KEY ELEMENTS OF THE R&D ACTIVITY SUPPORTING THE STEAM GENERATOR AGEING MANAGEMENT PROGRAM

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Abstract

The steam generator (SG) tubing degradation caused by stress corrosion cracking, fretting, vibration induced fatigue and other age-related mechanisms continues to be a significant safety and cost concern for many steam generators, even for some of the replacement steam generators with improved materials and designs. Therefore, systematic SG ageing management programs (AMP) are needed at all NPPs. The understanding of SG ageing is derived from the steam generator baseline data, the operating and maintenance histories, and external experience. External experience consists of the operating and maintenance experience of: steam generators of similar design, materials of construction and fabrication, steam generators operated under similar water chemistry or with similar tube alloy material, even if the steam generator designs are different and relevant research results and relevant R&D results. The paper aims to present the Steam Generator R&D Program, developed in the Institute for Nuclear Research Pitesti since 2000. During this period a lot of experimental results were obtained, in the paper being presented only one example of experimental research regarding the steam generator tubing corrosion behaviour. The purpose of the experimental research consists in the assessment of the Incoloy 800 corrosion behaviour at the normal secondary circuit parameters (260 °C, 5.1 MPa). The testing environment was the demineralised water, at pH = 9.5 regulated by All Volatile Treatment. The results are presented like micrographs and graphics representing the loss of metal through corrosion, corrosion rate, total corrosion products, adherent corrosion product, released corrosion products and the release of the metal.

Keywords: *Steam generator, Corrosion, Water chemistry, Incoloy 800, AMP*

Introduction

Research and development tasks are needed with the aim to establish clear definitions and objectives for all the programs related to the NPP components lifetime, not only in the long term extrapolation of the component integrity and behavior, but also in the development of new management strategies at the plan, able to address organizational issues, asset management, human reliability and ageing issues, all at once, in a coordinated approach.

Plant life management (PLIM) plan is an action program whose aim is to achieve the original design life without safety deterioration and to keep the possibility of the nuclear power plant license renewal open for its Long Term Operation (LTO). In recent times, this concept applies to CANDU technology reactors but in the past, it was referred to as ageing management plan (AMP), with a similar methodology. A PLIM plan must integrate and, if necessary, complement all the activities related to the assessment and control of the ageing mechanisms affecting passive and long term Systems, Structures and Components (SSCs) relevant to safety.

Ageing management programs (AMPs) represent a structured set of activities oriented to the surveillance, control and mitigation of ageing effects which affect the SSCs comprised in the ageing management process scope. Management programs are based on different predictive, preventive and corrective maintenance practices, environmental qualification programs, periodic testing and surveillance of technical specifications (TS), in service inspection programs, erosion-corrosion programs, etc., as well as any other specific activity which might be performed at the NPP with the same purposes.

Key elements of a steam generator Ageing Management Program (AMP) have like objective to maintain the fitness for service of the steam generators at a nuclear power plant throughout their service life. These key elements are integrated within a plant specific steam generator AMP. Such an AMP should be implemented in accordance with guidance prepared by an interdisciplinary steam generator ageing management team organized at a corporate or owners' group level.

The key elements of steam generator AMP are, as follows:

1. understanding ageing of a structure/component;
2. development and optimization of activities for ageing management of a structure/component;
3. SG operation;
4. SG inspection, monitoring, and assessment;
5. maintenance of a structure/component

Understanding steam generator ageing and feedback of operating experience consist in:

- Integrating ageing management activities within a systematic NPP AMP, managing ageing mechanisms through prudent operating procedures and practices.
- Detecting and assessing ageing effects through effective and practical inspection, monitoring and assessment methods.
- Managing ageing affects using proven maintenance methods.

This understanding consists of a knowledge of steam generator design, technical specifications and performance requirements, materials and material properties, stressors and operating conditions, likely degradation sites and ageing mechanisms, condition monitoring indicators/data needed for the assessment and management of steam generator ageing, and of the consequences of age-related degradation and failures both under normal operating conditions and design basis event (DBE) conditions. In addition, the following aspects contribute to understanding of steam generator ageing:

- acceptance criteria including applicable regulatory or code requirements, and safety analysis limits and conditions;
- available analytical models (i.e., based on theory) or empirical models (i.e., based on observation or experiment) for predicting future degradation;
- data requirements for the assessment of ageing (including any deficiencies in the availability and quality of existing records materials and material properties);
- relevant R&D results.

