LESSONS LEARNED
FROM TUBES PULLED FROM FRENCH STEAM GENERATORS

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ABSTRACT

Since 1981, the Chinon Hot Laboratory has completed more than 380 metallurgical examinations of pulled French steam generator tubes. *Electricité de France* decided to perform such investigations from the very outset of the French nuclear program, in order to contribute to nuclear power plant safety.

The main reasons for withdrawing tubes are to evaluate the degradation, to validate non destructive examination (NDE) techniques, to gain a better understanding of cracking phenomena, and to ensure that the criteria on which plugging operations are based remain conservative.

Considerable experience has been accumulated in the field of primary water stress corrosion cracking (PWSCC), OD (secondary) side corrosion, leak and burst tests, and various tube plugging techniques.

This paper focuses on the PWSCC phenomenon and on the secondary side corrosion process, and in particular, attempts to correlate French data from pulled tubes with the results of fundamental R&D studies.

Finally, within the framework of the Nuclear Power Plant Safety and Maintenance Policy, all these results are discussed in terms of optimization of the field inspection of tube bundles and plugging criteria.

INTRODUCTION

Steam generators are critical components of pressurized water reactor systems, since they enable the heat produced by the reactor to be transferred from the primary water to the secondary circuit. Indeed, the steam generator tube bundles play a vital safety function, representing the second and third safety barriers, and are therefore subjected to stringent controls.

Unfortunately, in the early stages of the nuclear program, the steam generator tubes were made from the nickel-base Alloy 600, which proved to be sensitive to corrosion phenomena for exposure times within the typical life of nuclear power plant [1]. An EPRI study published at the end of 1995 [2] revealed that more than 60% of all the tube plugging operations performed throughout the world were due either to PWSCC or to corrosion in the secondary side environment. Since 1981, the Chinon Hot Laboratory has completed more than 380 metallurgical examinations of tubes pulled out from French steam generators. The main reasons for withdrawing tubes are to characterize the degradation, to validate non destructive examination (NDE) techniques, to gain a better understanding of cracking phenomena, and to ensure that the criteria on which plugging operations are based remain conservative. Considerable experience has been accumulated in the field of primary water stress corrosion cracking (PWSCC), secondary side corrosion, leak and burst tests, and various tube plugging techniques.

The present paper focuses on the PWSCC phenomenon and on the secondary side corrosion process. In each case, the corrosion phenomenon is described first of all in terms of cracking location, degradation parameters, basic causes, etc., before attempting to correlate the data from pulled tubes with the results of fundamental R&D studies. Finally, within the framework of the Nuclear Power Plant Safety and Maintenance Policy, all these results are discussed in terms of optimization of the field inspection of tube bundles and plugging criteria. The use of examinations of pulled tubing to validate NDE techniques has been presented in previous publications [3-4], and will not be further considered in this paper.

PRIMARY WATER STRESS CORROSION CRACKING

In France, the first cracks due to primary water stress corrosion were discovered in 1981, in the steam generator tubes of the Fessenheim nuclear power unit 1. Since then, this kind of corrosion has been found to have caused degradation in numerous mill-annealed Alloy 600 steam generator bundles, and also in some thermally treated Alloy 600 tubes. The principal results of the metallurgical examinations carried out in the Chinon Hot Laboratory on more than 280 pulled tubes are summarized below in terms of :

- the phenomenology of cracking,
- the behavior of heat treated alloy 600 tubes,
- the relationship between observations on pulled tubes and fundamental R & D studies concerning material properties.

1 - Cracking phenomenology

Primary side cracking in French steam generator tubes occurred in 3 areas : in the rolled transition zone, in the rolled region within the tubesheet, and in the small U-Bend. In all cases, the PWSCC morphology is purely intergranular.

1.1 - Rolled transition zone

In the rolled transition area, cracking can be either longitudinal or circumferential.

A - Longitudinal cracking

The main reasons for pulling tubes due to PWSCC were :

- the presence of many longitudinal cracks on a given circumference, which could possibly have prevented the detection of a circumferential crack,
- the presence of cracks close to one another endways and aligned almost parallel,
- the combination of longitudinal internal cracks and secondary side corrosion.

Generally, the longitudinal cracks are located in the rolled transition zone between the two expanded regions (Figure 1). In some cases, a very long crack was found propagating in the kiss rolled area. The location of the longitudinal cracks is consistent with the evaluation of the stress level [5-6], which showed a high circumferential stress in the rolled transition zone (Figure 2, Table 1).

For the numerous longitudinal cracks, the plugging criteria [7] are as follows :

" *Due to the possibility of circumferential cracks not being detected, tubes with more than 11 longitudinal cracks on 270° detected by the rotating probe will be plugged* ".

Moreover, an additional plugging criterion must be applied in the case of the detection of a longitudinal crack whose length in the free span is equal to or greater than 13 mm.

" *If the lower end of the crack is not in contact with the tubesheet, and the upper end is situated at 13 mm or more from the secondary face of this sheet, the tube must be plugged provided that the length of the crack is at least 10 mm* ".

In some of the metallurgical examinations on pulled tubes, longitudinal cracks aligned almost end to end have been observed. The first crack is located in the rolled transition area and the second one in the transition between the kiss rolled zone and the normal tube diameter. For this unusual case, the plugging criterion is the following :

" *two cracks located at orientations separated by 35° or less, whose opposite ends are separated by a distance less than or equal to 7 mm, are considered to be a single crack and the above plugging criteria must be applied* ".

The third reason for pulling tubes is the combined presence of longitudinal internal cracks and secondary side corrosion. Generally, the bottom of the area affected by secondary side corrosion is located a few millimeters above the top of the internal longitudinal cracks. In fact, this situation was relatively rare because of the small proportion of tubes sensitive to both PWSCC and secondary side corrosion. In this case, the important thing is to make sure that the burst pressure determined by the presence of longitudinal cracks is not significantly reduced by the secondary side corrosion damage.

