted against their size before growth. It should be mentioned here, that the bobbin coil signal amplitude in Volts is used as the measure of the defect size in this paper. The vast majority of points in **Figure 2** are clustered along the zero growth line, which is also consistent with the trend of plotted points (Trend of TSP 5 is given in **Figure 2** as an example). Similar behavior is observed for growth at different tube support plates (TSP), although the TSP 5 seems to generate the largest individual growth values. Lower limit of observed growth seems to be (at least in probabilistic sense) consistent with about -50% of the size before growth.

As already mentioned above, we assume that the measurement errors are fully and solely responsible for the negative growth. Further, a random error with standard deviation of about 23% of the initial defect size was reported for the technology used in field (see [5] and references therein). In two consecutive measurements (typical for empirical growth data!), two independent measurement errors would accumulate to the standard deviation of 23%•√2 = 32.5% of the initial size of the defect. At least 90% of all points should therefore reside above the line of -50% (≈1.5•32.5%) of initial defect size, which in fact is shown in **Figure 2.**

Numerical investigations of eq. (4) confirmed above discussion. The following model was therefore adopted to describe the measurement error:

$$f_{G|\Delta A}(g|\Delta a) = \frac{1}{\sqrt{2\pi(\sigma \cdot \Delta a)^2}} e^{\frac{-(g-\Delta a)^2}{2(\sigma \cdot \Delta a)^2}} \qquad (5)$$

with σ set at 0.325.

2.4 Variability of Operational Conditions

The qualitative and quantitative impact of operating conditions on the development of ODSCC is not yet explained to the level allowing for accurate modeling [6]. However, previous work [7] indicated that certain irregularities in the inspection results could be attributed to the changes in operating conditions during different periods between successive inspections. The following consequences were noticed during cycles with more demanding operating conditions:

- ☑ Significantly faster growth of defects;
- ☑ Moderate increase in number of new defects.

Both observations were correlated with the conditions during the (planned and unplanned) plant shutdowns included in the simulation through appropriate changes in magnitudes of defect initiation and growth.

3 NUMERICAL EXAMPLE

3.1 Input Data

All simulations presented in this paper are using the distribution of defects in SG 2 as reported after ISI 1995 as the starting distribution of defect sizes.

Data for simulation modules representing defect initiation, growth, repair and measurement errors were derived from the inspection results ([2], [3] and [4]) using classical statistical methods. It is beyond the purpose of this paper to describe the results of the statistical analyses performed.

Table 1 Differences in the operational conditions

Cycle	Intensity of		Comments
	Initiation	Growth	
1995->1996	2	1	
1996->1997	3	3	Most severe development of ODSCC observed!
1997->1998	2	1	
1998->1999	2	1	
1999->2000	2	1	

The differences in the operating conditions were modeled by a rather simple approach summarized in Table 1. Intensity figures denote number of recursive levels applied while modeling initiations and growth, respectively. For example, intensity of growth of 3 during the cycle 1996->1997 indicates that the average defect growth was targeted at about 3 times the defect growth during for example 1995->1996.

3.2 Testing the Algorithm

This section describes the basic test performed to validate the algorithm. The basic idea of the performance testing was to simulate the development of the defects over a few of cycles and to compare the results with inspection results available. The period between inspection in 1995 (starting distribution of defect sizes) and 1998 was chosen, since it exhibits rather high variability in the operating conditions encountered.

A simple sensitivity analysis was performed during the demonstration of the performance. The results are presented in Figures 3-5: the predicted relative frequency of defect sizes after the 1998 inspection and repair campaign are compared with observed distributions. 1000 direct Monte Carlo simulation runs were performed for each figure. The results are plotted in form of 5-95% confidence intervals with average predictions indicated.

