On the integrity of steam generator tubes and plugging assessment

D.Azodi & H.Schulz
Gesellschaft für Reaktorsicherheit, Köln, FR Germany
R.Arenz
Kraftwerk Union AG, Erlangen, FR Germany

SUMMARY

The long-term operation of steam generators has shown wall degradation of steam generator tubes. The extent of the damage depends on the design, material and water chemistry. In the licensing process conservative procedures are established, which require an early blockage of the damaged tubes to avoid a leakage.

The aim of the research work reported here, was to develop criteria to be applied for evaluation of the limit load and the margin of safety of the steam generator tubes in which defects are found during inservice inspections.

Typical damage shapes of degraded steam generator tubes made of INCOLOY 800 have been investigated. The wastage corrosion was found to be the most frequent damage type.

With respect to the radiological burden to be expected in case of steam generator replacement or retubing, new methods to predict the integrity of degraded steam generator tubes were submitted.

Results of burst and collapse tests which were carried out by different organisations have been specifically evaluated and a system of analytical solution was established to determine the limit load of degraded tubes. These results have also been compared with the experimental data.

Further investigation was made to define the critical defect sizes for steam generator tubes. The procedures of ductile crack extension based on GE-EPRI Handbook was also used to find out the crack growth and the instability point for different loading levels and defect geometries.

The load carrying capacity of degraded tubes at higher temperatures resulting from loads beyond design basis accidents and the probability of multiple tube failures were investigated and are also reported.

Regarding the achieved analytical results in this research project, one is able to predict the limit load for the defective tube and estimate the safety margin for different operational events.

1 INTRODUCTION

In the long-term operation of steam generators (SG) the degradation of SG tubes (SGT) has been a matter of concern. The problem has re-

sulted in unplanned plant outages and costly repair operations such as plugging or SG replacement. The extension of the damage in SGTs depends on the design, material and chemical environment. In the licensing process conservative procedures are established which lead to an early plugging of defective tubes (e.g. 50 % wall degradation).

In order to evaluate the type of failure more specifically a research project was launched (see Figure 1). The specific aims of this research were [1] to find the typical damage shapes of degraded SGTs (see Figure 2) operating in Federal Germany and to develop a system of analytical solutions to determine the limit load of defective tubes.

2 SGT DEGRADATION MECHANISMS

INCOLOY 800 is the tube material that is being used in all operating steam generators in Federal Germany, supplied by the KWU. The principal cause of corrosion damage for this material is the local concentration of aggressive chemicals within the secondary side of steam generators with phosphate treatment. The major source of these impurities is inleakage of condenser cooling water. The concentration of these impurities is affected by the thermal and mechanical design parameters of steam generators by accumulation of chemicals and corrosion products within the steam generators as plants age.

Wastage (localized tube wall thinning) and pitting (relatively deep, small volume attack) are generally two types of corrosion that may occur when regions of restricted water flow and high heat flux tube surfaces cause nonvolatile impurities to concentrate or to precipitate. These high concentrations may occur in areas where sludge deposits have built up on the tube sheet.

A few German plants have experienced some degree of wastage and one plant pitting corrosion while operating with phosphate treatment of the secondary coolant water [2]. As a consequence, there is a change in some plants with KWU SGs from a phosphate treatment to an all volatile treatment (AVT) (see Figure 3). Since the establishment of AVT chemistry control, both the evidence and the extent of wastage have diminished and no further substantial tube degradation due to this mechanism is expected to occur. Nevertheless, the authors have found that the wastage corrosion is still the most frequent type of damage in SGTs using secondary side phosphate treatment.

Further degradation mechanism that are generally being considered are (see Figure 2):

- Stress corrosion cracking and intergranular attack. INCOLOY 800 has a high resistance against intergranular as well as transgranular stress corrosion cracking.
- Denting: The annulars between tubes and support plates if made of carbon steel, will be filled with hardened corrosion products that continue to form by the corrosion of the support plates and exert sufficient forces to "dent" the tubes diametrically. The tube support plates material in the German SGs is the stabilized austenitic stainless steel 1.4550 (ASTM 347), therefore no degradation due to denting is expected to occur.
- Fretting or tube wear is primarily a mechanical degradation. Only two plants in Germany have experienced tube's fretting, however, the extent of the wear has been small and only a few tubes have been removed from service by plugging.

