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Degradations of
Incoloy 800 Steam Generator Tubing

Dumitra Lucan
Department of Corrosion and Circuits Chemistry,
Institute for Nuclear Research, POB 78, Pitesti
Romania

1. Introduction

In our days, the nuclear energy becomes more and more important. The efficient operation of a Nuclear Power Plant (NPP) supposes the assurance of the performances established by design for all entire life of the NPP key components. Steam Generator (SG) is one of the key components for a NPP because this equipment assures the separation boundary between the primary and secondary circuit and its unavailability suppose the NPP shutdown. The synergetic action of the high pressures and temperatures, constraints (stresses, vibrations) and the chemical parameters of the cooling agents make the steam generator susceptible for more types of degradations. Because of the unavailability of the measures for monitoring and mitigation of these degradations the performances of the steam generators decrease and determine direct and indirect losses. The replacement of the steam generator is very expensive and very difficult. For these reasons it becomes necessary the assurance of the steam generator performances for the entire life established by design, 30 years with the possibility of extension to 40 or 60 years.

The optimization of the steam generator operation, by implementation of the management complex system for the monitoring of the operation processes, periodical inspections, and preventive maintenance determine economies by order of hundreds of millions dollars, for entire life of a nuclear power plant.

In this scope it is very important to intensify of the applicative research in the purpose of establishing the newest solutions, methods, mechanisms in order to characterize the specific processes for the operation of the steam generator. The principal objective of the research consists in the establishing of the fundamental knowledge, theories, methods and models necessary for qualitative and quantitative characterization of steam generator degradation processes. The complementary research activity should be oriented towards the management of ageing and, implicitly, towards the preservation of the steam generator structural integrity.

The principal objective of the work presented in this chapter consists in the characterization of specific processes and mechanisms referring to steam generator tubing degradation.

The specific objectives are the following: the establishment of the main corrosive degradation mechanisms which contribute at steam generator tubing material (Incolloy-800) failures; knowledge of the phenomena which appear in steam generator because of the material/environment interaction; elucidation of corrosion product release, transport and

deposition mechanisms in the secondary circuit of the steam generator, which depend by physical-mechanical properties of materials and physical-chemical properties of thermal agent (temperature, pressure, pH, electrochemical potential).

All steam generator tube failures result in the transfer of the radioactive materials from the primary coolant circuit to the steam generator secondary circuit, and necessitate downtime to locate and plug failed tubes. For the particular case of the CANDU plants, any steam generator tube failure results in an additional economic penalty through the loss of heavy water. Nearly all the failures were attributed to secondary side water chemistry conditions and excursions, many of which resulted from condenser cooling water ingress.

The investigation of the structural materials corrosion in correlation with the water chemistry, as well as the impurities and corrosion products concentration and deposition and their removing from the CANDU steam generators is a very active field and both the experimental works and the understanding of the mechanisms involved are submitted to some rapid changes and permanently open to the research. To provide information about the corrosion behaviour of the structural materials from CANDU steam generators under normal and abnormal conditions of operation and to identify the failure types produced by corrosion were performed a lot of corrosion experiments. These experiments consisted in chemical accelerated tests, static autoclaving and electrochemical investigations.

The goal of this work consists in the assessment of corrosion behaviour of the tubes material, Incoloy-800, at normal secondary circuit parameters ((temperature - 260°C, pressure - 5.1MPa). The testing environment was the demineralised water without impurities, at different pH values regulated with morpholine and cyclohexylamine (all volatile treatment – AVT).

The results are presented like micrographics and graphics representing weight loss of metal due to corrosion, corrosion rate, total corrosion products formed, the adherent corrosion products, released corrosion products, release rate of corrosion products and release rate of the metal.

This work contributes to the establishing of causes that produced components degradation, the knowledge of mechanisms degradation, evaluation of corrosion evolution in time by extrapolation of obtained results and estimation of remaining safe operation life for the nuclear power plant key-components.

The knowledge of corrosion behavior of structural materials of equipments from nuclear power plants gives the possibility to effectuate of some correct diagnosis and following of necessary measures to prevent and diminish the ageing process of which the evolution supposes some considerable economic costs.

2. Types of corrosion specific to the steam generator

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, (IAEA, 1997).

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

1. 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.   correct the 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.   implement 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 SG tubing degradation caused by corrosion and other age-related mechanisms continues to be a significant safety and cost concern for many SGs. The understanding SG degradation mechanisms is the key to effective management of SG ageing and consists in the knowledge of SG materials and these one properties, stressors and operating conditions, like degradation sites and wear mechanisms.

