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HOW TO OPERATE SAFELY STEAM GENERATORS WITH MULTIPLE TUBE THROUGH-WALL DEFECTS

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1 INTRODUCTION

For a Nuclear Power Plant (NPP) of the Pressurized Water Reactor (PWR) type, the Steam Generator (SG) tube bundle represents the major but also the thinnest part of the primary pressure boundary. To the extent that no tube material has yet been identified to be immune to corrosion, defects may initiate in service and easily propagate through wall. While not a desirable feature, a Through Wall Deep (TWD) defect does not necessarily pose a threat to either the structural integrity or leaktightness and this paper shows how SG can (and indeed, do) operate safely and reliably while having many tubes affected by deep and even TWD defects.

2 PLUGGING CRITERIA AND DEFECT MANAGEMENT

The degraded tube issue is addressed by
. development and implementation of inspection techniques for proper detection and characterization of defects,
. definition and licensing of "plugging" or "repair" criteria.

Historically, the first plugging limit was developped on basis of the then prevailing damage form (i.e. a uniform corrosion thinning process called "wastage") and somewhat abusively generalized into a requirement of a maximum depth of 40 % (of the tube wall thickness) for any type of defect.

When other generic corrosion problems showed up later on, with highly localized defect morphologies (such as pits or cracks), the famous "40 % limit" appeared overly conservative and a trend developed towards Mechanism Specific Defect Management (MSDM). This new policy is already implemented in a number of countries but is still under licencing review in some others [1]. It results in Alternate Repair Criteria (ARC) which are dedicated to each particular form of generic tube degradation.

3 DETERMINISTIC VERSUS STATISTICAL APPROACHES

Two main approaches need be differentiated :
- deterministic : when the defect morphology is simple enough that it can be sized (e.g. in length and/or depth) by an In Service Inspection (ISI) examination technique. A characteristic defect dimension is then compared to the corresponding calculated critical value, taking appropriate service

conditions and safety margins into account,
- statistical : when a complex defect morphology does not allow a dimensional characterization. An overall measure of the degraded tube residual strength (such as burst pressure) is then statistically correlated to some feature of an ISI signal. A lower bound of this correlation allows to define a signal limit, with proper safety factor.

In both cases there is a further consideration of additional margins for measurement uncertainties and defect growth during the next operating cycle.

As the here above defined "structural limit" allows TWD defects to remain in service, there is an additional concern about the leak rate during normal operation or accident conditions (secondary side depressurization), thus leading to the additional consideration of a "leakage limit".

4 ESTABLISHMENT OF THE STRUCTURAL LIMIT

The methodology of deriving the structural repair limit is presented hereafter, with an aim at showing the consistency between the two mentionned approaches, deterministic or statistical.

What needs to be first defined is the residual strength of the degraded tube ; let us assume the simple (and frequent) case when it can be related to a single measurable feature of the tube inspection, which can be called a "degradation index".

For the deterministic approach, this could be the length of a crack which is either through-wall or conservatively assumed as such ; this length is measured by appropriate Non Destructive Testing (NDT) techniques such as Eddy Current Testing (ECT) or Ultrasonic Testing (UT). The theory of collapse load then allows to calculate the burst pressure as a function of the crack length. Different curves will be obtained as the result of variations in

- the tube wall thickness
- the material mechanical properties
- the coefficient relating the "flow stress" to the conventional tensile properties.

Selection of these parameters at their most conservative value (minimum specified, lower tolerance , ...) will generate a single reference lower bound curve.

For the statistical approach, the degradation index could be any characteristic of the NDT signal that exhibits a reasonable correlation with the tube burst strength ; let this be the signal amplitude under a well defined inspection and calibration procedure. The burst pressure has to be effectively measured as a function of signal amplitude for a sufficient number of test pieces (either from actual degraded pulled tubes or from simulated laboratory corrosion specimens) ; to reduce the data scatter the burst pressures should be normalized to a reference flow stress and, possibly, a given wall thickness (both could be taken at their minimum specified or lower tolerance value). By proper selection of axes transformation the resulting data plot may generally be analyzed by linear reegression to establish a lower bound curve.

