Behaviour of Steam Generator Tubes in Belgium and their Consequences

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1. INTRODUCTION.

In Belgium like in other countries, steam generator is considered as the most critical NSSS equipment with respect to life expectation. Primary Water Stress Corrosion Cracking (PWSCC) in the roll transition zone of the tubes is the main degradation mechanism affecting Belgian steam generators. For the time being, the strategy used in Belgium to avoid replacing steam generators relies on preventive or corrective measures and acceptance of reactor operation with through wall cracks in unplugged tubes. Such a strategy clearly requires :

- the development of inspection techniques allowing reliable detection and accurate sizing of the tube defects.
- the development of preventive or corrective measures such as roto/shotpeening and heat treatment of small radius U-bends or repair techniques such as sleeving and nickel plating.
- the definition of new plugging criteria allowing through wall cracks and the corresponding amendment of the existing technical specification.

Through its sections 5 and 6, this paper focuses on the last requirement.
However, to better highlight the process of defining new tube plugging criteria and issuing a revision of the technical specification for steam generator tubes inservice inspection, a survey of the Belgian nuclear power plants is made in section 2 and a description of the degradations affecting the integrity of the steam generator tubing is given in sections 3 and 4.

2. SURVEY OF THE BELGIAN NUCLEAR POWER PLANTS.

The Belgian utilities are operating seven PWR's located at two sites : Doel and Tihange.
Units 1 and 2 of the Doel nuclear power plant are twin units (2 x 400 MW) of the two loops type provided with Westinghouse model 44 steam generators.
Units 1 and 2 of Tihange site and unit 3 of Doel site are 900 MW units, 3 loops, with Westinghouse model 51 steam generators. Unit 4 of Doel site and unit 3 of Tihange site are 1,000 MW units, 3 loops, with Westinghouse model E steam generators.
Table I gives some basic information on the steam generators.

3. DEGRADATIONS ENCOUNTERED IN STEAM GENERATOR TUBING IN BELGIUM.

Operating experience shows some degradation mechanisms to occur in the steam generator tubing. These include corrosion induced degradations and mechanical damages.

3.1. Corrosion induced degradation.

Wastage never affected the Belgian steam generators.
Denting is only reported on the five units where steam generators were provided with carbon steel support plates. Inspection experience indicates that denting is so far well below the critical threshold. However, its low but constant growing rate is a concern, especially in the oldest units.
The extent of secondary side SCC and intergranular attack is limited.
Primary water SCC is the most serious degradation mechanism affecting steam generator tubing. The next section will be devoted to this problem.

3.2. Mechanical damage.

Mechanical damage due to foreign objects inadvertently left in steam generators is reported occasionally.
Fretting between the tubes and the antivibration bars was observed on one unit after about six years of operation. This problem was solved by installing new antivibration bars of a different design.
Potential risk of wear in the preheater section of the steam generators of Tihange 3 and Doel 4 led to reduce the gap between the peripheral tubes and the baffle plates by a local hydraulic expansion. After three years of operation, some wear indication is reported on one plant.

4. STATUS OF PWSCC.

At the exception of the Doel 1 and Tihange 1 units which have not given so far any evidence of sensitivity to PWSCC, all the other units are shown to be highly sensitive to this degradation mechanism. The roll transition zone and the overlap zones between rolling steps are particularly susceptible to PWSCC. This form of attack is also a concern in the small radius U-bends. An historical and descriptive report is given hereafter. More details can be found in (Hernalsteen & Leblois, 1989).

Doel 2.
Doel 2 experienced its first leak due to stress corrosion in 1977 after two years of operation. Since then, the problem has been increasing and at the present time over 80% of the tubes in the most affected steam generator are cracked. All the cracks observed in Doel 2 are axial. Most of them are located at the roll transition and are (close to) through thickness. A maximum crack length of 18mm was recorded after twelve years of operation. However as the tubes were part depth rolled, unstable propagation of axial cracks within the tubesheet is not possible.
A tube rupture which occurred in 1979 from an axial crack at the apex of a first row U-bend shows evidence of the sensitivity to PWSCC in the small radius bend U tubes.
Cracking at this location was deemed to result from high stress level due to overovalization. As a consequence, first and second row tubes with excessive ovality were plugged in both steam generators. All remaining first row tubes were plugged in 1985 when a few axial indications were detected.