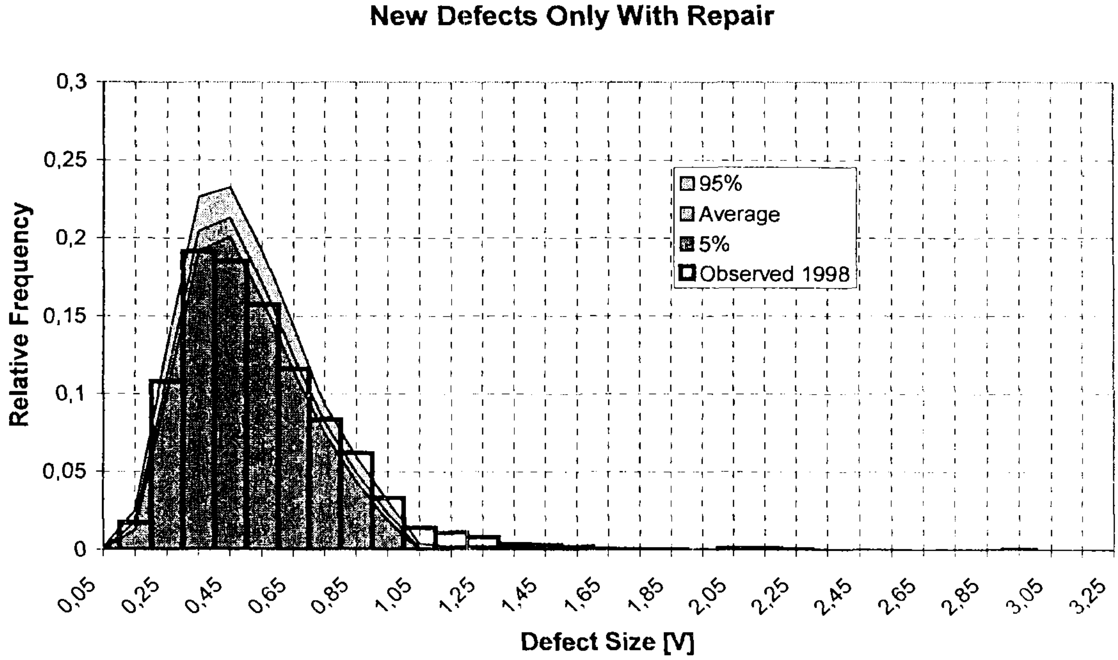

Figure 3 Simulated development of defect initiation (Baseline 1995 -> 1998)

Fig. 3 depicts the predicted defect size distribution for the case, which was limited to the initiation of new defects only. No defect growth was simulated here. Very good fit can be observed, but only for defect sizes below 1 V. From Fig. 3 it is quite obvious, that "no growth" also means "no repair".

Fig. 4 depicts the predicted defect size distribution for the case, which was limited to the growth without any initiation of new defects. Excellent fit is observed for defect sizes exceeding 1V, which also indicates dominance of old (grown!) defects among the repaired defects.

Fig. 5 depicts the predicted defect size distribution for the mixed case: the initiation and growth rates were balanced appropriately to comply with observed rates. Reasonable fit is observed here for the entire range of defect sizes. Slight discrepancy at defect sizes just below 1 V suggests overprediction of tube repair rates. Visual comparison of Figs. 3-5 suggests the dominance of old defects in the 1998 population of defects.

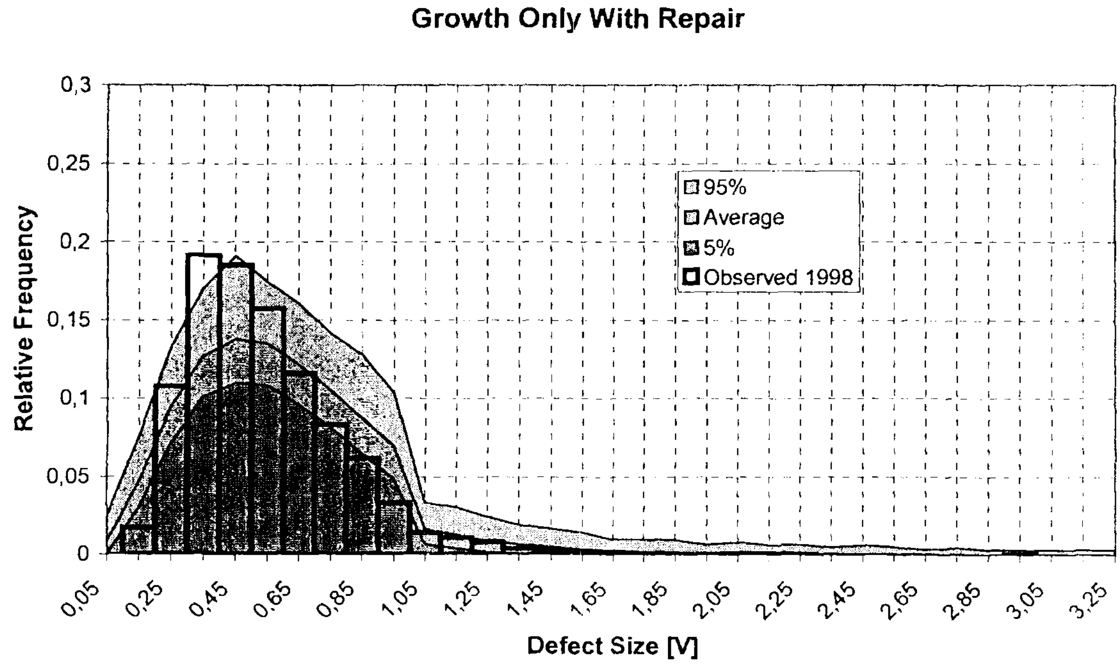

Figure 4 Simulated development of defect growth (Baseline 1995 -> 1998)