- Crevice corrosion: The SG tubes have been expanded by a rolling procedure at the upper and lower ends of the tube sheet. Consequently the crevice between the tube and tube sheet is closed, up to now crevice corrosion has not been observed.

3 SGT Integrity, Defect Evaluation and Plugging Criteria

A defect in a SG tube grows slowly during service by the wastage corrosion mechanism, until it attains a critical size defect at which it is able to propagate unstably by a plastic fracture. Regarding the known defect geometry and in-service conditions the burst test results (see. 3.1) can be used to determine the critical wall degradation. For crack-like defects there is a further possibility by using the equations in 3.2.

If a degraded tubing is found during in-service inspection with a knowledge of the critical wall degradation and the rate of corrosion as determind via appropriate laboratory test, and evaluation of operating experience, the remaining useful life of the tubing can in principle be estimated and a rational run/retire decision can be made.

3.1 Burst Test Results

Many series of burst tests [3], and [4] were performed to establish the margin-to-failure predictions for mechanically defected SG tubing. Defect geometries tested were selected because they simulate known or expected defects in SGs. These defect geometries are uniform thinning, elliptical wastage, Electric Discharge Machining (EDM) slots.

The material characteristic data of test tubes are given in Figure 4. These data were also being used for the analytical investigations that are reported here. The dimensions of the tubes are 22 mm external diameter and 1.2 mm wall thickness.

This part summarizes the work made to develop a simple analytical expression to describe the burst test results (see Figure 5).

For an elliptical wastage defect the normalized burst pressure is (Figure 6):

$$\frac{p}{po} = (1 - h/s)^{0.33 + 0.45 \cdot h/s} \qquad (1)$$

Whereby:

p_o: burst pressure of an undegraded tube
s: wall thickness and
h: defect depth

The normalized burst pressure for unform thinning defect is:

$$\frac{p}{po} = (1-h/s)^{1-e^{F \cdot L \sqrt{r_i (s-h)}}} \qquad (2)$$

Whereby:

L: defect length
r_i: inner radius of the degraded tube
F: depends on the defect length L:

For $L \leqq 5$ mm is $F = -0.12$
For $L > 5$ mm is $F = -0.13$

The empirical burst relationship for an axial surface defect is

$$\frac{p}{po} = 1 - h/s + h/s \cdot e^{F \cdot L \sqrt{r_i - s}} \qquad (3)$$

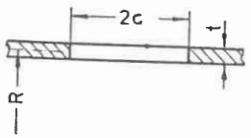
For $L \leqq 7$ mm is $F = -0.55$
For $L > 7$ mm is $F = -0.37$

3.2 Estimation of Critical Defect Sizes

If the degradation growth rate of SGT in-service is greater than anticipated, it is desirable and essential, to demonstrate that a slowly growing defect will develop into a small leak rather than propagate unstably and lead to a large break (see Figure 7). In this context it is usefull to determine the critical axial or circumferential defect size for conditions under consideration in order to compare it with the real SGT defect [5] - [8].

The correlation between internal pressure p and the critical through-wall defect size 2c in axial direction is derived as follows:

$\sigma = \sigma_f / M$
σ: hoop stress
σ_f: flow stress
$\sigma_f = 0.57 \, (R_{p0.2} + R_m)$
M: bulging factor
$M = 0.614 + 0.386 \cdot e^{-\lambda} + 0.481 \cdot \lambda$
λ: shell parameter
$\lambda = [12 \, (1-\nu^2)]^{0.25} \, \frac{a}{\sqrt{R \cdot t}}$

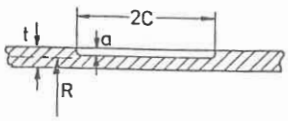


For the geometry and material properties discussed previously SGT failure occurs if:

$$p = 57.74 \; / \; (0.614 + 0.248 \cdot c + 0.386 \cdot e^{-0.51 \cdot c}) \; [N/mm^2] \qquad (4)$$

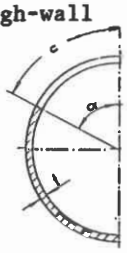
The critical depth a of an axial part through wall defect is:

$$\frac{\sigma_u}{\sigma_f} = \left[\frac{1 - \frac{a}{t}}{1 - \frac{a}{t \cdot M}} \right] \qquad (5)$$



