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HOW SAFE IS DEFECT SPECIFIC MAINTENANCE OF STEAM GENERATOR TUBES?

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ABSTRACT

Outside diameter stress corrosion cracking at the tube to tube support plate intersections is assessed in the paper. The impact of defect specific maintenance on steam generator operation safety and reliability was investigated. This was performed by comparing efficiencies of defect specific and traditional maintenance strategy. The efficiency was studied through expected primary-to-secondary leak rate and tube rupture probability in a case of postulated accidental operating conditions, and number of tubes which shall be plugged using both maintenance strategies. In general, the efficiency of specific maintenance is function of particular steam generator and operating cycle.

1. INTRODUCTION

Tubes in steam generators (SG) represent more than half of reactor coolant pressure boundary in PWR nuclear power plants (NPP). They are exposed to tough loading and environmental conditions. This results in degradation of tubes which could decrease the tube load carrying capabilities. Decrease in structural reliability of degraded tubes may imply reduced plant availability and safety.

To control the effect of degradation of tubes on NPP operation, tubes are periodically inspected and maintained. Tubes with degradations exceeding certain predefined size are repaired or removed from service. Tube plugging is the most common way of tube repair, therefore this predefined size is also called plugging criterion. Technically speaking, plugging criterion defines the largest permissible defect size which still enable safe operation of NPP. This has to be achieved for the last minute before inspection in a case of a postulated accident (the worst expected accidental conditions).

Recently, Outside Diameter Stress Corrosion Cracking (ODSCC) has been found as one of the major causes for tube plugging in SG with tubes made of Inconel 600. ODSCC is a degradation mechanism which includes intergranular stress corrosion cracking and intergranular attack on the outside surface of the tubing. This degradation takes place in the tube to tubesheet and tube to tube support plate (TSP) crevice.

With increased number of defects at TSP a comprehensive investigation has been performed in USA to define an alternate repair criterion specific to ODSCC degradation type. In this approach Eddy Current Testing (ECT) signal amplitude (voltage) was used to define repair limit instead of traditional minimum tube wall thickness. Some of western countries, e.g. Belgium, France, and USA have already adopted voltage based alternate criterion [1].

The alternate criterion is limited to ODSCC defects which can be found at tube to tube support intersections. Cracks may be through-wall and the main direction of the crack pattern is axially oriented. In analysis no credit was taken to reinforcement effect of TSP. It was conservatively assumed that affected region of the tube is not covered by the support plate during postulated accident conditions.

The aim of this paper is to evaluate the impact of ODSCC specific maintenance on steam generator operational safety. This has been done by comparison of efficiency of defect specific maintenance with the efficiency of traditional (generic) maintenance. This comparison answered the question postulated in the title of the paper: How safe is defect specific maintenance? Defect specific maintenance strategy for ODSCC defect type is briefly introduced bellow.

2. DEFECT SPECIFIC PLUGGING CRITERION

To define defect specific plugging criterion for ODSCC at TSP a procedure was introduced which defines maximum allowable defect size in two steps. First step includes deterministic analysis limiting the flaw to a size which is not expected to burst during normal operation and postulated accident conditions. Safety factors of 3 for normal operation and 1.43 for postulated accidents have been taken into account satisfy the RG 1.121 [2] requirements.

In addition to satisfying adequate margins against tube burst for normal operation and limiting accidental conditions as a second step a predicted accident leak rate is calculated. If the predicted leak rates for any one steam generator exceeds the plant allowable accident leak rate plugging limit has to be further reduced. Both steps are shortly described in following sections.

Voltage repair limit

Tube burst test results are evaluated to define a conservative correlation between bobbin coil voltage and burst pressure. This correlation was adjusted to account for operating temperature and minimum material properties. To establish the voltage structural limit (V_{SL}) that satisfies the RG 1.121 guidelines for margin against tube burst, the burst correlation must be evaluated at the higher of 1.43 faulted pressure and three times the normal operating pressure differential.

The voltage limit V_{VL} for repair is then calculated following eq. (1).

$$V_{VL} = V_{SL} - V_{NDE} - V_{CG} \qquad (1)$$

where V_{NDE} represents measurement error and V_{CG} voltage growth associated with the expected crack growth during next operating cycle. V_{NDE} and V_{CG} can be defined either from generic or plant specific data.

