THE AGEING OF CANDU STEAM GENERATOR DUE TO LOCALIZED CORROSION

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Abstract

The Steam Generator (SG) tubing degradation caused by corrosion and other age-related mechanisms continues to be a significant safety and cost concern for many Nuclear Power Plants (NPP).The understanding of the steam generator ageing mechanisms is the key to effective management of steam generator ageing and consists of the knowledge of steam generator materials and these one properties,stressors and operating conditions, like degradation sites and wear mechanisms. ~~The paper presents~~ the principal types of corrosion which can occur in CANDU steam generator. There are also presented the operation conditions, the specifications referring to the water chemistry and the construction materials of Steam Generator, the factors that have a great influence on the corrosion behaviour during the whole exploitation period of this equipment.

Also the paper presents the most important elements of CANDU Steam Generator ageing management program.

Introduction

The maintenance operations in a nuclear power plant are particularly complex and difficult due to its specific nature. It is, therefore, necessary that by an appropriate design and a proper choice of construction materials assisted by a correct operation, long operation periods be ensured.

The important steps of a maintenance programme for NPP related facilities are the disassembling and the inspection of components in order to:

1.the detect of the problems that occurred after the last inspection, including:

a)the determination of their causes;

b) the notification of the supplier if a material defect is involved;

2. the corrective actions proposal considering the estimated period that the component is still able to operate, implying either the elimination of the main defect causes or the re-design of the part.

3. the implementation of corrective measures by:

a) the cleaning operations;

b) the repairs;

c) the replacement of the defective component, if possible by an upgraded one, if this exists.

Maintenance should be done periodically, according to a pre-established plan. In this way, besides repairing the known defects, others can be identified, as well as their causes and the corrective actions required.

Maintenance is especially difficult at nuclear facilities due to the presence of radiation fields and to the complexity of the facilities.

The steam generators , equipments that ensure the connection between the primary and the secondary circuits, create several safety problems during operation, mainly due to corrosion and mechanical damages. Maintenance is also difficult in the steam generator because of the limited access to various components and because of the presence of the high radiation field existing on the side of the primary circuit.

For manufacturing the steam generator several types of steels are used, whose coexistence in the environmental conditions of the steam generator arises special problems with respect to corrosion.

Corrosion and the mechanical damage in the SG are the result of complex interaction between various factors:

- strict control of water chemistry;
- adequate thermo-hydraulic design;
- selection of generator construction materials;
- utilisation of compatible materials for the entire secondary circuit;
- conditions of achieving equipments and facilities;
- the operation technique.

This is why a careful analysis of corrosion problems is required, necessary both from an economic point of view and for the safe operation [1,2].

Materials and environment conditions specific to the steam generator

The most important element in selecting the SG construction materials is their resistance to corrosion in special operation conditions.

The main operation parameters of the SG are:

D_2O	H_2O
$t_{in} = 309^0C$	$t_{in} = 187.2^0C$
$t_{ou} = 290^0C$	$t_{ou} = 260^0C$
$P_{in} = 9.887$ MPa	$P_{in} = 6.700$ MPa
$P_{ou} = 9.625$ MPa	$P_{ou} = 4.695$ MPa

Incoloy-800 is utilised for tubes for the following reasons:

- presents good resistance to stress corrosion cracking , as compared to Inconel-600;
- releases a much smaller amount of radioactive products in the primary circuit;
- has a high resistance to cracking corrosion in alkaline environment (20% higher than Inconel-600).

The SG includes the following types of steels: Incoloy-800 (tubes), Inconel-600 (tubesheet-cover), stainless steel SA 240-410 S (intermediate supports), carbon steel SA 516-gr. 70 (shell), carbon steel SA 508 cl.2 (tubesheet) [3].

The chemical control of water is done by the maintaining of the parameters between certain limits that influence the corrosion behaviour of SG materials: the amount and composition of corrosion products, impurities (dissolved salts) and oxidation agents.