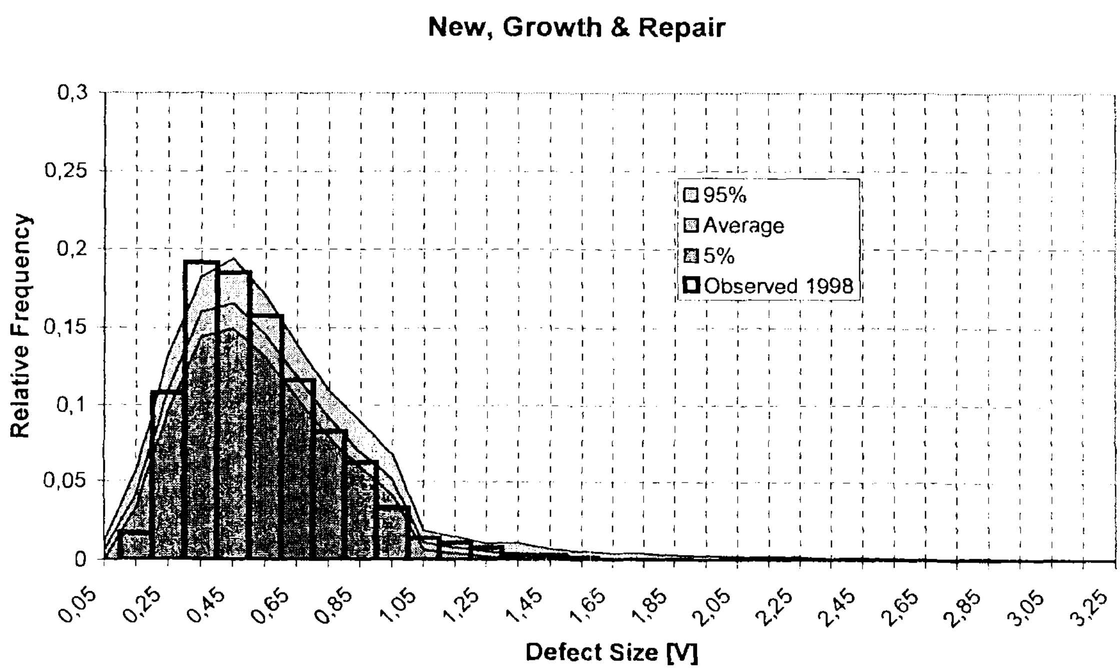

Figure 5 Simulated development of defect initiation and growth (1995 -> 1998)

3.3 Predictions for 1999 and 2000

Predicted development of defect size distributions for potential inspections 1999 and 2000 are shown in Fig. 6. The distributions of defect sizes are predicted to remain relatively stable for the period 1998-2000. This is attributed to the fact that the old defects survive a significant number of inspections. With time, they increasingly outnumber the newly developed defects and therefore completely dominate the population.

This observation is very important from the viewpoint of safety and reliability. The increasing dominance of old defects namely increases the predictability of the process and increases the confidence in the inspection methods implemented in the field.

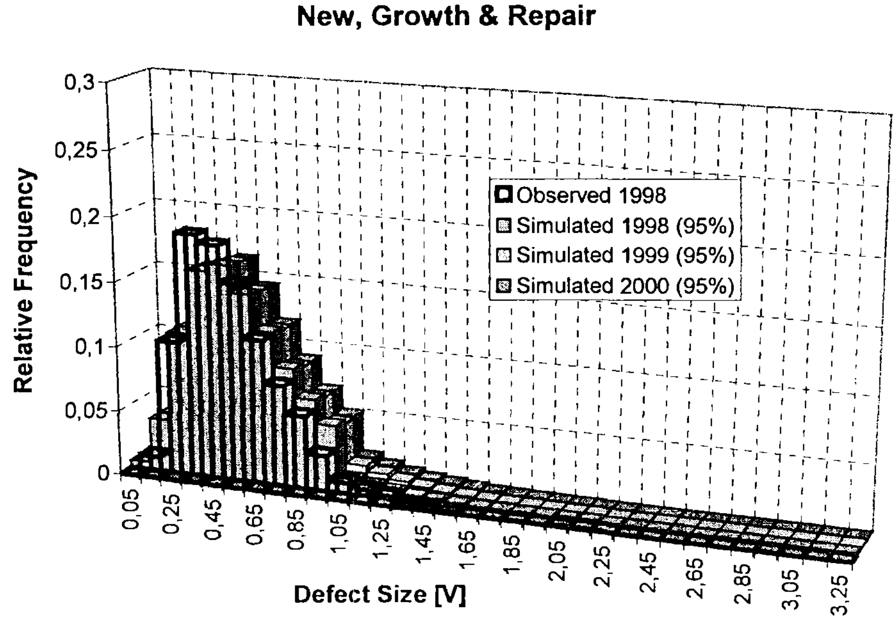

Figure 6 Predicted development of defects for 1999 and 2000

4 CONCLUSIONS

A computational algorithm was developed to simulate life cycle of ODSCC defects: initiation, growth, measurement, and repair. The main feature of the algorithm is the possibility to address some important changes in the operating parameters, especially those related to the conditions during the plant shutdown. The algorithm can be used to get better insight into the background of SG aging and to predict the future populations of defects, as shown in a realistic numerical example.

One of the main values of results is valuable insight in the relative importance of new and old defects. In the examples studied, the defects tended to survive two or more inspections before exceeding the repair criteria. This is consistent with field observations in Krško steam generators.

The future improvements of the model may be gained by (1) more rigorous modeling of the measurement errors and (2) further investigations of the correlation between operating conditions and defect initiation and growth.

5 REFERENCES

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