B - Circumferential cracking

Circumferential cracking in the PWR primary water environment is less frequent than longitudinal cracking. However, some tubes have been withdrawn after the detection of circumferential cracking by non destructive inspection. The circumferential cracks are located just above the top of the tubesheet, and are associated with the deformation of the walls of certain tubes due to the effect of oxidized steel or iron particles in the sludge on the tubesheet (denting). The growth of these oxides induces an increase of longitudinal stresses which produce circumferential cracking.

" *Any sign detected by the rotating probe indicating the existence of a circumferential crack requires that the tube be plugged* "

1.2 - Rolled area within the tubesheet

Cracking in the rolled area within the tubesheet was observed on a few tubes, in the following cases:

i) lack of rolling ("skip roll"),
ii) lack of overlap between rolling passes,
iii) excessive bore diameter,
iiii) tubesheet drilling defects (Figure 3).

All these conditions result in sudden changes in the internal surface profile and develop high residual stresses that cause cracks. However, these various degradations are only of limited importance in terms of safety, since the tubesheet is secured to the tubes.

1.3 - Small U-Bends

In 1990, *Electricité de France* decided to examine the first steam generator replaced in France. The aim of this investigation [8-9] was to use the steam generator as a test bench for maintenance operations, and to gain a better understanding of steam generator degradation.

On this occasion, 50 small U-bends removed from the first and second rows were examined. The metallurgical examinations revealed some longitudinal cracks initiated in the PWR primary water and located at the bend transition in the hot leg (Figure 4). Some longer cracks completely traverse the tube wall.

2 - Behavior of thermally treated Alloy 600 tubes

The behavior of the thermally treated Alloy 600 tubes in PWR primary water is effectively better than that of mill-annealed Alloy 600 tubes. Therefore, only 31 thermally treated Alloy 600 tubes have been pulled out and examined in the hot laboratory. Among these 31 tubes, 16 showed evidence of stress corrosion cracking damage (8 with longitudinal cracks and 8 with circumferential cracks).

The occurrence of the longitudinal cracking was clearly correlated with a " bad " microstructure in terms of PWSCC resistance (see § 3). As for the mill-annealed Alloy 600, the cracking path was always intergranular and the stress corrosion cracks were located in the rolled transition area.

The circumferential cracking was associated with the deformation of the wall of certain tubes due to the effect of the oxidation of steel or iron particles in the sludge on the tubesheet. This denting resulted in an increase in longitudinal stresses, causing circumferential stress corrosion cracks. However, this phenomenon is now considered to be under control, and no other unit has been significantly affected by it over the last few years.

3 - Correlation between observations on pulled tubes and fundamental R & D studies

As early as 1959, Coriou et al. [10] proved that solution-annealed nickel base alloys were susceptible to intergranular stress corrosion cracking in deaerated water at high temperature. Since then, numerous R&D studies have been undertaken [11-15] concerning Alloy 600 stress corrosion cracking in PWR systems. Metallurgical examinations carried out on pulled tubes have also provided information on the influence of material characteristics, such as carbon content, microstructure, and final heat treatment at 700°C. The aim of the present comparison is to correlate the field observations of steam generator tube behavior to the fundamental R&D laboratory studies.

3.1 - Carbon content

Statistically, the stress corrosion cracking resistance of mill-annealed Alloy 600 is better for low carbon contents (0.02-0.03%) than for high carbon contents (>0.035%). This behavior is consistent with laboratory studies [12]. In fact, the main effect of the carbon content is related to the microstructure, and especially to the precipitation of chromium carbides.

3.2 - Microstructure

The microstructure of the mill-annealed Alloy 600 tubing depended essentially on the fabrication process and particularly on the final temperature, which determines the chromium carbide distribution and grain size. 3 types of structure have been defined relating to the chromium carbide distribution, as thereunder described :

- Structure I : most precipitates are intergranular,
- Structure II : the precipitates are mostly intragranular, but clearly follow the outline of prior grain boundaries (ghost boundaries),
- Structure III : most precipitates are intragranular and are more uniformly distributed than in structure II.

The PWSCC resistance of Alloy 600 is well correlated to the type of structure [16]. The tube sensitivity can be classified in 4 categories, defined by the time to cracking in reverse U-bend tests in primary water at 360°C. Laboratory studies have shown that tubes with type I structures present the highest resistance to PWSCC [15-17], and the same correlation has been clearly revealed by the field behavior of tubes [18].

Recently, two different studies have clearly shown the beneficial role of grain boundary carbide precipitation. Hertzberg et al. [19] isolated the role of carbon distribution on IGSCC in both commercial and well characterized controlled purity Ni-16Cr-9Fe-xC alloys. Constant extension rate tests performed in 360°C primary water clearly determined the respective effects of carbon content and chromium carbide precipitation. The results proved that the higher resistance to PWSCC was better correlated with the intergranular carbide precipitation than with the carbon content. Furthermore, some AEM investigations performed by Lewis et al. [20] have identified metallurgical features that affect cracking, in particular, grain boundary composition and the interaction of cracks with carbides.

3.3 - Thermal treatment at 700°C

The final thermal treatment at 700°C is a stress-relieving treatment designed to reduce the residual stresses induced by tube straightening. However, under certain conditions, this treatment could modify the grain boundary carbide coverage, and therefore the PWSCC resistance.

In the field, the behavior of thermally treated Alloy 600 tubes is better than that for mill-annealed tubes (Figure 5) [18], although the improvement depends markedly on the carbon content [12]. The beneficial effect of this heat treatment is extremely clear for material without cold work, with a carbon content lower than 0.033 %.

SECONDARY SIDE CORROSION

Secondary side corrosion of mill annealed Alloy 600 occurred in France later than PWSCC. The first tubing to be pulled for secondary side corrosion was removed from Fessenheim 1 in 1986. At that time, 97 tubes had already been withdrawn due to PWSCC. However, over the last few years, the number of tubes plugged due to secondary side cracking has rapidly increased, and in 1995 *Electricité de France* decided to replace a steam generator for the first time due to secondary side damage, at the Saint-Laurent nuclear power plant B Unit 1. Numerous studies were undertaken in order to describe and understand the cracking phenomenon [21-24]. The large amount of information obtained from the metallurgical examinations performed on the pulled tubes is summarized below in terms of :

- the location of cracking,
- the analyses of the tube deposits,
- the influence of material characteristics.