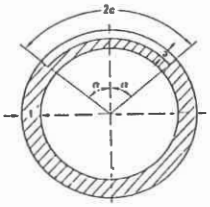
A circumferential defect in SG tubing, has the critical through-wall size 2α as

$$\frac{\sigma_{ax}}{\sigma_f} = \left[\frac{\pi}{\pi\alpha} \cdot \left(1 + \frac{2 \cdot \sin\alpha \left(\cos\alpha + \frac{\sin\alpha}{\pi\alpha}\right)}{(\pi\alpha) \quad \frac{2\cdot\sin^2\alpha}{\pi \quad \alpha} \quad \frac{1}{2}\sin 2\cdot\alpha}\right)\right]^{-1} \quad (6)$$



The critical part through-wall defect depth a in circumferential direction is

$$\frac{\sigma_{ax}}{\sigma_f} = \frac{\pi}{\pi - \frac{a}{t} \cdot \alpha} \left[1 + \frac{2 \cdot \frac{a}{t} \cdot \sin\alpha}{\pi \cdot \left(1 - \frac{a}{t}\right)}\right] - 1 \quad (7)$$



3.3 Tube Integrity Assessment Based on a Simplified Fracture Mechanics Approach

For safety and integrity assessment of the flaws in the nuclear components, the analysis based on the elasto-plastic fracture mechanics and J-Integral concept are more qualified.

The J-Integral has shown its applicability for the description of crack initiation and for a limited amount of stable growth.

Based on detailed finite element (FE) analyses and on fracture mechanics experiments, GE sponsored by EPRI has published the ductile fracture handbook (FH) [9] and [10]. The FH uses mainly approximative equations and tabulated functions for the estimation of the crack behaviour, in two dimensional (2D-), precracked structure in the elastic plastic range of material, see. Figure 8.

The dimensionless values h are functions of the geometrical parameters a/b, R_i/R_o and of the exponent n of the Ramberg-Osgood-equation.

With catalogued function h, the geometrical parameters of the flawed structure and the loads p/p_o, the material behaviour governed by the stress-strain-curve gives the following expressions for the J-integrals, the fully plastic solution:

$$J_p = \alpha \cdot \sigma_o \cdot \varepsilon_o \cdot c \cdot h\ (a/b,\ R_i/R_o,\ n)\ (p/p_o)^{n+1} \quad (8)$$

the elastic solution

$$J_E = K_I^2/E', \quad (9)$$

and the elasto-plastic-solution

$$J_{EP} = J_E + J_P \quad (10)$$

K_I is the stress intensity factor and E' is the modulus of elasticity.

For given SGT values as mentioned above the J-integral can easily be computed for a range of crack length a and loads p of interest.

The experimentally determined J-resistance curve for Incoloy 800 H is superimposed at the initial crack length. Equilibrium of crack

growth requires that the applied J-curve equals the material resistance to crack growth (J_R). Thus, a fixed load line and a fixed displacement line intersect at a point on J_R curve at the defined values of J_{IC}. The maximum attainable load during crack growth is defined at the point of tangency of a constant p curve and the J_R curve, J_{in}.

In this way, the following condition is accomplished

$$(dJ/da)_{structure} \geqq (dJ/da)_{material}. \qquad (11)$$

Some typical results of FH computations for circumferential part through-wall crack in SGT are shown in Figure 9.

3.4 Plugging Criteria

In the Federal Germany's licensing process, defected SGTs are assessed on the basis of a case-by-case decision. A wall degradation from 50 % leads in general to the plugging of the tubing.

The plugging criteria for establishing the SGT plugging limits are based on the allowable defect sizes. Apart from using analyses and burst test results, the determination of the allowable defect size includes also:

a) Margins of the accuracy for the periodic in-service inspections (f.e. about ± 10 % for eddy current testing and about ± 5 % for ultra sonic technique).
b) A factor of safety of not less than 2.7 for part through-wall defects against failure by bursting under normal operating conditions at any tube location and a factor of safety of not less than 1.43 under accident loading conditions.
c) The operational allowance for degradation growth between the inspection periods. The degradation growth rate, obtained from periodic in-service inspections, is roughly about 3 % of wall thickness for SG's with phosphate treatment.