Doel 3 and Tihange 2.
Doel 3 and Tihange 2 show a high sensitivity to PWSCC. Both plants experienced leaks during the first cycle. Examination of pulled tubes at Doel 3 confirmed the existence of PWSCC. The cracks were found to be axial and close to 100% through thickness. Extensive Rotating Pancake Coil (RPC) eddy current inspection during the subsequent outages showed the rapid extension of cracking. Most of the cracks were located at the overlap zones of the upper rolling steps and at the roll transition. It should be emphasized that on plants such as Doel 3 and Tihange 2 where the mechanical rolling is "full depth", the occurrence of cracks in the roll transition is a safety concern : clearly, unstable crack growth out of the tubesheet cannot be prevented.

Shotpeening was performed on both plants after three cycles as an attempt to remedy this degradation problem. The shotpeening extended as a minimum over the transition zone plus five roll steps on the hot leg side.
Based on the results of the first two eddy current examinations carried out after shotpeening implementation, it was hoped that the shotpeening treatment (which is known to be efficient to prevent cracking when performed on tubing before reactor start-up) had also a beneficial effect when performed after a few cycles. Now, as the number of cracked tubes at Doel 3 is found to steadily increase, the question of the efficiency of shotpeening in activated steam generators is raised. In the most affected steam generator, over 50% of the tubes show PWSCC in the roll transition.
Sensitivity to PWSCC in U-bend is also a concern. In 1987, a large leak from a 40mm axial crack at the tangent point of a first row U-bend occurred in Tihange 2. As a corrective action, the U-bends of all row 1 and 2 tubes were heat treated in Tihange 2 while all row 1 tubes were plugged with removable plugs in Doel 3.

Doel 4 and Tihange 3.
Preventive measures were applied to the steam generators of the Doel 4 and Tihange 3 units. Rotopeening was performed before start-up, as a minimum over the full length of the expanded zone on the hot leg side and heat treatment of the small radius U-bends was carried out after a few years of operation.
So far the results of the RPC eddy current inspections show the efficiency of rotopeening to prevent or a least to delay the rapid increase of PWSCC in the roll transition. Even though the few witness tubes which were not rotopeened give evidence of the high sensitivy of tubing material to PWSCC, on the average only 3% of the peened tubes show some indications of cracking after three years of operation. It should also be mentioned that there is no preferential concentration of the cracks in the roll transition.

5. TECHNICAL SPECIFICATION REVISION.

5.1. Facing the problem.

The regulatory requirements for steam generator tube integrity set forth in the plant technical specification were considered out of date and hard to use. The necessity for updating the technical specification was therefore recognized in 1987 but after some investigation it was felt that a revision at that time would have been premature. Revision is being reconsidered now because of recently completed research work.

In order to put the subsequent discussion in context, it is necessary to recall the content of the actual technical specification for steam generator tube inservice inspection. Most of the requirements are based on the Standard Technical Specification 4.4.5. for Westinghouse PWR's (NUREG-0452, 1981). They address mainly the following matters :
- Schedule and sampling requirements : multiple sampling (increase of the sample size in step by step increments) and stratified sampling (division of the population into subpopulations) are used.
- Inspection method : the requirements for inspection method and procedure are defined with reference to Section XI of the (ASME Boiler and Pressure Vessel Code).
- Plugging criteria : the 40% wall loss criterion is stated.

For some reasons developped hereafter, the technical specification is considered out of date.

-Strict adherence to the minimum inspection requirements of the ASME B & PV Code asks for single frequency eddy current testing.