1 - Cracking location

In France, secondary side cracking has been found to involve two restricted flow regions :

- the tubesheet, in the sludge pile zone or in the crevice between the tube and the tubesheet,
- the crevice between the tube and the tube support plate.

1.1 Tubesheet

Cracking can be either longitudinal, in the free span above the top of the tubesheet, or circumferential, under the secondary side of the tubesheet.

A - Free span corrosion in the tubesheet sludge pile area

From the pulled tube investigations, free span corrosion in the tubesheet sludge pile area can be described as follows (Figure 6) :

- many short (less than 2 millimeters) longitudinal cracks,
- intergranular path,
- the cracking occurrence appears to be linked with the presence of sludge, and corrosion can therefore be found many centimeters above the top of the tubesheet.

B - Circumferential cracking under the top of the tubesheet

By the beginning of 1998, 40 tubes showing circumferential OD cracking had been pulled out and examined in the Chinon Hot Laboratory. The circumferential cracks are located a few millimeters beneath the top of the tubesheet on a section where contact between the tube and tubesheet is not tight. The upper section of this area is limited by the secondary side of the tubesheet. In the lower section, the ODSCC can reach a height of -16 mm with respect to the secondary side of the tubesheet (Figure 7). This means that in some instances, although the hard rolling specifications were met, the tubes did not press sufficiently against the tubesheet.

The circumferential cracks have been classified in two different categories [5], which can be described as follows :

" a " type : - the rupture is coplanar,
- the tubes are not located in the sludge pile area,
- in many instances, the cracking is connected to the presence of a drilling or rolling defect,
- the tube is hard rolled + kiss rolled.

" b " type : - the cracking is not coplanar. Numerous short cracks propagate on various planes,
- the tubes are located in the sludge pile area,
- the tubes are hard rolled with or without kiss rolling.

Based on the population of pulled tubes examined, type " a " cracks are deeper (average depth 44% compared to 29%) and longer (average length 250° in circumference compared to 220°) than type " b " cracks.

These two cracking morphologies may be related to different stress patterns (Table 1, [5-6]) and/or liquid flow conditions.

Table 1 - Estimation of total axial stresses at expansion transitions (after [5-6]).

LOCATION	NO SLUDGE	WITH SLUDGE
Inner Diameter		
Hard Rolling	345 MPa (50 ksi)	379 MPa (55 ksi)
Kiss Rolling	310 MPa (45 ksi)	414 MPa (60 ksi)
Explosive expansion	276 MPa (40 ksi)	310 MPa (45 ksi)
Hydraulic expansion	276 MPa (40 ksi)	310 MPa (45 ksi)
Outer Diameter		
Hard Rolling	172 MPa (25 ksi)	138 MPa (20 ksi)
Kiss Rolling	138 MPa (20 ksi)	103 MPa (15 ksi)
Explosive expansion	103 MPa (15 ksi)	69 MPa (10 ksi)
Hydraulic expansion	103 MPa (15 ksi)	69 MPa (10 ksi)

C - Mixed cracking path (intergranular and transgranular cracking)

Mixed cracking paths have been observed in a few tubes and plugs. This typical longitudinal cracking (inter and transgranular propagation) is linked to the presence of lead in the sludge pile area (5 times more lead in an area suffering mixed intergranular and transgranular stress corrosion cracking than in an area showing only IGSCC). This phenomenon is now well understood and well-documented by laboratory R&D testing [25].

D - Plugging criteria

The associated plugging criteria for 900 MWe nuclear power plants affected by secondary side corrosion in the tubesheet area are the following :

- Circumferential cracking : " *Any sign detected by the rotating probe indicating the existence of a circumferential crack requires that the tube be plugged* ".
- Secondary side corrosion in the sludge pile area : " *bobbin coil signal ≥ 500 mV or bobbin coil signal ≥ 200 mV and presence of an internal longitudinal crack (length ≥ 10 mm) with a difference in height less than 8 mm* "

1.2 Tube support plate elevations

This type of cracking mainly concerns the steam generator bundles made of mill annealed Alloy 600 and equipped with drilled hole tube support plates (TSP). The metallurgical investigations carried out on 30 pulled tubes for secondary side corrosion at TSP elevations and on a replaced steam generator at Dampierre Unit 1 [26] have shown that corrosion occurs in the crevices between the tube and the TSP, which are totally filled with deposits or oxides. Two kinds of corrosion have been observed : intergranular attack (IGA) and intergranular stress corrosion cracking (IGSCC). Based on the pulled tube population, the corrosion morphology at TSP elevations is close to that observed above the tubesheet in the sludge pile area, and can be summarized as follows (Figure 8):

- numerous short longitudinal cracks with a part of IGA,
- the closer to the TSP mid-thickness, the deeper the IGSCC and the IGA,
- the corrosion does not extend beyond the TSP limits,
- on one steam generator, shallow and narrow transverse bands of IGA (300 μm) have been found in front of the top and bottom of the TSP.
- generally, the extent of the secondary side corrosion decreases with the TSP elevation.

Corrosion of similar morphology has been encountered at the flow distribution baffle (FDB) on 4 pulled tubes, and on 2 tubes withdrawn from a steam generator equipped with broached TSPs. In both cases, the damage occurred where the tube was close to or in contact with the FDB or the broached TSP, thus reducing the corresponding clearance, allowing the crevices to be filled by the deposits or oxides.

The plugging criterion for mill annealed Alloy 600 steam generator tubes for corrosion at TSP elevations is as follows:

- Corrosion at TSP elevations : " *Bobbin coil signal ≥ 2 V (and ≥ 1 V for TSP nos. 7 and 8)* ".