3.5 Integrity Beyond The Design Basis Accident

In the course of the Federal Germany's risk studies loading conditions beyond the design basis accident loading have been investigated with respect to the ultimate load carrying capacity of degraded SG tubes. A summary of results is presented here. Due to core-meltdown the loading conditions investigated were - in the worst case (main steam line break) - pressure about 161 bars and temperature about 600 °C.

The material properties at this temperature are: yield stress 137 (N/mm^2) and ultimate stress 349 (N/mm^2). The failure pressure of undefected SG tubing is about 353 (bars) at 600 °C. Regarding the pressure relation $\frac{p}{p_o} = 0.46$ the critical wall degradation is shown in Figure 10. It is still about 68 % of wall thickness.

4 Discussion of results and conclusions

The goal of the investigations was to determine and assess the most frequent type of defect mechanism in SGTs with respect to its potential for producing tube failure and bound their growth rate characteristic so that a flaw evaluation and a plugging assessment may be conducted.

The authors found that for the tubes made of INCOLOY 800 the wasta-

ge corrosion is the most frequent type of damage, however only in SG's using secondary side phosphate treatment.

Based on different analytical relationships mentioned in part 3, the correlation between degraded tube wall and normalized burst pressure (Figure 6) and the critical defect size (Figure 7) has been demonstrated. Regarding the safety factors under normal operating and accident loading conditions, and the corrosion growth rate per year, the plugging limit estimated was not less than 60 % of wall degradation.

The comparison of tube integrity evaluation methods is shown in Figure 11 for axial and in Figure 12 for circumferential part-through wall defect with respect to some defect lengths. A relatively good agreement was attained between the procedures up to 9 mm defect length for circumferential and up to 35 mm length for axial defects. Therefore if one needs more information about the defect behaviour, the use of FH is recommended.

Regarding the achieved analytical results in this research project, one is able to predict the limit load for the defective tube, to estimate the safety margin and to assess the plugging limit for different operational events.

Acknowledgement

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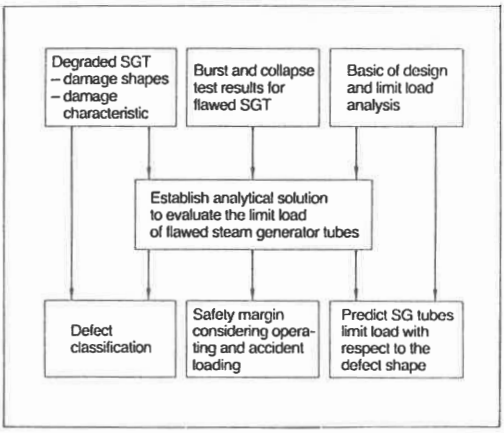

Figure 1

Reseach Program

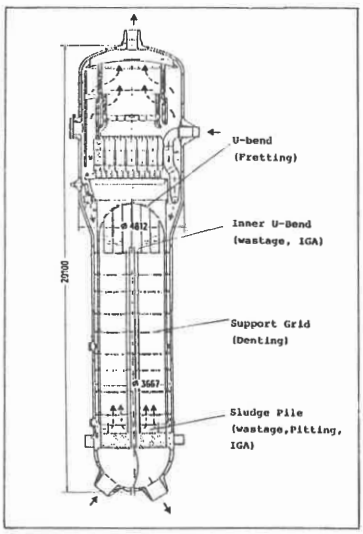

Figure 2
Steam Generator without Economizer and Typical Problem Areas

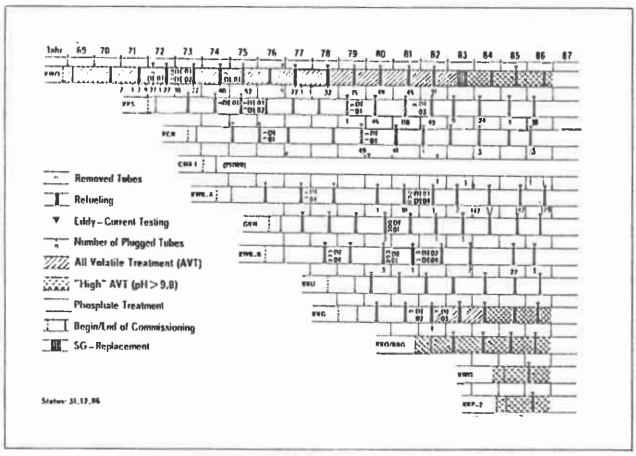

Figure 3
Operating Experience with Steam Generators Operation Periods and Inspection Times /KWU/