Although the corrosion products are not directly responsible for corrosion, they are the main cause of the accumulation and concentration of aggressive species that can lead to a variety of corrosion forms. The corrosion products will be carried from the steam generator in the entire system, determining the occurrence of corrosion-related inconveniences, even and in areas where apparently this would not be possible. The main source of penetration of oxygen and impurities is coolant leakage from the condenser. The impurities concentration is responsible for the initiation, propagation and acceleration of corrosion processes in the SG tubing. This is why it is compulsory a careful control of water chemistry, of reactants addition and of the cleaning degree after maintenance or repairs.

The chemical parameters of the cooling water in the SG are presented in Table 1 [2].

Table 1
Chemical parameters of cooling water in the steam generator [2]

Parameter ($\mu g/kg\ H_2O$)	Permitted range	Optimal value
pH (25^0C)	8.9 - 9.4	9.4
natrium	70	as small as possible
dissolved oxygen	5	5
hydrazine	200	200
dissolved solids	10	as small as possible
silicon	1	1
chloride	0.1	as small as possible
iron	10	10
copper	2	2

Types of corrosion specific to the steam generator

Degradations due to corrosion can be divided into two large groups: degradations that end up in cracking and those which do not imply cracking. Corrosive degradations produced in the absence of a significant stress (applied, residual or due to corrosion products deposition) will not end up in cracking, except for certain cases such as intergranular corrosion.

Corrosion that does not imply cracking can appear itself under the following three specific forms:

1) generalised corrosion;
2) localized corrosion (pitting of Incoloy-800 tubes);
3) crevice corrosion.

The corrosion cracking degradations are favoured by the following conditions:

a) stress corrosion cracking (SCC) under constant stress in the thermally affected area close to welds;

b) SCC under monotonous increasing stress, during denting occurrence in the SG;

c) fatigue (wear) corrosion of Incoloy-800 tubes under cyclic stress.

Generalized corrosion

Many research workers [1] have demonstrated that stainless steels and nickel-rich alloys present in the SG undertake a generalized corrosion; their corrosion rates vary in time approximately parabolically.

The corrosion products release rates decrease in time, following various kinetics.

Generalized corrosion prevails in the case of carbon steels.

Since most of the studies were performed in static autoclaves, particular care is required if one desires the extrapolation of results for typical conditions in nuclear facilities, where the influence of the thermal transfer and of coolant circulation is added, due to thermo-hydraulic parameters.

The corrosion mechanism of these materials consists in the formation of two overlapped layers of compounds, the outer one being crystalline. Based on this model, Lesurf [4] assumed that the total rate of the film formation is controlled by the migration rate of iron species soluble in water through the pores of the oxide layer: part of the oxidized iron is included in the magnetite formed in the area of contact with the metallic under-layer (forming thus the inner film), while the remaining is carried into the solution, at the outer edge of the oxide layer where it can precipitate, forming the crystalline outer film, or its release can occur in the solution mass, precipitating at random.

The corrosion products entailed in the working fluid will deposit in the restricted circulation regions, thus contributing to the initiation of corrosion in those areas.

Localized corrosion

Localized corrosion supposes the fast local dissolving on a significant depth and it can induce destruction of the base material.

Localized corrosion is an extremely dangerous phenomenon, since it usually takes place in less aggressive environments - where generalized corrosion is negligible - and it is quite difficult to be detected, due to its location and very small dimensions.

Denting corrosion

If the cooling water was phosphate-treated and then treated with volatile amines (AVT) one noticed the occurrence of a corrosive attack called denting. This means the deformation of Incoloy-800 tubing due to the increase in volume of corrosion products formed between the intermediary carbon steel support plate and the Incoloy-800 tube.

Around each Incoloy-800 tube that penetrates the intermediary support plate there is a gap of a few tenths of a millimetre. Within this space an accelerated corrosion of carbon steel was noticed, resulting in magnetite. Magnetite accumulates in time and exerts a compression force on the tube; this one can distort, leading to a local striction in the tube, called dent.

This denting corrosion can also lead to the blocking of the sondes used in eddy-current examinations of the tubular bundle.

Consequently, denting is a form of corrosion in the crevice between the tube and the support plate, where an initial concentration of acid species (chlorides, sulphates) takes place.