Definition of steam generator ageing management program

Existing programs relating to the management of SG ageing include operations, surveillance and maintenance programs as well as operating experience feedback, research and development (R&D) and technical support programs. Experience shows that ageing management effectiveness can be improved by integrating and coordinating relevant programs and activities within a systematic ageing management program.

Prevention of steam generator ageing

Operating conditions and practices significantly influence steam generator degradation, and therefore, are the primary means for the staff of a nuclear power plant to minimize degradation caused by potential ageing mechanisms. These practices include primary and secondary water chemistry control, control of secondary side impurity incursions (condenser integrity, use of condensate polishers, recycle of the blowdown water, control of lead contamination, and removal of copper from the secondary coolant system), removal of secondary side crevice impurities (flushes and soaks), and control of steam generator deposits and crud (air in-leakage, steam generator lay-up practice, pH, steam generator blowdown system performance, and crud lancing). These activities are, of course, closely related and are summarized below.

The secondary side water chemistry is extremely important and a secondary side chemistry program 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. In general, an all-volatile treatment program is used with:

• one or more amines to maintain cycle pH;

• moderate to high concentrations of hydrazine to maintain a reducing environment and scavenge small amounts of dissolved oxygen in the final feedwater;

• other additives (e.g., boric acid) to modify the crevice chemistry/

The exact combination of additives to be used will vary somewhat from plant to plant depending on such things as the tube degradation experiences, steam generator design, make-up water chemistry, type and use of condensate polishers, balance of plant materials and corrosion experience, hideout return experience, etc. In addition, the water chemistry program should limit the steam generator secondary side water impurity concentrations to certain specified values. The program must include adequate sampling and specific action levels up to and including plant shutdown.

A second closely related area of plant operation is the control of secondary side impurities incursions. This includes policies and practices associated with condenser integrity, use or not use of the condensate polishing system, recycling of the blowdown water, lead contamination and removal of copper from the secondary side systems. The condenser must be essentially leak-tight over the life of the plant. Although condensate polishers are an effective means of achieving water purity during startup and can protect against major chemistry excursions, they can also release low concentrations of impurities that are known to cause corrosive conditions in steam generators. They need to be used with care, if any. A blowdown recovery system is used to reduce the quantity of make-up water and the chlorides and other impurities carried by the make-up water and introduced into the steam generator. Effective operating procedures should be used to control both acute and chronic sources of lead contamination. And, copper-bearing alloys should be removed from the secondary systems and replaced with stainless steel components.

A third related area of plant operation is removal of impurities from the secondary side crevices. Impurities concentrate in the tube sheet and tube to tube support plate crevices, the sludge pile, and under free span crud (bridging) deposits. Steam generator hot soaks and flushes or chemical cleanings are used, as necessary, to remove impurities from these locations (after sludge lancing).

The fourth important and related area of plant operation is control of the steam generator deposits (crud). Plant procedures should be in place to minimize the leakage of air into the secondary coolant system through the aggressive use of state-of-the-art detection and repair technologies. Wet lay-up with chemically treated, de-oxygenated water (and a positive pressure nitrogen blanket if allowed due to safety issues) can be used whenever possible when the steam generator is in a shutdown condition.

Detection and monitoring of ageing

SG inspection, monitoring and assessment activities are designed to detect and characterize significant component degradation before the steam generator safety margins are compromised. Together with an understanding of the steam generator ageing degradation, the results of the steam generator inspections provide a basis for decisions regarding the type and timing of maintenance actions and decisions regarding changes in operating conditions and practices to manage detected ageing effects. 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 scheduled inspection.

Generally, a graduated approach with three levels of assessment is used to demonstrate fitness for service:

• The simplest and most conservative assessment method uses generic criteria (e.g., 'No flaws allowed' or '40% of wall limit') for all types of defects and degradation mechanisms;

• When the generic criterion is exceeded, a degradation specific assessment can be applied. This method reduces the conservatism of the generic criteria by using a deterministic analysis of the specific types of degradation detected, (e.g., per ASME rules and safety margins). It is used by plant operators to reduce steam generator repair work (e.g., plugging) that would be required by the generic criteria;

• A probabilistic assessment may be used to demonstrate fitness for service, when a degradation specific assessment fails to meet the criteria. This method requires probabilistic calculations to assess the conditional probability of tube failures, leak rates, and ultimately risk of core damage or of exceeding site dose limits. Risk calculations should take into account the probability that some degraded tubes may be inadvertently left in service and that non-steam generator design basis events may increase with time due to other age-related degradation. Although probabilistic assessments of steam generators have not been widely used, this method provides a useful way for handling uncertainty while avoiding excessive conservatism.