Although multifrequency bobbin coil technique is actually used, it is important to note that this technique does not ensure the reliable detection and the accurate sizing of some of the main defect types occuring today, specially the through wall cracks of short length (a few mm) in geometric discontinuities such as the roll transition zone.
At the same time, efforts have enhanced the capabilities of eddy current testing. The development by LABORELEC in Belgium of data acquisition and analysis systems to meet the challenges presented by operational experience allows now the multifrequency Rotating Pancake Coil to be used for the inspection of stress corrosion cracks within the tubesheet and at the roll transition (Dobbeni, 1989). When compared to the regulatory technique, the RPC technique provides a significant sensitivity increase in detection, sizing and multiple defect discrimination.
-The 40% wall loss plugging criterion was formulated at a time when the only generic degradation problem encountered in steam generators was wastage in the sludge pile, i.e. a general corrosion of the Inconel tubes leading to a uniform thinning. This criterion was derived from a model of remaining tube integrity as a function of uniform wall loss. Assuming the 40% criterion applicable to the other types of degradation may be overconservative. Research work recently performed as well in Belgium (Hernalsteen, 1984) as in other countries like US or France demonstrate that through wall cracked tubes with a limited crack length have a safety margin against bursting.
-The technical specification requires the tubes to be plugged when the degradation exceeds the specified limit. Repair techniques such as sleeving or nickel plating which have been implemented by the Belgian utilities (Stubbe & Leblois, 1989) are, strictly speaking, not allowed.

In addition, the technical specification is considered hard to use. The main concern is the sampling technique. The required increase of the sample size depending on the results of the current inspection clearly implies the availability of a signal analysis system of high time efficiency.

The observance of the regulatory requirements leads therefore to some paradoxical or unrealistic situations, some of those being summarized hereafter.
-The regulatory eddy current technique has poor capability to detect and to size the PWSCC which is known to be the predominant degradation. On the other hand, the existing high performance RPC technique is not used on a regulatory basis but only at the utilities discretion.
-Applying the regulatory plugging criterion to PWSCC in the roll transition would have required the utilities to plug a high number of tubes, up to more than 80% in a steam generator on one plant.

5.2. Bases, form, and regulatory approach of the revised technical specification.

The availability of a reliable technique for the sizing of cracks and the completion of research work on the strength of cracked tubes were the two necessary steps to be achieved before revising the technical specification.
It is considered advisable, before going further in the description of the revised technical specification, to address the question of the bases, form and regulatory approach of the technical specification.

Bases.
According to the licencing documents, the Belgian utilities have to apply the US nuclear safety rules although duly justified deviations can be obtained on a case by case basis. It is therefore useful to recall which are in US the bases for the regulation of steam generator operation.

General Design Criterion 32 of Appendix A "General Design Criteria for Nuclear Power Plants" to (Code of Federal Regulations, Title 10, 1988) requires that "components which are part of the reactor coolant pressure boundary be designed to permit periodic inspection and testing of important areas and features to assess their structural and leaktight integrity". Inservice inspection and testing are therefore the regulatory approach to ensure the integrity of the steam generator tubes once the plant is in service.
The regulatory instruments to ensure steam generator tube integrity include :

- (Regulatory Guide 1.83, 1975), "Inservice Inspection of PWR Steam Generator Tubes",
- (Regulatory Guide 1.121, 1976), "Bases for Plugging Degraded PWR Steam Generator Tubes",
- Article IWB-2000 of Section XI of (ASME Boiler and Pressure Vessel Code)

Another instrument is the specific plant technical specification for inservice inspection of steam generator tube. Such a technical specification is asked for by paragraph 50.36 of (Code of Federal Regulations, Title 10, 1988) which requires that the technical specifications will include surveillance requirements "to assure that the necessary quality of systems and components is maintained".

Form.

The revised technical specification should also be constructed with an eye on the two following problems :

-Technical specifications include regulatory requirements. As it is well known, regulatory matters ask for prescriptive language which becomes ambiguous when uncertainties are present. In several areas our knowledge is limited : for instance the possible occurrence of new types of degradation, the potential improvement of existing inspection techniques or the development of new ones, the better understanding of the effects of degradation on the structural integrity of the steam generator tubes.

-The technical specification amendment process in itself is a lengthy one because it is a involved process. So, frequently revising a technical specification should be avoided.

It was therefore concluded that the revised technical specification should be written with the aim of simplicity and flexibility. The idea was to generalize the technical specification and to rely on the more informal inservice inspection program to complete the prescription. This way of doing is not contradictory to the (Regulatory Guide 1.83, 1975) which states in its regulatory position that the requirements for steam generator tubing inspection i.e. inspection equipment and procedures, sample selection and testing, inspection intervals and acceptance limits should be included in a program for inservice inspection.