The oxygen, copper and nickel ions act as accelerators of denting. The occurrence of this event can be avoided by choosing appropriate construction solutions for the intermediate supports, utilization of stainless steel for these supports, treatment, from the very beginning, with volatile amines and removal of copper from the composition of the secondary circuit equipments.

Corrosion under the impurities layer (wastage)

Another type of corrosion likely to occur when treating water with phosphates is the "wastage" corrosion. This one takes place under the deposits on the tube surface, in the areas where wet and dry periods alternate.

It is known that during SG operation a sludge accumulates on the tubesheet, reaching a height of 30 cm or more. As the sludge content increases, the coolant cannot reach the surface in order to replace the evaporated liquid. The temperature in this region becomes equal to that of the coolant. The area where the strongest corrosion is encountered is the interface, where wetting and drying alternate, which determines the thinning of the Incoloy-800 tube .

Using adequate constructive solutions can diminish the phenomenon.

The crevice corrosion in the presence of deposits have been investigated ,in detail, in our laboratory[5]÷[8].

Pitting corrosion

Pitting corrosion can appear both on the Incoloy-800 tubing and on the tubesheet. Thus, pits with a depth of 0.02-0.05 mm have been observed on the Incoloy-800 tubes in the crevices where denting occurred, determined by a high concentration of chlorides. Pitting was also observed on the tubesheet, especially under the sludge [5] ,[6].

Stress corrosion cracking

This type of corrosion was more frequently identified on the U-shaped upper region of Incoloy-800 tubes, but cracks have been noticed in other areas, too.

The crack that appeared in the U-bend region has been generally initiated from the inside of the tube. The examination of such tubes shown that these cracks initiated on the side of the primary agent are of intergranular nature, oriented along the longitudinal axis of the tube [3].

The factors involved in the cracking of the U-bend region are:

a) microstructural factors, features referring to material strength and hardness;

b) residual or latent stresses that emerge during fabrication, bending and installation;

c) shape of the tube, bending radius resulting from processing;

d) the extent and frequency of cycling, shape of strains induced during steam generator operation;

e) environment chemistry or environment factors.

The inspection of cracks on the unbended side of damaged tubes revealed that SCC appeared in points where denting progressed to such extent so that the tubes became ovalized or wave-shaped, instead of circular. Cracks occurrence was noticed in places where the highest strain was applied; they were initiated either on the inner or on the outer surface. A third type of SCC initiated by granular attack from the interior is in the transfer region from the expanded area to the non-expanded one - at the joint with the tubular plate - where high strains affect the tube walls.

Mechanical degradations of the SG tubing

Mechanical degradations that may alter SG tubing can be divided into: vibrations wear (fretting) and fatigue wear.

These degradations belong to the category of localized attack.

The strength that determines them is produced by tubes vibration, induced by flow circulation.

This time, corrosion appears as an additional factor that accelerates mechanical degradation of the tubes; it acts synergistically. The effect of the synergetic action of the two factors varies from the erosion of passive films on the materials surface to the accelerating effects of certain aggressive environments on the quality of the metal.