The lower bound curve obtained either way (deterministic or statistical) is now used to derive a structural repair limit as illustrated in figure 1. In accordance with applicable safety requirements a reference pressure is obtained by multiplication of the actual maximum differential pressure with an appropriate safety margin (either 3 for normal operating conditions or $\sqrt{2}$ for accidental conditions). This reference pressure intersects the resistance curve at a value "I" (either length or amplitude) which is acceptable at the End Of Cycle (EOC) or at the time of the next scheduled inspection. Thus the degradation index has to be reduced by a growth allowance (upperbound expected during the next operating cycle) before yielding the desired allowable value at the Beginning Of Cycle (BOC). Such a growth is often dependant on the initial value of the degradation index and the appropriate growth value "ΔI" is thus obtained from the statistical correlation between the growth and the final value, observed during the previous operating cycles of the plant and/or other similarly affected plants.

5 ESTABLISHMENT OF THE LEAKAGE LIMIT

The plugging (repair) structural limit derived from the ARC methodoloy may leave in service a (potentially) large number of through-wall defects. This does usually not result in any significant operational leakage, as the cracks are very tight and moreover kept closed by thin remaining ligaments or clogged by cruds and precipitates.

However the leak rate may initiate or considerably increase under accident conditions, such as a secondary side depressurization resulting from a Main Steam Line or Feedwater Line Break (MSLB or FWLB). If the leak rate Q from a crack is approximated by the following model

$$Q = K\ S\ \sqrt{2\Delta p/\rho}$$

it can be seen that there are 3 sources of uncreased leakage :

- Increase of differential pressure Δp, from about 100 to 180 bar.
- Increase of leakage area S, both elastically and plastically.
- Increase of the flow discharge coefficient K, because of the decreasing tortuosity through a widened crack.

Moreover some ligaments of the cracks are likely to break under the increased loading while any clogging material is likely to be wiped away by the increasing flow rate.

As it is not possible to establish a reliable ratio of accident to service leakage, the leak rate resulting from a secondary side depressurization is directly obtained from a probabilistic assessment, taking into consideration the statistical distributions of all contributing parameters. Alternatively, each parameter may be taken at some acceptable upper bound value in order to generate a deterministic leak rate as a function of the degradation index.

Depending on the selected approach, the total expected leakrate is obtained by either performing the full probabilistic assessment or by adding together the elemental leak rates associated with the degradation index of each affected tube to be left in service.

The result is compared to the allowable total leak rate ; this value, established in accordance with appropriate safety and licensing rules, insures that the radioactive release to the environment will be kept within acceptable limits. If the allowable leakrate is exceeded, a number of additional tubes are selected for plugging and/or repair and the calculation is rerun ; this procedure is repeated until compliance is achieved.

Thus the "leakage limit" may require more tubes to be plugged/repaired than dictated by the "structural limit". The "leakage limit" is not a single value that can be predefined ; moreover it is likely to decrease with time, for the same SG and an unchanged set of safety criteria.

The establishment of both limits will now be illustrated in the frame of two generic degradation processes affecting many SG.

6 THE ODSCC PROBLEM IN THE SLUDGE PILE ON TOP OF THE TUBE SHEET

The statistical approach of the "structural limit" is illustrated hereafter for the case of the Outside Diameter Stress Corrosion Cracking (ODSCC) occuring within the sludge pile on top of the Tube Sheet (TS) as well as, to a limited extent, in the similar sludge lying on top of the lower Tube Support Plates (TSP). The corrosion process is initiated by concentration of the aggressive chemical species within the sludge pile ; however, once initiated, the process propagates even in absence of sludge (which may have been removed by chemical cleaning and/or routine sludge lancing).

The defective area ranges typically from 10 to 250 mm above the TS top, which corresponds to the (prior) heigth of the sludge pile. The morphology is complex, from a multidirectional crack pattern (called therefore "cellular") at the OD initiation surface to dominant by axial cracks in depth, which may grow very deep but generally not entirely through-wall.

It is impossible to size such defects by any existing NDT technique. However a good detection sensitivity is achieved by the conventional Eddy Current methodology using a Bobbin Coil (BC) in the absolute mode and the signal amplitude has been correlated with the burst pressure of tubes pulled from several plants of two European countries (see figure 2). Also, the amplitude growth rate (expressed in mV/cycle) has been correlated with the initial (or final) amplitude, as illustrated by figure 3. Implementation of the methodology described under § 3, at a confidence level of 95 % has resulted in a plugging limit of about 500 mV which is now routinely applied at the outcome of the 100 % BC inspection performed at each refueling outage of the affected units.