Mitigation of ageing effects

A variety of maintenance actions are available to manage ageing effects detected by inspection and monitoring methods in different parts of a steam generator. Decisions on the type and timing of the maintenance actions are based on an assessment of the observed ageing effects, available decision criteria (e.g., for tube plugging), an understanding of the applicable ageing mechanism(s), and the effectiveness of available maintenance technologies.

Maintenance actions for managing/repair of steam generator tube degradation include preventive/mitigation methods such as roto-peening, shot-peening and stress relieving and corrective/repair methods such as plugging, sleeving and nickel plating. Tube wear/fretting problems have been treated by preheater design modifications that reduce turbulence and peak feedwater flow velocities and by installing additional or longer antivibration bars. Design modifications have been used to mitigate the thermal fatigue of the feedwater nozzles and adjacent piping. Maintenance actions for steam generators with highly susceptible material or exposed to very poor water chemistry may have to include certain additional measures such as chemical cleaning, and ultimately steam generator replacement.

In general, an ageing effect may be defined as a change in performance of a system, structure or component (SSC), or change in physical or chemical properties resulting in whole or part from one or more active degradation mechanisms. Examples of ageing effects include: change in material properties, cracking, flow blockage, loss of fracture toughness, loss of heat exchanger performance (reduction of heat transfer), loss of material, loss of preload etc., [1-15].

INR's R&D Steam Generator Program

Having permanently in view all the key elements of a steam generator ageing management program (AMP), in 2000, Institute for Nuclear Research initiated and developed a R&D Program related to Steam Generator. The principal objective of this program consists in the effective management of the processes specific to the operation in normal and abnormal operating conditions of this equipment in order to operate in safe and efficient conditions throughout its life, aiming at its extension, with implications in obtaining a safe, clean and cheap energy.

The main research areas and the principal experimental results of this program are given in the following:

- *Assessment of materials behaviour and current candidate for the construction of the steam generator in normal and abnormal operation conditions.*
  - Identification of corrosive degradation processes of the structural materials depending on the material conditions, environment conditions and the test parameters.
  - Establishment of a correlation between the operating conditions and degradation mechanisms of the main structural materials from the primary and secondary circuits of the SG and modelling involved processes.
  - Development of mathematical models intended to forecast the intensity of the corrosive degradation during certain operating conditions.
  - Extension of the long-term safe operation of the steam generator (Long Term Operation - LTO).

- *Water chemistry and specific processes for the transport, deposit and removal of the corrosion products and impurities in steam generator.*
  - Decrease of the structural materials corrosion by improving water chemistry or by applying chemical treatments to the surface;
  - Implementation of the experimental results obtained in laboratory, of the operating parameters recorded during the equipment operation, as well as of the information and parameters from specialty literature or operation of similar facilities in other countries, into the database to assess the corrosion behaviour of structural materials and the formation and transport of corrosion products inside the steam generator circuits.

- *Operation, non-destructive testing, maintenance, repairing and modernization of the steam generator*.
  - Experimental program dedicated to new technologies for plugging the steam generator tubes in order to restore structural integrity.

- *Providing technical support for Cernavoda NPP in the field of steam generator*.
  - Provision of expertise in order to identify the types of degradation occurring due to corrosion of structural components during operation and proposals for decreasing them.
  - Characterization of deposits on tube plate of the steam generator and establishment of their influence on the corrosion behaviour of the tubing material of the steam generator and of the heat transfer efficiency.

- *Developing, implementing, monitoring of program C-D no.7 and dissemination of the obtained results.*

Experimental set-up

The principal goals of the experimental program referring of the most important steam generator material, (Incoloy 800 – material of the tubes) consisted in: the assessment of the corrosion kinetics, corrosion testing simulation devices of tube-tube sheet joint with and without deposits in normal and abnormal SG operation conditions, chemical cleaning of deposits placed in the simulation crevice devices and the assessment of corrosion intensity at the operation resuming after the chemical cleaning, concentration of impurities and corrosion products on simulated defects and the influence on the corrosion of tubes and tube sheet materials, the achievement of correlation between the presence of deposits and the intensity of crevice corrosion at tube-tube sheet joint, [16-24].