Regulatory approach.

The regulatory approach used in the technical specification was of the directing type, consisting in prescribing in a poorly flexible way all the inspection requirements.
A less directing or more flexible approach was adopted for the revision of the technical specification. The objectives of the inservice inspection will be clearly defined in the technical specification but the plant operator will be responsible for the means to reach these objectives. These means will be included in the inspection program to be submitted to the Safety Authorities.
This regulatory approach is by no way less stringent but rather it leads the utility to assume his safety responsibilities.

5.3. Content of the revised technical specification.

The content of the revised technical specification intends to meet the above mentioned principles.

First the objectives of the inservice inspection of steam generator tubes are stated. These are :

- to determine whether tube degradation processes are occurring and to identify them.
- to assess the rate of degradation growth and to compare it with the value used when defining the plugging/repairing criteria.
- to identify the tubes to be plugged or repaired and to perform the corresponding corrective actions.

Then the content of the inservice inspection program is given. It must include, as a minimum :

- the definition of the inspection techniques to be used and the applicable procedures.
- the selection, for each type of degradation, of the steam generator tubes and tube zones to be inspected.
- the definition, for each type of degradation, of the plugging/repairing criteria.

Finally, some specific requirements concerning the criteria for the selection of the inspection techniques and procedures as well as for the selection of the steam generators and tubes to be inspected are prescribed. Nevertheless, these requirements shall not be considered as supplementary requirements but rather as a regulatory commentary on the means to reach the objectives of the inservice inspection for some specific matters.

-The technical specification requires the inspection techniques and procedures to be selected on basis of their capability to detect, identify and size the concerned degradations and also on basis of their assessed reliability.

-The technical specification also requires a three-level inspection. A "general basic inspection" of at least 3% of the total number of tubes shall be performed during each outage in order to check the good behaviour of the tubes independently of any type of degradation, i.e. to detect any unsuspected degradation.

Should any degradation process be detected, inspection with a dedicated technique (if required) of an extended sample shall be performed to assess the parameters characterizing the degradation, e.g. the percentage of the degraded tubes, the distribution curve of the defect size and the rate of degradation growth.

When the observed defects are such that the presence of tubes with defect size in excess of the plugging/repairing criterion may be expected, inspection shall be extended in order to allow identification of the tubes to be plugged or repaired.

6. PLUGGING/REPAIRING CRITERIA.

Although the revised technical specification is intended to be generic and to fit in with any kind of degradation, its first concern was to deal with PWSCC in the roll transition. The steps having led to the proposal of plugging criteria specific to PWSCC is hereafter developped.

6.1. Regulatory approach.

The acceptability of through wall cracks was examined with an eye on the US regulation. (Regulatory Guide 1.83, 1975) does not explicitely mention any plugging criteria. (Regulatory Guide 1.121, 1976) states that through wall cracks having adequate margin of safety are acceptable. Section XI of (ASME Boiler and Pressure Vessel Code) states in subparagraph IWB-3521.1 that "the depth of an allowable O.D. flaw shall not exceed 40% of the tube wall thickness". No criterion is given for the flaws on the internal skin.

However, according to subsubarticle IWB-3630, the evaluation of flaws "that exceed the allowable flaw standards of IWB-3521 shall be performed by analyses acceptable to the regulatory Authority having juridiction at the plant site" Paragraph 50.55 a(b)(2)(iii) of (Code of Federal Regulations, Title 10, 1988) states that the technical specification for steam generator tubing may include surveillance requirements different from those in Article IWB-2000.
Therefore, the acceptance of through wall cracks is concluded to be not basically contradictory to the US safety rules.

6.2. Research work.

Extensive research work has been performed by BELGATOM (Hernalsteen, 1984) to analytically establish and to experimentally verify a model to predict the bursting pressure of steam generator tube with axial or circumferential through wall cracks. This research work has demonstrated that stress criteria based on the concept of instability by plastic flow give reliable predictions of tube rupture. The model can therefore be used to reliably predict the critical length of a through wall crack for a steam generator tube with given dimensions, material mechanical properties and differential pressure.
From supplementary experimental work studying the tube behaviour with through wall cracks located between supports, it was possible to demonstrate and to quantify the reinforcing effect of the tubesheet for axial cracks in the roll transition and the constraining effect of the support plate for the circumferential cracks in the roll transition.