Material	Material properties					
	at room temperature			at 300 °C		
	$R_{p\,0,2}$ [N/mm²]	R_m [N/mm²]	A_5 [%]	$R_{p\,0,2}$ [N/mm²]	R_m [N/mm²]	A_5 [%]
Incoloy 800	334 - 471	569 - 697	30	≧ 295[1)]	≧ 495[1)]	
Incoloy 800 H	170	450 - 700	30	95	390	54
Inconel 600	240	550	30	240	550	

[1)] Valid for 350 °C

Figure 4
Characteristic Data of Steam Generaror Tube Material

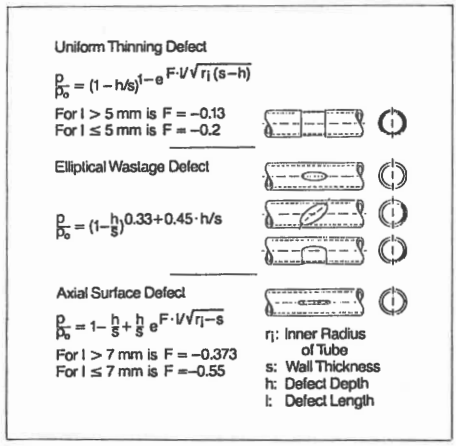

Figure 5
Empirical Burst Equations

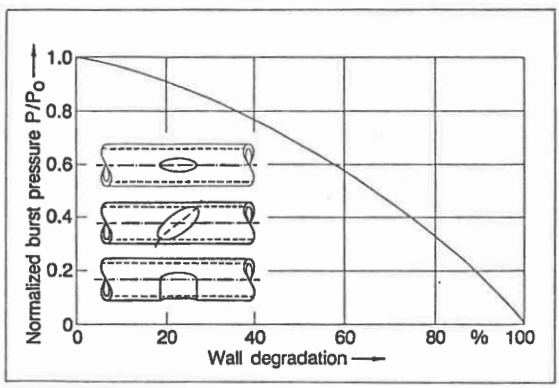

Figure 6
Normalized Failure Pressure as a Function of Wall Degradation for Elliptical Wastage Defects