2 - Analyses of the tube deposits and underlying surfaces

Since 1984, the Chinon hot Laboratory has carried out numerous chemical analyses on deposits scraped from the OD surface of pulled steam generator tubes. More than 250 deposits located at various tube/tube support plate elevations and also at the top of the tubesheet have been analyzed. These analyses provided more than 2,300 results that have been presented in several publications [27-29]. Analysis of these results, in order to obtain an improved understanding of the chemical medium actually responsible for secondary side corrosion, has highlighted the following features:

- The secondary side corrosion is associated with deposits which create or originate from restricted flow areas, where deleterious chemical species can concentrate.
- In French PWR units, corrosion occurs essentially only in restricted areas where the water flow rate is reduced, in tube-TSP crevices and at the top of the tubesheet.
- ZnO, Cu and especially SiO_2 concentrations are significantly higher in the damaged areas than in sound regions. In the restricted flow area, the major chemical species found close to the tube is silica (20% in weight).
- No significant difference has been revealed in the chemical composition of the deposit at various elevations. Therefore, the higher corrosion rates at lower TSP locations compared to upper ones seem to be due to the temperature difference between the bottom and top of the steam generator bundle.

- Some surface analyses performed on pulled tubes showed that silicate compounds were deposited with an alumino-silicate gel sublayer, more or less bound to organic compounds. Beneath this gel, a brittle, unprotective chromium and iron rich layer was observed at the interface with the matrix.

Considerable work is still in progress in order to try to correlate this brittle layer to ODSCC behavior, and in particular, to determine the role of the surface films and their stability as defined by potential/pH diagrams [30].

3 - Influence of material characteristics

The study of pulled tubes has also provided information on the influence of material characteristics such as carbon content, yield stress, microstructure, and final heat treatment at 700°C.

Based on the pulled tube population (i.e., only on cracked tubes), the average *carbon content* of the tubes which experienced OD IGA/IGSCC in the field is lower than for those which suffered PWSCC (0.02 wt. % compared to 0.03 wt. %).

Statistically, tubes with a low *yield stress* are more sensitive to secondary side corrosion than tubes with a high yield stress. This result is in good agreement with R&D studies which have shown that the stress threshold for secondary side corrosion is close to the yield stress [31]. It is also consistent with the observed effect of the carbon content, since the latter is correlated with the yield stress.

Concerning the influence of the material *microstructure*, no correlation between the sensitivity to secondary side corrosion and structural parameters such as grain size and chromium carbide precipitation has yet been established from the pulled tubes. However, further studies are still in progress, particularly aimed to improve understanding of the behavior of thermally treated tubes.

Despite a 30,000 hours difference in operating time between the longest lived mill-annealed Alloy 600 tube bundles and thermally treated Alloy 600 tube bundles, the ODSCC behavior of thermally treated Alloy 600 in the field is significantly better. Up to date, no secondary side corrosion has been observed on pulled heat treated Alloy 600 tubes.

E.D.F MAINTENANCE POLICY ON STEAM GENERATOR TUBE PLUGGING

Since 1983, the general E.D.F approach in terms of steam generator maintenance policy has been to use "Degradation Specific Management". Each type of degradation is associated with a specific analysis of root causes, the identification of the steam generator potentially affected, and the consequences on the safety (Steam Generator Tube Rupture risk) and availability (leak risk) of the nuclear power unit [32]. This analysis is mainly based on destructive and non-destructive examinations, theoretical and experimental studies, and burst tests performed on pulled tubes. This required multiple plugging criteria, a large number of pulled tubes and numerous leak and burst tests.

1 - Number of plugged tubes and root causes

Figure 9 summarizes the total number of plugged tubes per year for 900 MWe nuclear power plants, for each type of degradation. Firstly, it can be seen that, since 1990, the number of plugged tubes has decreased year after year. Secondly, the number of preventive plugging operations (AVB unsupported, TSP degradation) is still large and represents in 1996 more than 65% of the total number of plugged tubes. Thirdly, by the fall of 1997, the PWSCC plug tube amount is higher than the secondary side plug tube amount. The main reason is preventive plugging operations concerning primary side degradation.

2 - Leak and burst tests performed in the hot laboratory

In order to estimate the safety margins provided by the plugging criteria and to evaluate the risk of leakage and the bursting risk due to corrosion, the hot laboratory has performed a considerable number of leak and burst tests on pulled tubes :

- more than 250 results on tubes having suffered damage in the tubesheet area (PWSCC or secondary side corrosion),
- more than 220 results on OD corroded tubes from various TSP elevations.

The procedure used for room temperature testing, together with some of the results, have already been published [33], and only the main findings concerning the risks of leakage and/or bursting associated with the different kinds of degradation will be presented here.

Risk of leakage

The variation of the leak flow rate at 100 and 172 bar with the extent of *internal longitudinal stress corrosion cracking located in the rolled transition area* is given in Figure 10. Although we have to be very prudent when considering the following assessment, we observe that the leak rates measured on the pulled tubes appear greatly overestimated when compared to the end-of-life primary to secondary leaks in steam generators. In order to explain this behavior, the following hypotheses seem the most plausible:

- the lower part of the crack may be located in the tubesheet and therefore not leak,
- the deposits on the secondary side of the tubesheet greatly hinder the leakage.

Concerning the *secondary side corrosion above the tubesheet*, the risk of leakage is almost zero, since on the pulled tubes without the tubesheet, none of the 17 tests carried out in the hot laboratory resulted in a leakage, either at 100 bar or at 172 bar.

The number of leak tests performed on pulled tubes affected by *circumferential cracking* is too small to draw significant conclusions (only 5 tests). However, the case of a 360° OD initiated crack which completely traversed the wall over 10°, and yet did not leak at 100 bar, is noteworthy. Moreover, it should be noted that the circumferential crack opening may be increased during the pulling process, and this could falsify the results.

The *secondary side cracking at TSP elevations* is associated with deposits. The tube/TSP crevice is then completely filled after a few cycles. Therefore, only tests performed with the configuration "tube + TSP + deposit" are representative. Such tests have been carried out on assemblies pulled from Dampierre Unit 1. The leak rate measured during the tests at 100 bar is extremely low (the average value is lower than 10 cm^3/h). This result agrees with field experience, since the steam generators with the greatest damage at TSP elevations leak very little in operation.

Bursting risk

Although tests were performed with *longitudinal internal cracks* much longer than those defined in the plugging criteria (up to 19 mm), no burst pressures less than 250 bar have been measured (Figure 11).