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 SG 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 SG, 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.

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^{0}C	t_{in} = 187.2^{0}C
t_{ou} = 290^{0}C	t_{ou} = 260^{0}C
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 having in view 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 cladding), stainless steel SA 240-410S (intermediate supports), carbon steel SA 516-gr. 70 (shells), carbon steel SA 508 cl.2 (tubesheet).

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

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 under the following three specific forms:

1. generalised corrosion;
2. localised 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.

Generalised corrosion

Many research workers 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 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 stiction 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 tubes.

Using adequate constructive solutions can diminish the phenomenon.

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.

Stress corrosion cracking (SCC)

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 shows that these cracks initiated on the side of the primary agent are of intergranular nature, oriented along the longitudinal axis of the tubes. The factors involved in the cracking of the U-bend region are:

• microstructural factors, features referring to material strength and hardness;
• residual or latent stresses that emerge during fabrication, bending and installation;
• shape of the tube, bending radius resulting from processing;
• the extent and frequency of cycling, shape of strains induced during SG operation;
• 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 tubesheet - 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.
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, (Lucan, D. 2006; Lucan, D. et al., 2007; Lucan, D. et al., 2008).
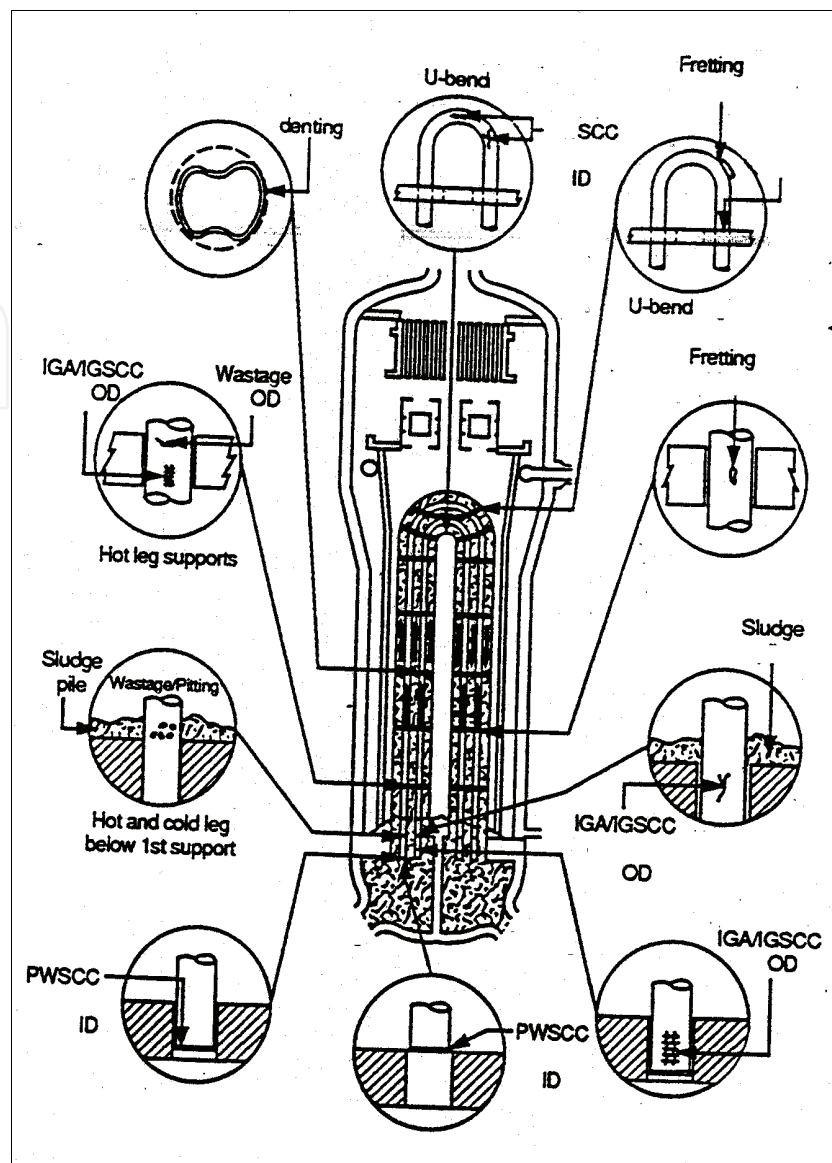Fig. 1. is a schematic layout of corrosive attacks specific to Steam Generators.