Corrosion experiments included in the present paper have been carried out by autoclaving at the parameters specific for the CANDU SG secondary circuit: temperature 260 ºC, pressure 5.1 MPa. The testing environment (solutions) utilized was demineralized water, pH=9.5 (AVT).

The experimental program consisted in testing of Iy-800 samples in demineralized water environments with pH=9.5 (AVT - morpholine and cyclohexylamine) at the secondary circuit specific parameters (temperature 260 °C, 5.1MPa pressure). The testing periods were 650 h, 2050 h and 3550 h, respectively. The specimens used were from Incoloy-800 steam generator tube (15.9 mm outside diameter and 1.13 mm wall thickness) which was sectioned on the diameter into 15 mm long pieces.

Experimental work included the following analyses: gravimetric analyses, optical microscopically analyses, and electrochemical measurements (potentiodynamic polarization and impedance spectrometry).

Results and discussions

The goal of the work consists in the assessment of the kinetics corrosion for the Incoloy-800 (material of the tubes) and the experimental results processing in the purpose to including in a future database related to the CANDU steam generator.

The corrosion process is strongly dependent of materials composition, environment properties and operational parameters of equipment. Based on the results obtained in the study of corrosion, the scientists may appreciate the corrosion intensity of the crevices materials or may draw up an experimental program, which could lead at immediate results.

Some examples of experimental results for the testing of the Incoloy 800 parallelepipedal samples for different times in demineralized water environments with pH=9.5 (AVT–morpholine and cyclohexylamine) at secondary circuit steam generator specifically parameters (260 °C and 5.1MPa) are presented in Figs 1- 3.

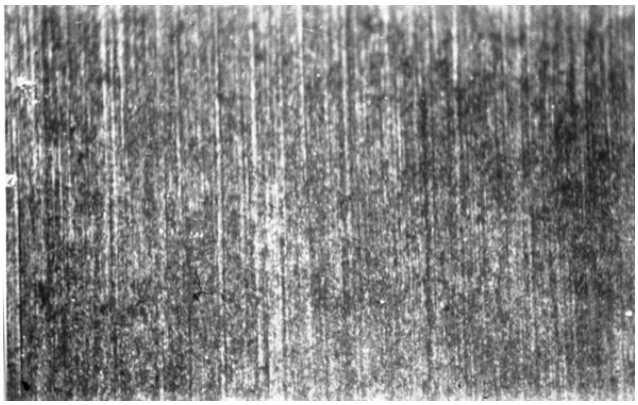


Fig. 1. The morphology of Iy-800 tested 648h (x 200)

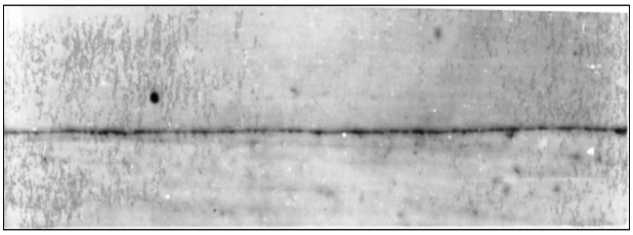


Fig. 2. The microscopic oxide layer on the Iy-800 sample exposed 648h in demineralised water, pH=9.5, t=260 °C and p=5.1MPa (original magnification, x1000)

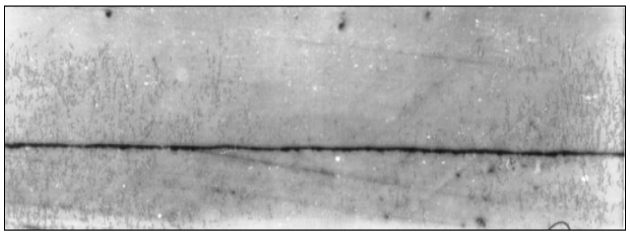


Fig. 3. The microscopic oxide layer on the Iy-800 sample exposed 3192h in demineralized water, pH=9.5, t=260 °C and p=5.1MPa (original magnification, x1000)

The Incoloy-800 tubes samples tested in demineralized water (pH=9.5), after a first period of exhibition (648 h), visually present as a shiny aspect colored in yellow-brown shades, while in steam they have a radiant aspect colored in blue-green shades on a brown light background. Continuing the testing of the samples, their aspect becomes dark-brown to brown for those, which were tested in water, and light-grey with bluish shades for those tested in steam.