All of the tests performed on pulled tubes affected by *secondary side corrosion above the tubesheet* resulted in a burst pressure greater than 400 bar.

None of the 18 tubes with *circumferential cracks* have burst at a pressure lower than 230 bar.

The various burst tests performed on tubes affected by *secondary side corrosion at TSP elevations* have shown a minimal burst pressure of 270 bar, even for tubes with much more severe damage than that defined by the plugging criterion.

In conclusion, all these results demonstrate that the plugging criteria are conservative and guarantee comfortable margins with respect to the Steam Generator Tube Rupture Risk.

This E.D.F. steam generator maintenance policy has two significant beneficial effects:

- on the forced outages (Figure 12),
- on maintenance costs.

Since 1985, the forced outages due to corrosion have considerably decreased, to almost zero in the 1990's. Moreover, no tube failure has been observed in any of the 55 French nuclear power units, corresponding to an equivalent of 750 reactor-years of field experience.
It should also be noted that this maintenance policy has led to a marked decrease in the steam generator maintenance costs (-25% between 1990 and the estimate for 1999).

CONCLUSIONS

An extensive program of investigation has been undertaken by Electricité de France over the last 15 years in order to describe, understand and model corrosion phenomena in steam generator tubing. Based on the metallurgical examination of 380 pulled tubes, this work has enabled the establishment of appropriate efficient plugging criteria, together with the development of a maintenance policy consistent with French steam generator field experience.

However, although only one steam generator replacement has so far been due to secondary side corrosion, the major concern for coming years is nevertheless related to the behavior of the Alloy 600 tubes in the secondary environment. There is a lot more to do with mitigating the secondary side corrosion than with the primary water stress corrosion cracking. The PWSCC problem can been solved by implementing efficient remedial actions such as shot peening, the use of Alloy 690, or repair techniques such as sleeving, nickel plating, etc. In the case of secondary side corrosion, remedial actions are less effective (except the implementation of Alloy 690), and few repair techniques are currently available.

As a matter of fact, additional work is still in progress on secondary side corrosion phenomena [34]. One of the aims is to develop a model based on both investigations on pulled tubes and fundamental laboratory studies, in order to describe and predict the occurrence of IGA/IGSCC in secondary side steam generator environments, particularly for thermally treated Alloy 600, and this is the major challenge for the future [35].

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[22] **A. STUTZMANN, F. NORDMANN, P. OLLAR**, " *Measurement of hideout return* ", EPRI Workshop, Airlie, October 9-13, 1995.

[23] **F. VAILLANT, D. BUISINE, B. PRIEUX, J.C. FOURNEL, A. GELPI**, " *Effects of microstructure and mechanical properties of Alloys 600 and 690 on secondary side SCC* ", EPRI Workshop, Airlie, October 9-13, 1995.

[24] **F. CATTANT**, " *Lessons learned from the examination of tubes pulled from Electricité de France steam generators* ", Nuclear Engineering and Design, no.168, p241-253, 1997.

[25] **F. VAILLANT, D. BUISINE, B. PRIEUX, D. GOMEZ-BRICENO, M. L. CASTANO**, " *Influence of lead on the secondary side cracking of Alloys 600, 690 and 800* ", EUROCORR'96, Nice, September 24-26, 1996.

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[27] **F. CATTANT, M. DUPIN,** " *Surface analysis of cracked tubes of Saint-Laurent B1 and secondary side water chemistry* ", EPRI Workshop, Saint-Louis, March 17-19, 1992.

[28] **B. SALA, K. HENRY, A.M. LANCHA, P. COMBRADE, R. ERRE, A. GELPI, M. DUPIN,** " *Analyses of the deposits and surface layers on pulled tubes from PWR French steam generators* ", EUROCORR'96, Nice, September 24-26, 1996.

[29] **B. SALA, K. HENRY, S. CHEVALIER, M. ORGANISTA, R. ERRE, A. GELPI, M. DUPIN, F. CATTANT,** " *Laboratory study of the IGA/SCC in the secondary side of steam generators* ", EUROCORR'96, Nice, September 24-26, 1996.

[30] **P. COMBRADE, P. SCOTT**, " *The role of surface films on Alloy 600 corrosion in PWR reactors* ", EUROCORR'96, Nice, September 24-26, 1996.

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[33] **F. CATTANT, B. FLESCH, L. MERCIER**, " *Leak and burst tests performed on pulled tubes* ", International Symposium Fontevraud III, September 12-16, 1994.

[34] **F. VAILLANT, O. de BOUVIER, M. BOUCHACOURT, A. STUTZMANN, P. LEMAIRE**, " *Secondary side IGA/IGSCC SG Alloys 600, 690 and 800 : R&D Program in EDF Laboratories* ", this conference.

[35] **M. BOUCHACOURT, J.M. BOURSIER, D. BUISINE, F. VAILLANT, P. LEMAIRE**, " *Modeling the occurrence of IGA/IGSCC in French PWR steam generators* ", International Symposium Fontevraud IV, September 14-18, 1998, to be published.