Fig. 1. Types of corrosion specific to the steam generator, (IAEA, 1997)

3. Experimental

The generalized corrosion is an undesirable process because it is accompanied by deposition of the corrosion products which affect the steam generator performances. It is very important to understand the corrosion mechanism with the purpose of evaluating the quantities of corrosion products which exist in the steam generator after a determined period of operation, (IAEA, 1997).

The nickel-based alloys (Incoloy-800) are currently used as corrosion resistant materials in the nuclear industry because their corrosion rates are quite low. This behavior is attributable to the protective character of the oxide film formed on their surface when the contact with the pressurized high-temperature water environment is realized. Nevertheless, oxidation processes or deposition of corrosion products can promote the development of particular corrosion problems. These phenomena result from changes in the structure of the oxide films throughout the cooling circuit, (Iglesias & Calderon, 2003).

Corrosion experiments included in the present work have been carried out on the Incoloy-800 samples by autoclaving in static autoclaves at parameters specific for the secondary circuit of the CANDU steam generator: temperature 260°C, pressure 5.1MPa. The specimens used were from Incoloy-800, steam generator tube, (15.9mm outside diameter and 1.13mm wall thickness) which was sectioned on the diameter into 15 mm long pieces polished with grit papers and cleaned ultrasonically. The testing environments utilized were demineralised water with pH = 7.5, 8.5 and 9.5 (AVT). The testing periods were 240h, 2050h and 3550h. Demineralised water had a dissolved oxygen content was below 2ppm (oxygen was released by thermal degassing at 100°C). The water pH and conductivity were measured with Multi – Channel Analyser CONSORT C835. Experimental work included: gravimetric analyses, optical microscopically analyses and electrochemical measurements (potentiodynamic polarization). The weight modifications due to oxidation or corrosion products removal by different methods were measured using a Shimadzu AUW 220 analytically balance providing a precision of ±0.01 mg. The surfaces morphologies and the cross sections of the corrosion samples were analyzed with the optical microscope OLYMPUS GX 71. The corrosion kinetic was additionally evaluated by potentiodynamic measurements using a PAR 2273 device.

4. Results and discussions

The goal of the work consists in the assessment of the kinetics corrosion for the Incoloy-800 - material of the tubes - tested in demineralised water with different pH values and the experimental results processing with the purpose of including results in a future database of a steam generator. To investigate the water chemistry effects on characteristics of corrosive films formed on Incoloy-800 material, a number of corrosion experiments by electrochemical methods and static autoclaving were performed. The electrochemical determinations were performed by potentiostatic method in aqueous solutions with different pH, at room temperature, (Lucan, D., 2010).
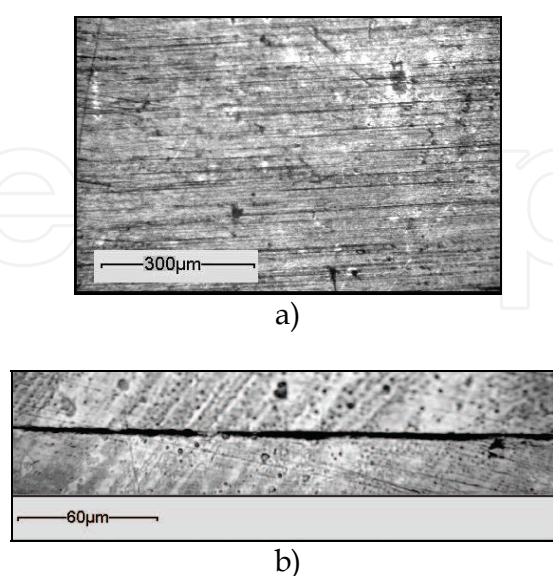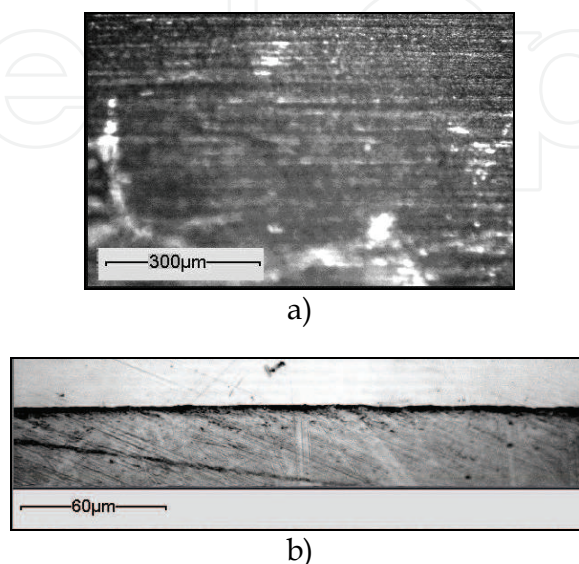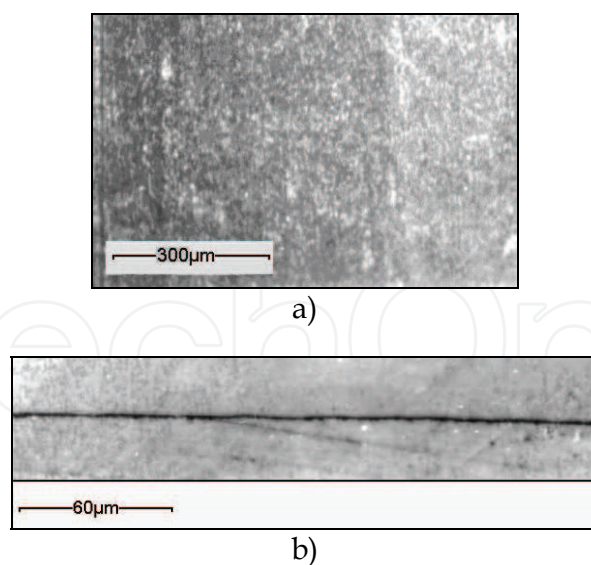