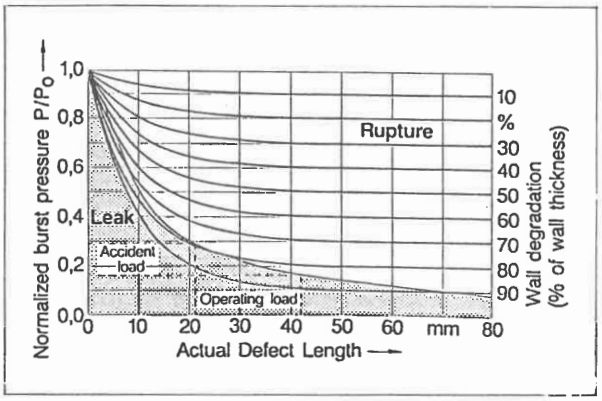

Figure 7
Leak before Break Demonstration for SGT

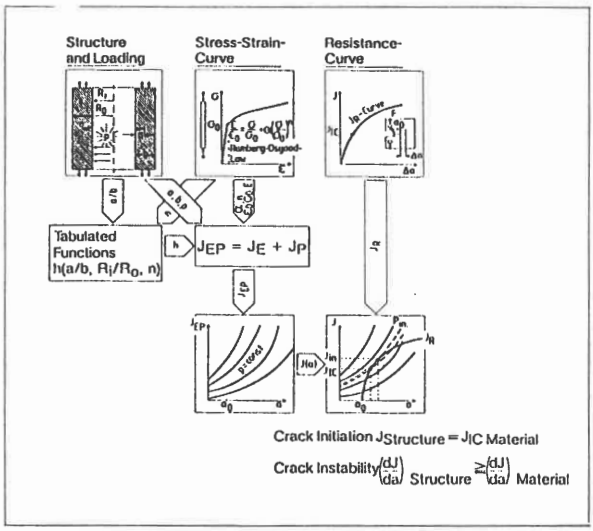

Figure 8
Technical Basis of the Ductile Fracture (GE/EPRI) Handbook

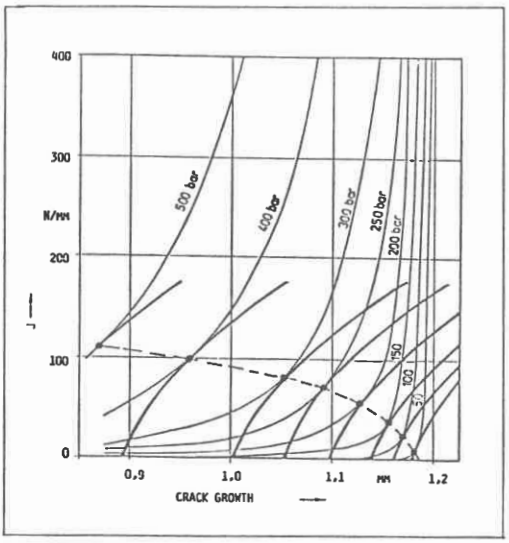

Figure 9
Estimation of Maximum Internal Pressure, SGT with an Axial Part-Through Crack

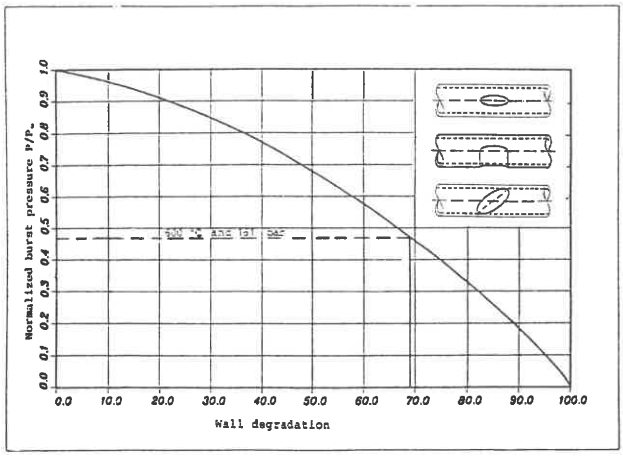

Figure 10
Normalized
Failure Pressure
as a Function of
Wall Degradation
for Conditions
beyond the Design
Basis Accident

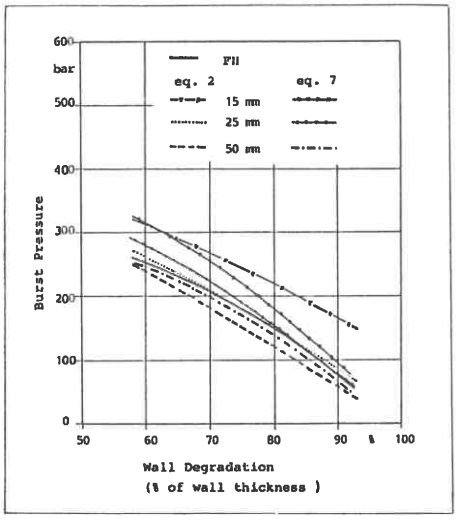

Figure 11
Comporison of
Results from
Different Analy-
tical Methods
SGT, Part-Through
Wall Axial Crack

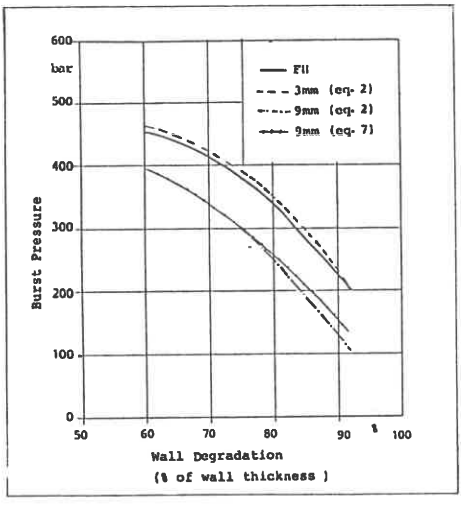

Figure 12
Comporison of
Results from
Different Analy-
tical Methods
SGT, Part-Through
Wall Circumf.
Crack