Figure 1 : Location of the inner longitudinal cracks Alloy 600 MA tube

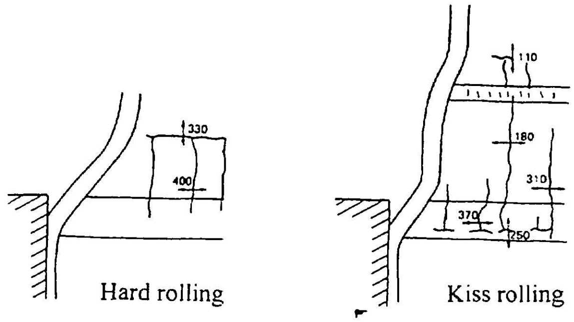


Figure 2 : Evaluation of the inner stresses

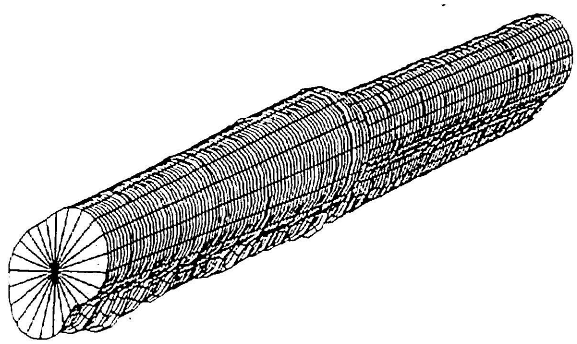
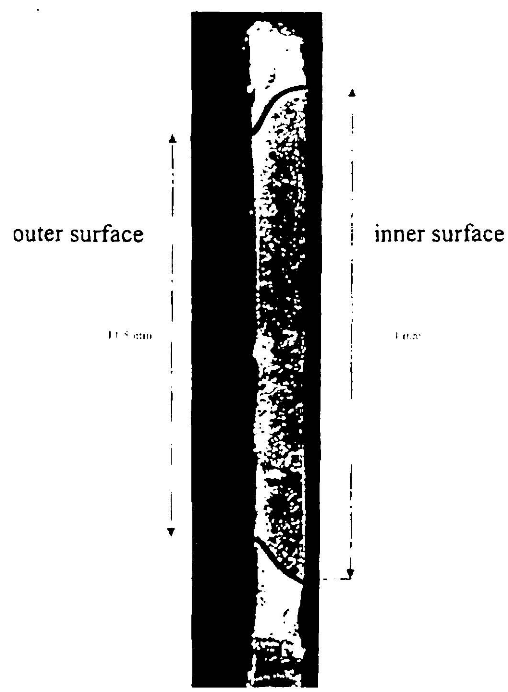


Figure 3 : Cracking in the rolled area in the tubesheet. Laser profilometry of a silastic mold of a rolled tube with a drilling defect.

A)



B)

Figure 4 : PWSCC in small U-bend.
Longitudinal cracking on MA Alloy 600.
a) Outer surface after leak test
b) Cross section of the main crack

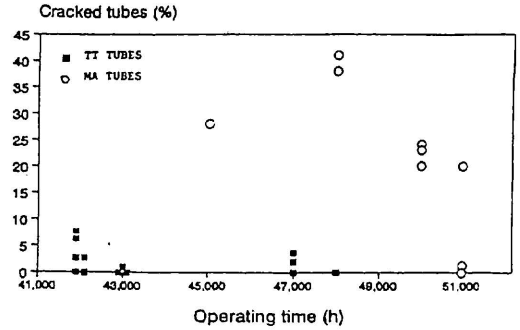
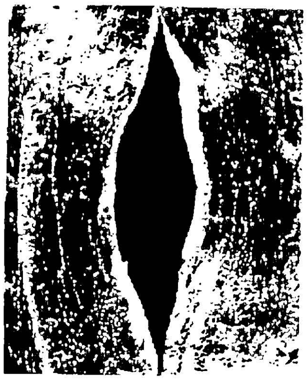
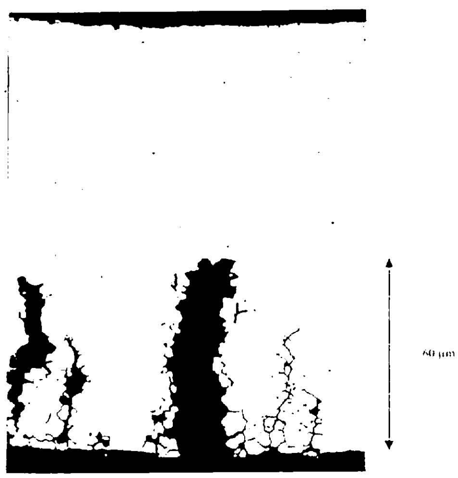


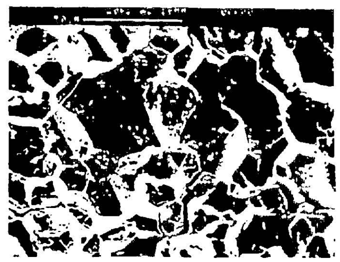
Figure 5 : Comparison of PWSCC rate on Alloy 600 MA and TT versus operating time.



a)



b)



c)

Figure 6 : Longitudinal intergranular OD corrosion in sludge pile area on MA Alloy 600 tube
a) outer surface after burst test
b) tranversal cut
c) SEM observation