Maximum expected leak rate

Maximum expected leak rate at the end of operating cycle (EOC) under accidental conditions can be estimated using Monte Carlo (MC) simulation outlined in [3]. The method is based on correlation of individual tube leak rate vs. eddy current bobbin coil voltage. The correlation was established for 3/4" Inconel 600 MA tubes using test data obtained for pulled tubes and model boiler specimens which exhibited ODSCC.

The following entities are explicitly accounted for in the calculation of leak rates:

- uncertainties inherent to ECT measurement variability,
- voltage growth by EOC, and
- individual tube leak rate.

To estimate total leak rate bobbin coil voltages observed during tube inspections are classified into classes of 0.1 volt. For each of the class an expected leak rate has to be determined using MC simulation. Expected leak rate specific for certain class multiplied by number of observations in this class represents contribution of the class to the total leak rate. Total leak rate itself can be than determined as a sum of contributions of all classes.

3. PROCEDURE UPGRADING

Appropriate margins against burst at normal and postulated accidental conditions could be satisfied by defining voltage repair limit outlined above. In addition an analysis of tube rupture probability was performed.

Tube rupture probability

The probabilistic analysis strictly follows the steps which have to be done in a deterministic analysis. The major difference is however in the treatment of uncertainties. Thus, the uncertainties are addressed explicitly instead of assuming safety factors as in deterministic analysis. The following uncertainties were taken into account:

- distribution of beginning of cycle (BOC) bobbin coil voltages,
- uncertainties in voltage growth,
- ECT measurement variability, and
- uncertainties in the burst pressure correlation.

It's rather straightforward to implement Monte Carlo procedure to determine the tube rupture probability. But reliable estimates of failure probabilities in the order of 10^{-4} and less could be prohibitive in the sense of computing time. In such cases approximate methods such as First and Second Order Reliability Methods (FORM and SORM) could be implemented. FORM and SORM have already been implemented in safety assessment of degraded steam generator tubing [4] and were shown to give reasonably accurate results compared to "exact" Monte Carlo methods [5].

Tubes with ODSCC in a given SG represent a sample of size N_{ODSCC} from the population of all tubes. Further, P_f represents the tube failure probability of tubes for this population.

A probability of having i tubes ruptured in a given SG is estimated using Poisson distribution:

$$p(i) = \frac{(N_{ODSCC} \cdot P_f)^i}{i!} \exp(-N_{ODSCC} \cdot P_f) \tag{2}$$

Number of tubes with reported ODSCC defects was used as N_{ODSCC} in the calculations performed by **ZERBERUS** code [6].

4. KRŠKO NPP SPECIFIC ANALYSIS

In 1994 an analysis was performed with Krško NPP specific data as a potential support for plant specific implementation of the degradation specific SG maintenance [3]. The approach used in the analysis presented bellow is in compliance with EPRI methodology, which is based on experience and data from US, French and Belgian plants.

The comparison of the efficiency of both different maintenance strategies (defect specific and generic) will be presented as a function of voltage plugging limit. The efficiency was evaluated through expected leak rate and tube rupture probability estimation at the EOC during accidental conditions, and number of tubes which shall be plugged using one or another maintenance strategy.

Maximum expected leak rate

An evaluation of cumulative leak rate for different maintenance strategies was performed. Leak rate prediction was performed for each SG separately and for operating under postulated SLB accidental conditions and under normal operating conditions.

The pressure difference between primary and secondary coolant during a postulated SLB accident was assumed to be 182.7 bar (2650 psi). This is consistent with conservative assumptions used by Westinghouse tube wall thickness plugging criterion for Krško NPP [7].

The voltage growth population was fitted by the lognormal distribution. Plugging strategies are reflected through different BOC voltage distributions. Only defects on tubes which shall remain in operation after implementing particular maintenance are used in defining BOC voltage distributions. Bobbin voltage data was taken from ISI'92 and '93 inspection results [8].

ECT uncertainties are assumed to be normally distributed with zero mean. Standard deviation of uncertainties has been given in [8] as a percentage of bobbin voltage. No upper limit was imposed on the ECT uncertainties in the calculation.

The efficiency of specific maintenance was estimated based on comparison between leak rates obtained by implementing specific and generic maintenance. Attribute generic denotes actually applied 45% tube wall thickness plugging criterion. Therefore, index 45% is used bellow to denote generic maintenance.