Because of the statistical nature of the approach, a small percentage of degraded tubes may not comply with the requested safety margin and one could argue that some tubes may have no margin at all and lead to a Steam Generator Tube Rupture (SGTR) in case of a MSLB (or FWLB) accident. This is only acceptable if the combined probability MSLB + SGTR is lower than 10^{-6}, which is a sufficiently low value for not to be considered as a safety issue, according to current licensing practices (the more so that the MSLB + SGTR event has also been shown to normally result in acceptable radioactive release to the environment). As the probability of MSLB/FWLB has been established at a level of about 10^{-4}/reactor year, the conditional probability of SGTR (i.e. given the occurence of MSLB) needs only be lower than 10^{-2} ; this can easily be verified when the described ARC policy is implemented, even for a large amount of tubes with a signal amplitude close to the "structural limit".

7 THE PWSCC PROBLEM IN THE TUBE ROLL TRANSITION

The probabilistic assessment of the "leakage limit" is illustrated hereafter for the case of the Primary Water Stress Corrosion Cracking (PWSCC) in the roll transition of tubes mechanically expanded in the SG tube sheet. The corrosion process is initiated by the primary side, in areas of high (residual) tensile stresses, even in the absence of any water contaminant. The morphology is simple as it involves a small number of parallel axial cracks (the longest of which governing the burst strength) which are usually very deep and can be approximated as TWD without undue conservatism.

The longest crack length is used as the degradation index, and can be accurately measured by such inspections techniques as ECT Rotating Pancake Coil (RPC) or UT rotating probe. While these techniques have long been considered as prohibitively slow for 100 % inspection of the roll transitions, the field performance has been recently improved to a dramatic extent ; for instance, with the Laborelec developed technology, a fully automated data acquisition and analysis ECT/RPC system produces a full report of the entire SG tube bundle in about 2 ½ days, while the UT system allows inspection of several hundreds tubes at a rate not exceeding twice that of the ECT/RPC system.

Based on the large data base thus produced for crack length distribution and growth, a probabilistic model was developed by Laborelec and implemented into a software program, called LABOLEAK [2], to provide a direct assessment of the SG leak rate under accident conditions. Figure 4 illustrates the flow diagram of the program which performs a Monte-Carlo type analysis of the various contributing parameters
. mechanical properties (YS + UTS)
. ratio of "flow stress" to (YS + UTS)
. wall thickness
. sizing uncertainty on crack length
. expected EOC crack length distribution,
the latter being generated by a subprogram (LABOGROW) based on a statistical knowledge of crack growth as a function of the BOC crack length.

8 CONCLUSIONS

The residual strength of degraded SG tubes can often be correlated to a measurable degradation index, either physical (such as a crack length) or empirical (such as a NDT signal amplitude).

Well established theoretical failure models or statistical techniques are used to give adequate confidence that a SG tube rupture will be avoided in the unlikely case of a large secondary side accidental depressurization.

Tubes complying with the "structural limit", may require plugging from a lower "leakage limit" in order to maintain at an acceptable level the radioactive release to the environment under accident conditions.

The proper implementation of these two plugging/repair limits requires performance of extensive inspections with sensitive and accurate NDT techniques. A better knowledge of the SG condition is thus achieved and is a key factor to the reliability of the MSDM policy and the resulting successful operation of SG with multiple tube through-wall defects.