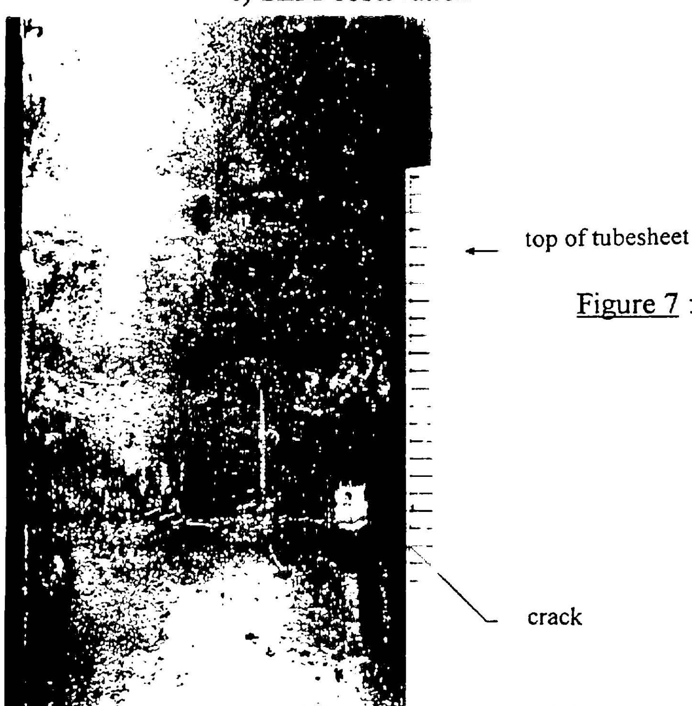


Figure 7 : Circumferential crack initiated on the outer surface of MA Alloy 600

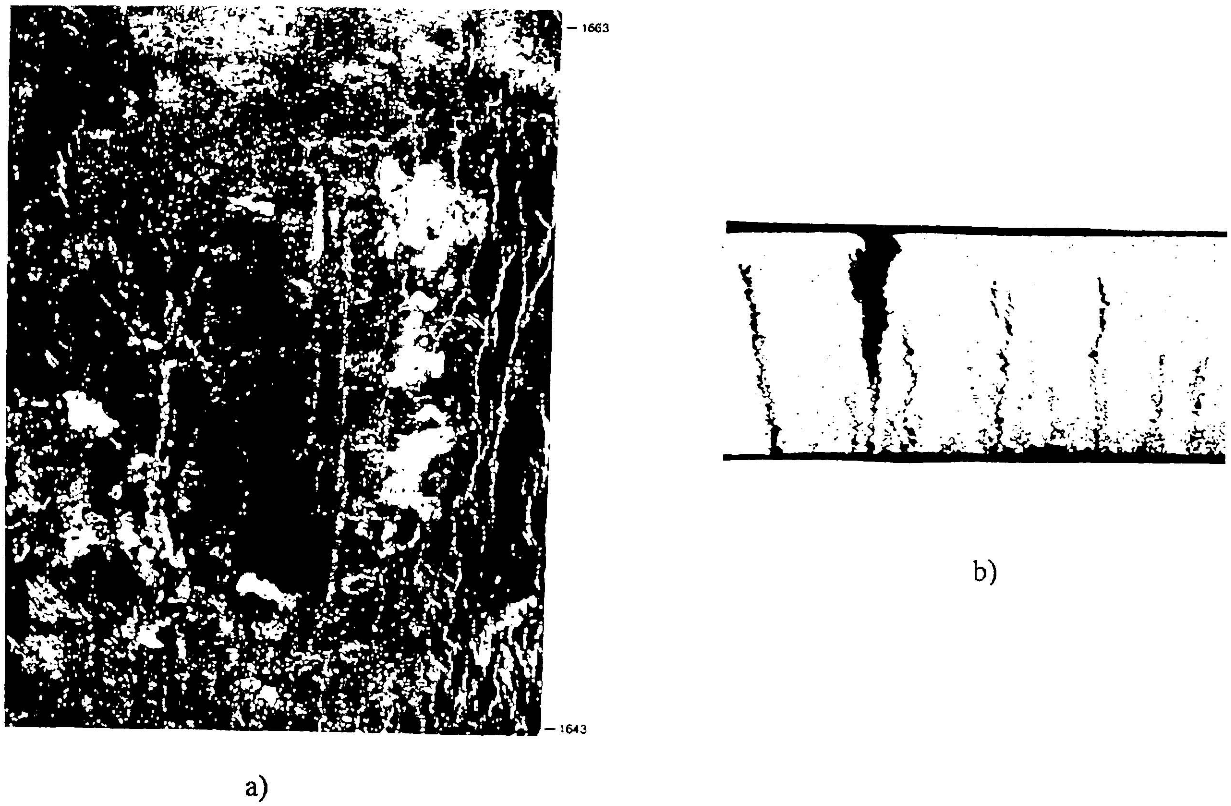


Figure 8 : OD corrosion at the Tube Support Plate Elevation - MA Alloy 600 tube
a) outer surface after burst tests
b) Transverse cut - Longitudinal IGSCC + IGA

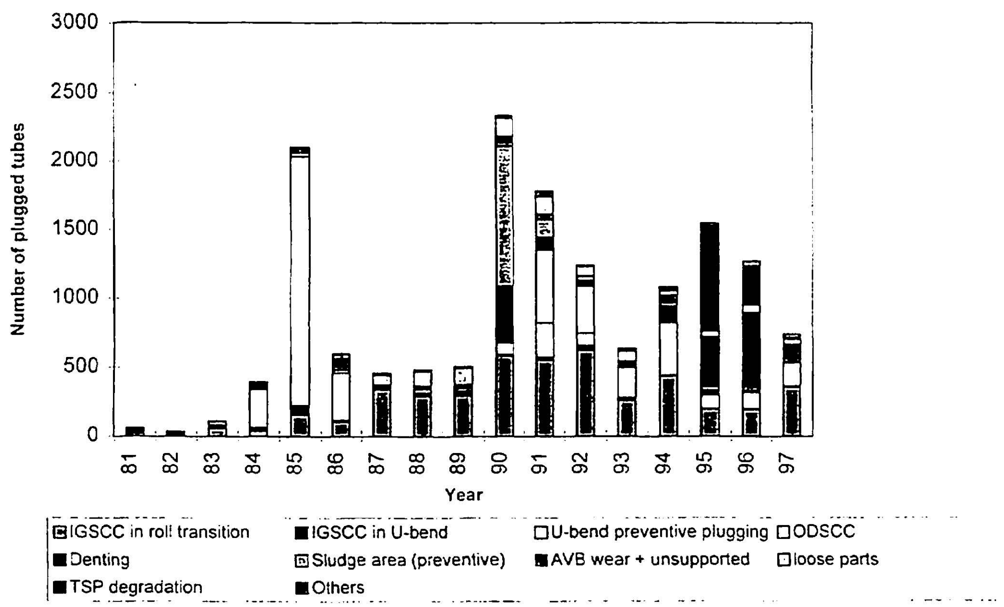
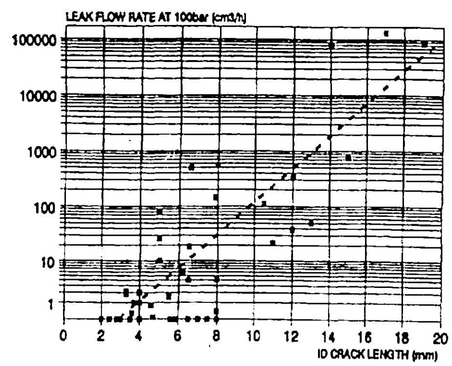
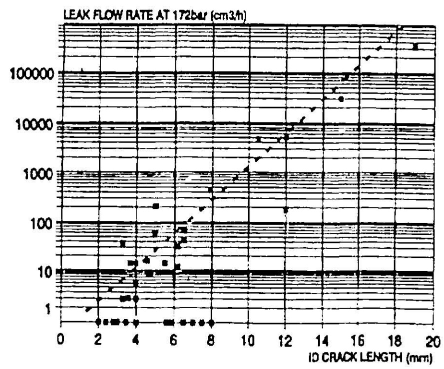


Figure 9 : Number of plugged tubes per year on french 900 MWe steam generators.



a)



b)

Figure 10 : Evolution of the leak flow rate at
a) 100 bar
b) 172 bar
versus the length of the longitudinal inner corrosion cracks.