6.3. Plugging/repairing limits for PWSCC in the roll transition.

The plugging/repairing limits for PWSCC in roll transition were derived from the predictive model described hereabove, using the principles of (Regulatory Guide 1.121, 1976) but with a few modifications or interpretations.

The only load to be considered is the pressure load differential. This is justified because :
- the effects of loads such as seismic motion or flow induced vibration which can be important at other locations along the tube are very low near the tubesheet and may therefore be ignored.
- the only loads to be taken into account are those responsible for primary stresses in the tube wall.

The safety factors against tube failure required by (Regulatory Guide 1.121, 1976) to determine the maximum acceptable length of a through wall crack should be applied to the internal pressure. It was however demonstrated that applying this method gave corresponding margins on crack length higher than the safety factors for axial cracks but very much lower for circumferential cracks. Consequently the safety factors were decided to be applied on the crack length. This way of modifying the Regulatory Guide is not exempt from physical meaning as the actual uncertainty lies more in the size of the crack than in the value of the pressure. The safety factor is 3 under normal operating conditions and square root of 2 under accident conditions.

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Basically the plugging/repairing limit is obtained by subtracting from the maximum permissible through wall crack length an adequate margin for sizing accurracy and crack size increase until the next inspection. The maximum permissible through wall crack length is the critical through wall crack length under a specific condition divided by the corresponding safety factor.
Two main features are to be pointed out in the process of determining the plugging/repairing limits :

- critical length calculations are based on the actual measured mechanical properties of tubing material and not on the Code minimum material properties.
- plugging/repairing limit calculations are developped along a twofold path :
  - a "best estimate" path where all data are taken at their nominal (for specified data) or mean (for measured data) value and the safety factors are applied. The criteria length calculation is performed for both normal and accident conditions
  - a "worst combination" path where all data are taken at their minimum or maximum value in order to minimize the end result. No safety factor is applied and the critical length calculation is only performed for accident condition.

The maximum allowable length is taken equal to the lowest of the allowable lengths obtained hereabove, rounded off to the next lower mm. Or otherwise stated, the plugging/repairing limit is taken equal to the lowest of the allowable lengths, rounded off to the next higher mm.
For a typical 7/8" tubing, the plugging/repairing limit for axial PWSCC in the roll transition is 15mm. More details can be found in (Leblois and Hernalsteen, 1989)
In the actual procedure for the examination of PWSCC in the roll transition region,

- any crack detected is assessed as if it were a through wall crack.
- for axial cracks partially within the tubesheet, the crack length to be considered is that extending above the last upper contact point of the rolled section.
- any crack with measured length greater or equal to the plugging limit shall be plugged or repaired.

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7. CONCLUSION.

The requirements of a safe operation with degraded steam generator tubes as well as the need of an adequate maintenance policy have both led to the development of a surveillance strategy based on the issue of specific plugging/repairing criteria and a large scale inspection of the affected areas of steam generator tubes.

Although this strategy has been set up to cope with PWSCC in the roll transition zone, it is believed that it should be applicable to all other types of generic degradation.

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TABLE I : BASIC CHARACTERISTICS OF STEAM GENERATORS ON BELGIAN UNITS.

Unit	Doel 1/2	Doel 3	Doel 4	Tihange 1	Tihange 2	Tihange 3
SG type (W Series)	44	51M	E	51	51M	E
First year of commercial operation	1974/1975	1982	1985	1975	1983	1985
Tube dia	7/8"	7/8"	3/4"	7/8"	7/8"	3/4"
Tube material	Inconel 600MA	Inconel 600MA	Inconel 600MA	Inconel 600MA	Inconel 600MA	Inconel 600MA
Rolling	partial roll on about 70mm	full depth roll + kiss roll		partial roll on about 70mm	full depth roll + kiss roll	
Support plate material	C-steel	C-steel	Stainless steel type 405	C-steel	C-steel	Stainless steel 405