A ratio between leak rates obtained following specific (LR_{ODSCC}) and generic maintenance ($LR_{45\%}$) was used as a criterion for the efficiency. Better efficiency of specific against generic maintenance is obtained when the ratio is less then 1 ($LR_{ODSCC} < LR_{45\%}$).

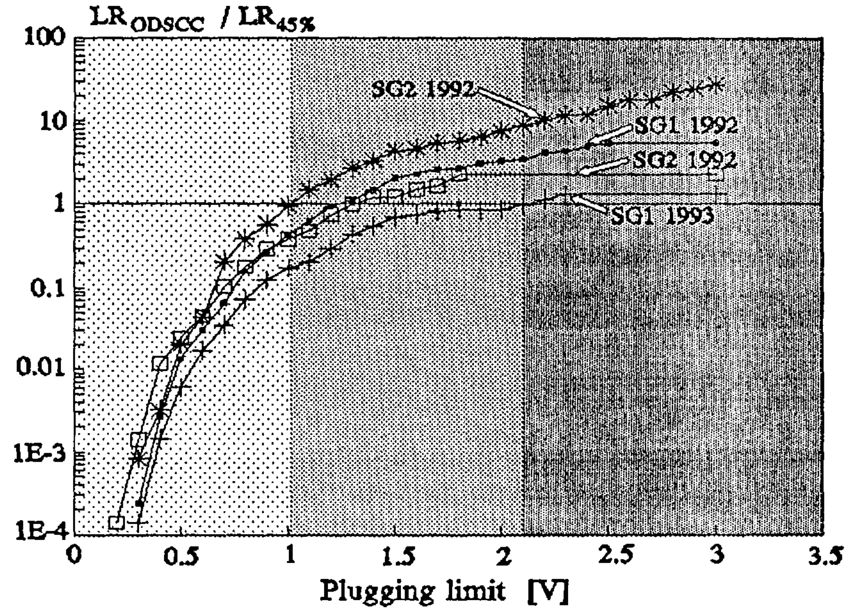

Figure 1 The efficiency of ODSCC specific maintenance strategy from a leak rate point of view

The plugging limit where specific maintenance becomes less effective compared to generic differs for each steam generator and operating cycle (BOC voltage distribution). Two plugging limit margins can be observed from Figure 1: approx. 1 volt (SG2, 1992) bellow which in all cases specific maintenance exhibits lower efficiency, and approx. 2.1 volts (SG1, 1993) above which better efficiency could be observed. In between the efficiency of specific maintenance depends on particular steam generator and operating cycle.

Tube rupture probability

To estimate tube rupture probability a postulated Feed Line Break (FLB) accident was assumed with predefined accidental differential pressure of 195.6 bar (2850 psi) [9].
The distributions of bobbin coil voltages have been estimated from the ISI results. Lognormal distributions were fitted to the frequency distributions of observed bobbin coil voltage.

At least two orders of magnitude lower multiple tube rupture probability than for single ones was obtained in the analysis. Thus, for operational periods 1992-93 and 1993-94, multiple tube rupture probability is not a concern. Therefore, only single tube rupture probabilities during postulated SLB accident were used in further investigation.

The efficiency of specific maintenance may be further estimated based on comparison between tube rupture probabilities obtained by implementing specific and generic maintenance. A ratio between tube rupture probabilities obtained following specific

(TRP_{ODSCC}) and generic maintenance ($TRP_{45\%}$) was used as a criterion for the efficiency. Better efficiency of specific against generic maintenance is obtained when the ratio is less than 1 ($TRP_{ODSCC} < TRP_{45\%}$, Figure 2, bellow approx. 1.3 volts).

Also, number of tubes which shall be plugged by implementing one or another maintenance can be used to define the efficiency of specific maintenance. A ratio between number of tubes which shall be plugged following specific (PLG_{ODSCC}) and generic maintenance ($PLG_{45\%}$) was used as a criterion for the efficiency. Better efficiency of specific against generic maintenance is obtained when the ratio is lower than 1 ($PLG_{ODSCC} < PLG_{45\%}$, Figure 2, above approx. 0.9 volt).

On Figure 2 all three criteria which can be used to define maintenance efficiency are presented for data observed during ISI'93 inspection of SG #1.