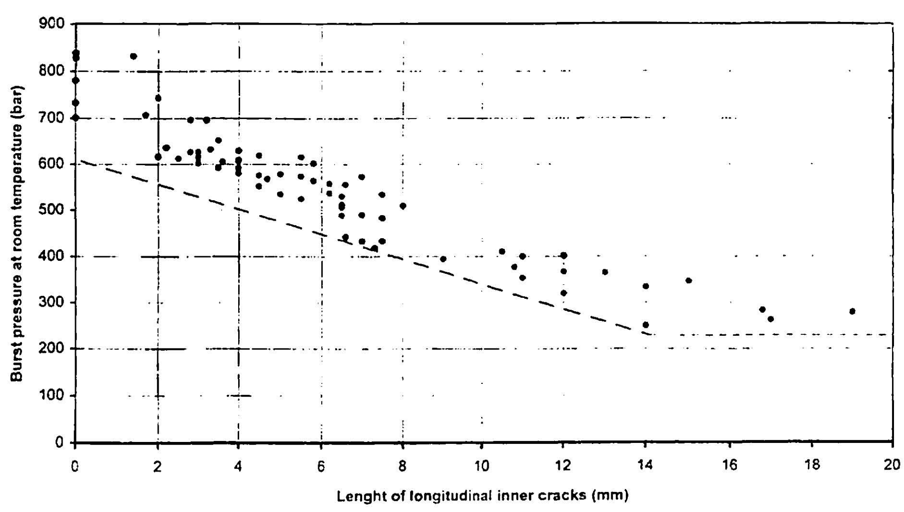


Figure 11 : Relation between the burst pressure at room temperature and the length of longitudinal inner corrosion cracks on pulled tubes.

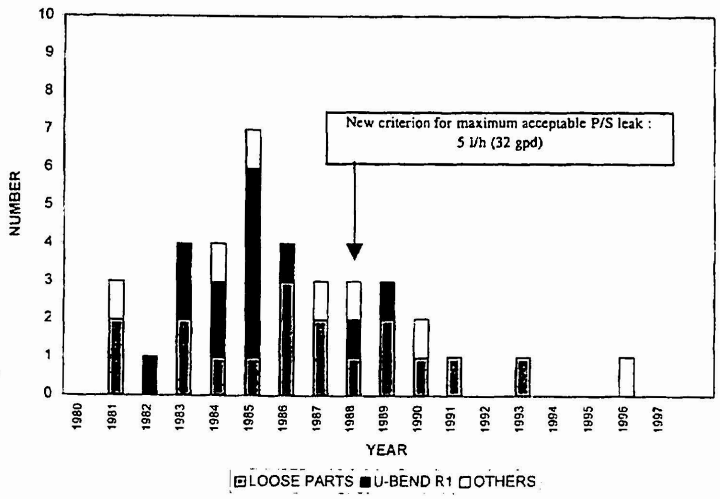


Figure 12 : Number of forced outages due to Primay to Secondary leak per year.

REGULATION OF AGEING STEAM GENERATORS

by

B.L. Jarman, I.M. Grant & R. Garg

ABSTRACT

Recent years have seen leaks and shutdowns of Canadian CANDU plants due to steam generator tube degradation by mechanisms including stress corrosion cracking, fretting and pitting.

Failure of a single steam generator tube, or even a few tubes, would not be a serious safety-related event in a CANDU reactor. The leakage from a ruptured tube is within the makeup capacity of the primary heat transport system, so that as long as the operator takes the correct actions, the off-site consequences will be negligible.

However, assurance that no tubes deteriorate to the point where their integrity could be seriously breached as result of potential accidents, and that any leakage caused by such an accident will be small enough to be inconsequential, can only be obtained through detailed monitoring and management of steam generator condition.

This paper presents the AECB's current approach and future regulatory directions regarding ageing steam generators.

Atomic Energy Control Board
Ottawa, Canada

DISCUSSION

Authors: P. Berge, J.M. Boursier, D. Dallery, F. de Keroulas, Y. Rouillon, EDF

Paper: Lessons Learned from Tubes Pulled from French Steam Generators

Questioner: J.P. Van Langen

Question/Comment:

What is the reason for the second expansion at the tubesheet rolled joint area?

Response:

The second expansion of the tube in the tubesheet area is called "kiss rolling". This kiss rolling operation has been done in order to reduce the stress level on the outer surface of the tube (increasing resistance to secondary side corrosion).

Questioner: R. Klarner, BWC

Question/Comment:

Recently there have been several tubes plugged due to U-bend wear indications. Has the root cause of this wear been identified?

Response:

Eight large U-bends have been removed from the first retired French steam generator at Dampierre. The metallurgical examinations of these pulled U-bends are still in progress. The main objectives of the metallurgical investigations are to validate the NDE techniques and to determine the root causes of the wear process. I hope that I can answer your question at the Fonteraud Conference!

Questioner: J.Gorman

Question/Comment:

(1) Have you ever observed either free span ODSCC or ID circumferential SCC at the TSP, such as seen in USA Model 51s?
(2) What inspections are done to monitor for the above possible modes of degradation?

Response:

(1) We have never observed either OD or IDSCC in the free span or circumferential cracking at the TSP. The main reason of this absence of cracking is linked to a "good" secondary side chemistry, associated with the absence of denting at TSP elevation.

(2) The answer is included in the final paper. At each planned outage, 100% of Alloy 600 MA SG tube bundle is made with bobbin coil.