Continuing the samples testing, their aspect becomes dark-brown to brown for those, which were tested in water, and light-grey with bluish shades for those tested in steam. The oxides obtained on the Incoloy 800 samples after 1200 h and 3192 h of testing are uniform, continuous, adherent and very thin. By X-ray diffraction there were determined the oxides layer thickness (0.50 μm - 1μm) and their chemical composition, which consists of Fe_3O_4 and NiO. That consists in the assessment of: loss of metal by corrosion, corrosion rate, the total formatted corrosion products, the adherent corrosion products, the released corrosion products, the release of corrosion products and the release of metal, shown in Figs 4 – 9.

The Ni-based alloys, Incoloy-800, are currently used as corrosion resistant materials in the nuclear industry because their corrosion rates are quite low. This behaviour is attributed to the protective character of the oxide film formed on their surface when the contact with pressurized high-temperature water environment is realized. However, oxidation processes or deposition of corrosion products can promote the development of particular corrosion problems. These phenomena result from changes in the oxide films structure throughout the cooling circuit. They also reflect the effect of impurities presence on the chemical composition and morphology of oxide films. Potentiodynamic curves and Bode and angle phase curves for Iy-800 in demineralized water pH=9.5 (AVT), are presented in the Figs. 10 - 12.

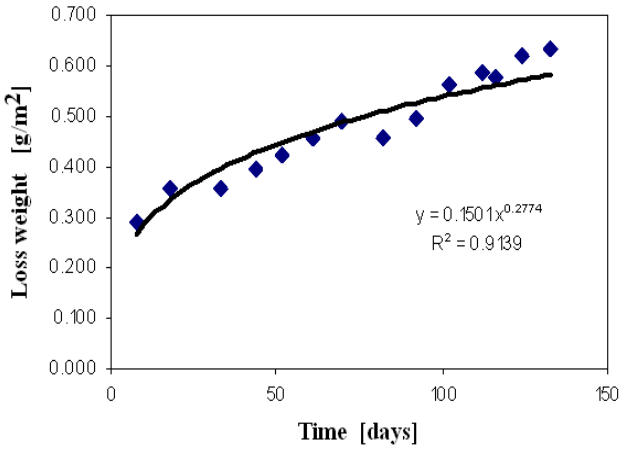


Fig. 4. Loss of metal by corrosion vs. Time

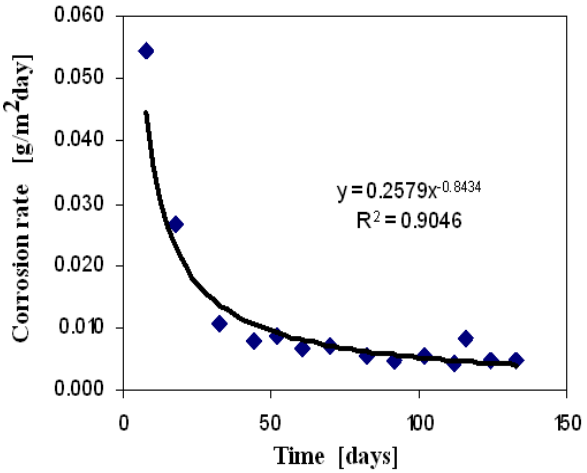