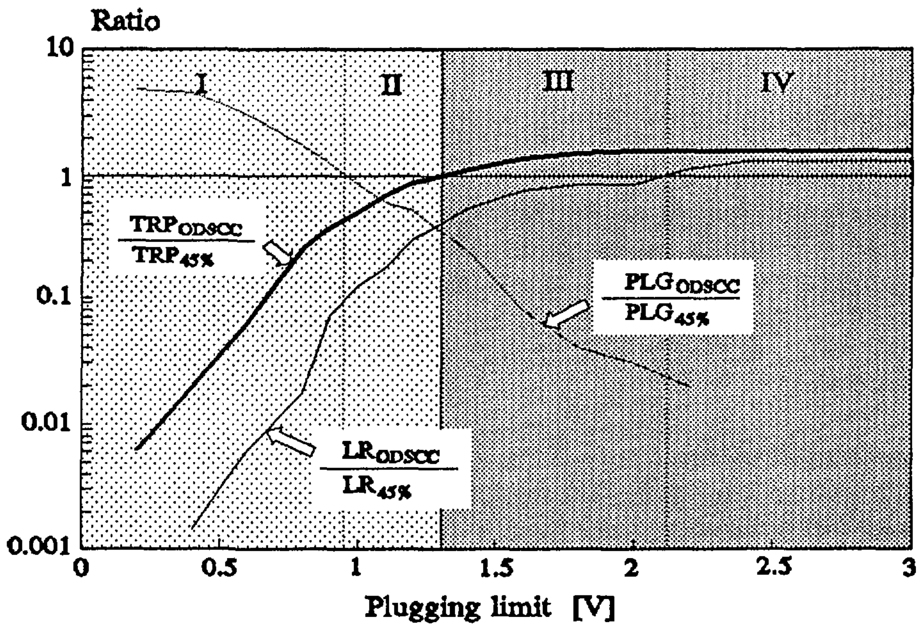

Figure 2 The efficiency of ODSCC specific maintenance (Krško NPP, SG1, 1993)

TRP	tube rupture probability
PLG	number of plugged tubes
LR	leak rate
ODSCC	index for specific maintenance
45%	index for generic maintenance

Plugging limit domain can be divided into two areas from a safety point of view: 1) an area where tube rupture probability and leak rate obtained for specific management are lower than was obtained by using generic maintenance (enhanced safety, include I and II), and 2) an area where at least one of safety parameters (tube rupture probability or leak rate) exceeds values obtained by generic maintenance (reduced safety, III and IV).

If number of tubes which shall be plugged following one or another maintenance is also taken into account than area of enhanced safety can be subdivided in further two smaller areas. For the first one (area I) it can be said that enhanced safety could be obtained by plugging of larger number of tubes following specific maintenance compared to generic. In the second one (area II) larger level of safety was obtained at lower number of plugged tubes.

How safe is ODSCC specific maintenance depends on in which area lies plugging limit. If plugging limit lies in area of enhanced safety than contribution of new approach using specific maintenance can be estimated as positive.

Optimum efficiency of specific maintenance can be achieved when plugging limit is in area II where higher safety level can be obtained with less plugged tubes compared to generic maintenance. Thus, better efficiency of new approach can be obtained due to better description of degradation phenomena.

The efficiency of specific maintenance is in general function of particular steam generator and operating cycle.

5. CONCLUSIONS

Defect specific maintenance strategy was presented for outside diameter stress corrosion cracking type of defects in the tube to tube support plate intersections. A specific analysis of Krško NPP data has been performed following procedure for defining defect specific plugging criterion. The procedure was implemented also in order to compare the efficiency of specific maintenance against the generic. The criteria of efficiency were: number of plugged tubes, maximum expected leak rate through all defects in SG, and probability of tube rupture.

To compare the efficiency of specific against generic maintenance ratios between all three criteria were estimated. For each criterion a plugging limit exists bellow or above which specific maintenance exhibits better efficiency. However, the efficiency is in general function of particular steam generator and operating cycle.

The criteria divide plugging limit domain into two areas which are important from a safety point of view: 1) tube rupture probability and leak rate obtained for specific management are lower than those using generic maintenance (enhanced safety) and 2) at least one of safety parameters (tube rupture probability or leak rate) exceeds values obtained by generic maintenance (reduced safety).

The safety of specific maintenance therefore depends on the plugging limit. It is improved if plugging limit lies in the area where lower tube rupture probability and leak rate is obtained by implementing specific maintenance than by using generic maintenance.

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