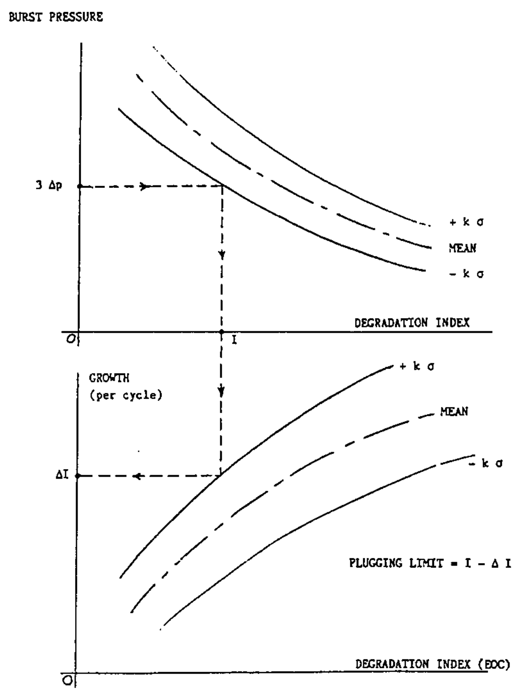

Figure 1-Arc Methodology

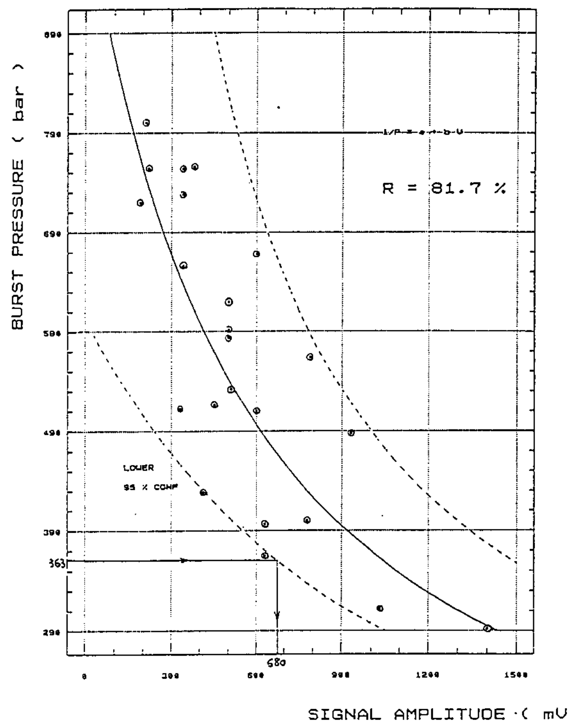

Figure 2-Pressure-Amplitude Correlation

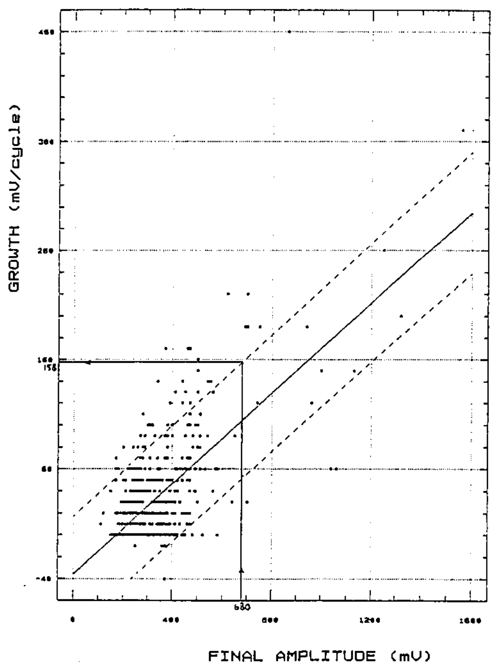

Figure 3-Growth-Amplitude Correlation

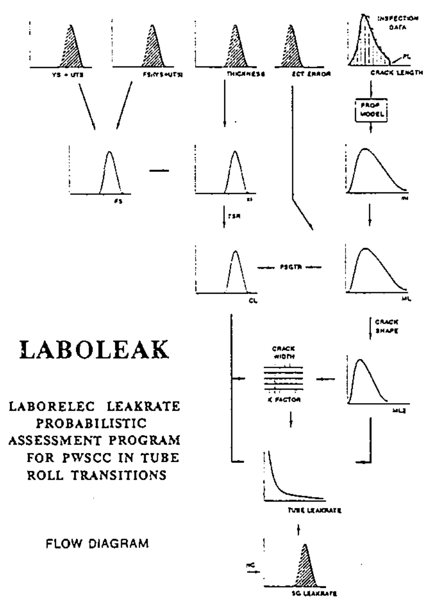

Figure 4

9 REFERENCES

[1] EPRI report TR 100407, March 1992, "PWR SG Tube Repair Limits : Technical Support Document for ODSCC at TSP".

[2] Hernalsteen P., 1991, "The Probabilistic Assessment of SG Leak Rate during a Secondary Side Accident", SMIRT 11, paper F 08/3, Tokyo.