Fig. 5. Corrosion rate vs. time

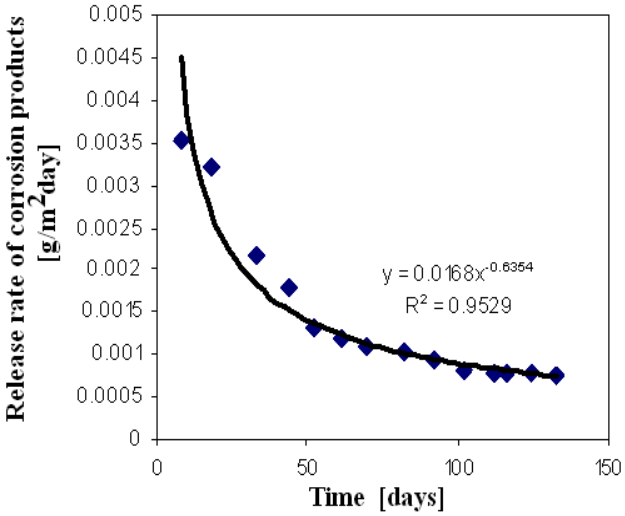


Fig. 6. Release rate of corrosion products vs. time

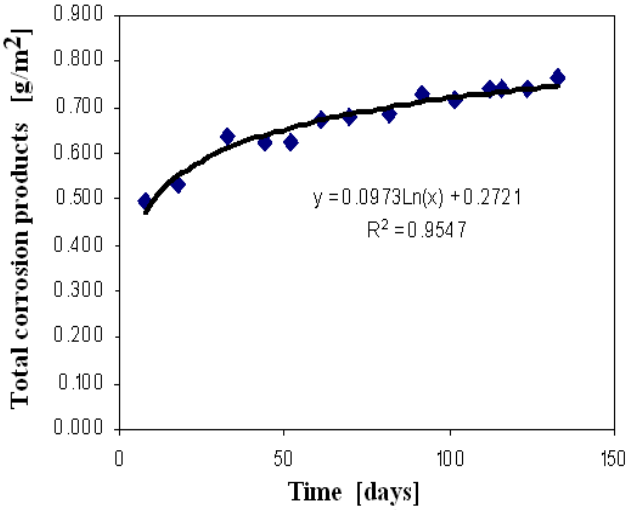


Fig. 7. Total corrosion products vs. time

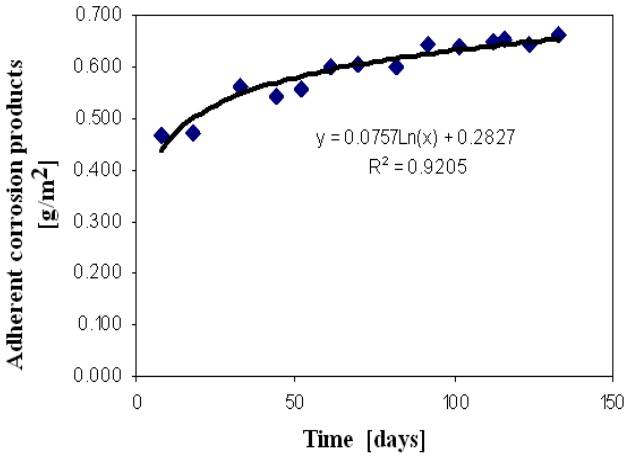


Fig. 8. Adherent corrosion products vs. time

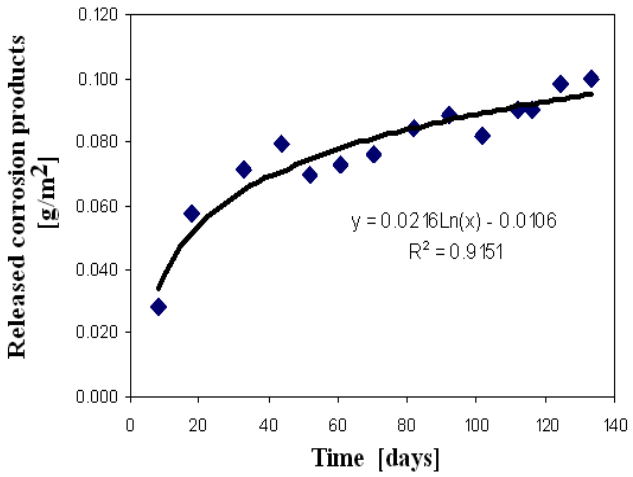


Fig. 9. Released corrosion products vs. time

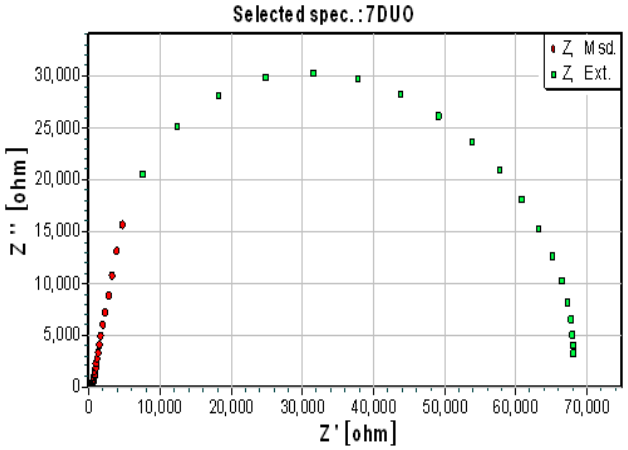


Fig. 11. Nyquist curve for Iy-800 – as received

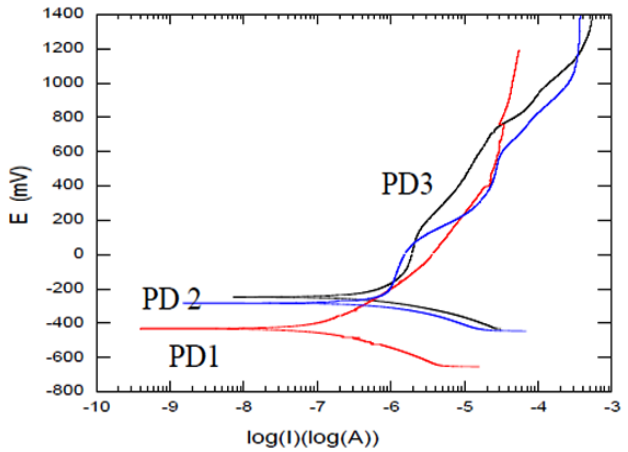


Fig. 10. Potentiodynamic curves for Iy-800 in demineralized water pH=9.5 (AVT): PD1- as received; PD2 – peroxided 10 days; PD3 – peroxided 150 days

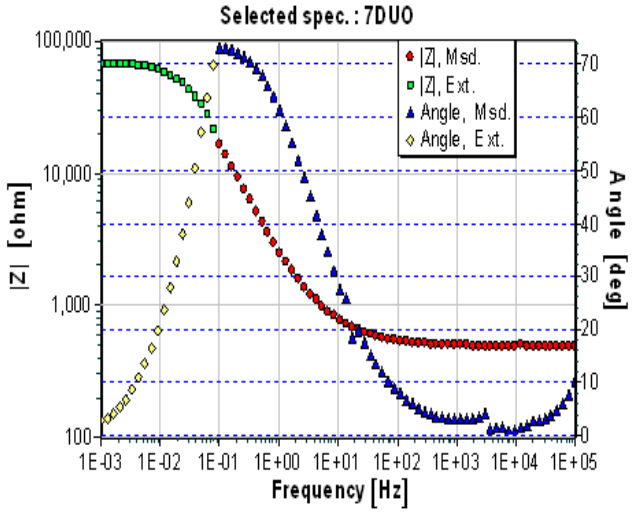


Fig. 12. Bode and angle phase curves for Iy-800 – as received

Conclusions

The key elements of a SG Ageing Management Program (AMP) are aimed to maintain the fitness for service of the steam generators at a nuclear power plant throughout their service life. These key elements are integrated within a plant specific SG AMP. Such a program should be implemented in accordance with guidance prepared by an interdisciplinary steam generator ageing management team organized at a corporate or owners' group level. R&D activity plays an important role in SG's AMP.

The main objective of Steam Generator R&D Program initiated and developed since 2000 at INR consists in the effective management of the processes specific to the operation in normal and abnormal operating conditions of SG in order to operate in safe and efficient conditions throughout its life, aiming at its extension, with implications in obtaining a safe, clean and cheap energy.

Corrosion testing presented in this paper has been performed on the Incoloy 800 samples for 3192h at a pH=9.5. By using gravimetric analysis and descaling of filmed samples assayed at certain intervals of time, the corrosion kinetics of Incoloy 800 has been established.

For the samples tested in solution for 648h, the films thickness was 0.3µm, increasing as the testing time became longer, and reaching 1.0µm after 3192h of testing.

The corrosion kinetics has been established for the corrosion induced loss of metal, corrosion rate, total formed corrosion products, adherent corrosion products, released corrosion products, released rate of corrosion products and released rate of metal.

The paper also presents the kinetic curves and the equations which describe these curves for the tests performed at the 9.5 values of the pH.

In the corrosion rate case, the highest values was obtained for the samples tested in a pH=9.5 solution at the beginning of the experiments. After 3192h of testing, the corrosion rate increases due to the magnetite layer that covers the samples surface and assures the corrosion protection.

If the chemical parameters of the cooling water on the secondary side of the steam generator are kept at the optimal values, the corrosion is not a problem for the Incoloy 800, material of the CANDU steam generator tubing, but corrosion, especially the localized corrosion, appears in the case of the impurities presence and this process has a great contribution in the steam generator ageing management, like NPP key component.

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