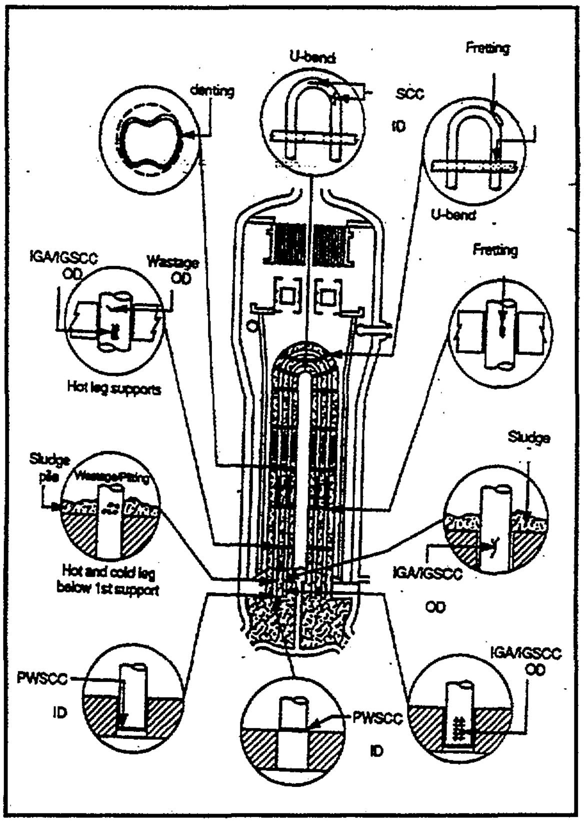

Fig. 1.Types of corrosion specific to the steam generator[1]

Due to vibrations in the region of contact tube - tubesheet, the tube can notably reduce its thickness, sometimes displaying cracks. Vibrations are also responsible for the excessive degradation of anti-vibration bars used in some SG: their replacement is prescribed. In the case of cracks initiated on defects (for example in regions where local thinning of tubing walls took place) a transgranular attack was identified on the tubes outer surface. The mechanism of these cracks includes the fatigue fretting corrosion in the presence of corrosive species in the environment.

Figure 1 is a schematic layout of corrosive attacks specific to Steam Generators.

CANDU Steam Generator ageing management programme

The most important elements of CANDU Steam Generator ageing management program are the following:

1. steam generator operation;
2. inspection ,monitoring and assessment;
3. maintenance:mitigation,repair and replacement.

Operation condition and practices include primary and secondary water chemistry control ,control of secondary side impurity incursions(condenser integrity ,use of condensate polishers) ,removal of secondary-side crevice impurities and control of steam generator deposits and crud.

The secondary coolant water chemistry is extremely important and a secondary side chemistry programme must be developed for the specific conditions of the plant and maintained to minimize the corrosion of the steam generator tube and shell and the balance of plant materials.The water chemistry programme should limit the steam generator secondary side water impurity concentrations to certain specified values.

The control of secondary side impurity incursions includes policies and practices associated with condenser integrity ,use of the condensate polishing system ,recycling of the blowdown water and removal of cooper from the secondary coolant system.

An another related area of plant operation is removal of impurities from the secondary –side crevices.The impurities concentrate in the tube-tubesheet crevices,in the mass of the deposits and under these deposits.Steam generator chemical cleaning is used ,as necessary,to remove impurities from these locations(after sludge lancing).

The control of the steam generator deposits consists in the mitigation of the leakage of air and impurities into the secondary coolant system.

Concerning the inspection and the monitoring it is very important to know the accuracy ,sensitivity,reliability and adequacy of the non-destructive methods used for the particular type of suspected degradation.The performance of the inspection methods must be demonstrated in order to rely on the results,particularly in cases where the results are used in fitness-for-service assessments.Inspection methods capable of detecting and sizing expected degradation are therefore selected from those proven by relevant operating experience.Current methods used for the inspection of steam generator tubes are the following:eddy current testing,ultrasonic testing and destructive testing.

A fitness-for-service assessment is used to assess the capability of the tubes to perform the required safety function,within the specified margins of safety,during the entire operating interval until the next sheduled inspection.

Maintenance actions for managing or repair of steam generator tube degradation include preventive or mitigation methods and corrective or repair methods.

Conclusions

- The occurrence of corrosion in the steam generator creates problems of economic nature, safety in operation and prediction of the operation period of components after damage.
- The factors that influence the corrosion behaviour of the steam generator components during operation and after maintenance are presented under the form of corrosion types susceptible to appear. Among them the most dangerous is the localized corrosion with its specific patterns: SCC, denting, wastage, pitting, intergranular etc.
- The paper presents the correlation between the nature of materials used for the construction of various components of the SG, the chemical characteristics of the circulating environment and the way in which certain of their abnormalities can lead to the occurrence of different types of corrosion.
- The paper also includes a short review of the measures to be taken in order to diminish or, if possible, to avoid the corrosion of the SG components.
- The most important elements of the CANDU Steam Generator Ageing Management Programme are presented in this paper.

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