a)

b)

Fig. 2. Surface morphology (x200) (a) and aspect of the superficial layer (x1000) (b) for Incoloy-800 exposed for 1680h in demineralised water, pH=7.5, T=260°C and p=5.1MPa

The chemical composition of Incoloy-800 in percent weight is: C=0.02%, Mn=0.64%, Si=0.49%, S=0.01%, Ni=33.40%, Cr=21.90%, Cu=0.01%, Al=0.24%, Ti=0.41% and Fe=42.88%. Some examples of experimental results for the testing of the Incoloy-800 samples for different times in demineralised water environments with pH=7.5, pH=8.5 and pH=9.5 (AVT) at secondary circuit steam generator specifically parameters (260^0C and 5.1MPa) are presented in the Fig.2 ÷ Fig.4.

a)

b)

Fig. 3. Surface morphology (x200) (a) and aspect of the superficial layer (x1000) (b) for Incoloy-800 exposed for 3600h in demineralised water, pH=8.5, T=260^0C, p=5.1MPa

a)

b)

Fig. 4. Surface morphology (x200) (a) and aspect of the superficial layer (x1000) (b) for Incoloy-800 exposed for 3192h in demineralised water, pH=9.5, T=260^0C, p=5.1MPa

The exposure times for the metallographic analysis of samples tested at a pH=7.5 were: 264h, 456h, 696h, 960h and 1680h. For the Incoloy-800 samples, tested for 264h in demineralised water at a pH=7.5 a uniform, continuous, adherent oxide layer is noticed, with thickness smaller than or equal to 0.6μm. When the testing time was 456h in the same

conditions the presence of the oxide is noticed on samples surface, brown-red in colour. The samples surface is entirely covered by oxide and there are no uncovered spots while the visual aspect is almost identical for the entire surface. Thickness of the oxide layer is about 0.8 μm. The oxide layer on the samples tested for 696h is uniform, continuous, adherent, while its thickness ranges between 0.6μm÷1.2μm. The results of the 960 hours exposure was the occurrence of an oxide layer with a thickness of 0.9μm÷1.5μm.

The thickness of the oxide layer existing on the samples tested for 1680h is about 3μm.

The aspect of the surface and film formed on the samples tested 1680h in demineralised water at a pH=7.5 are presented in Fig.2. The exposure times for the metallographic analysis of the samples tested at a pH=8.5 were: 240h, 720h, 1200h, 1416h, 1656h, 1824h, 2064h, and 3600h. On the Incoloy-800 samples, tested for 240h in demineralised water with a pH=8.5 adjusted with morpholine and cyclohexylamine, at 260⁰C and a pressure of 5.1MPa a uniform, continuous and adherent oxide layer is noticed, whose thickness is smaller than or equal to 1.9μm. The surface morphology for some samples exposed for 240h in demineralised water at a pH=8.5 (AVT) at parameters specific to the steam generator secondary circuit shows the presence of the oxide, its colour being brown-red. The samples surface is completely covered by oxide and there are no uncovered spots, while the visual aspect is almost identical for the entire surface. It is to be noticed that the oxide layer for the samples tested 720h in demineralised water with a pH=8.5 is in this case, uniform, continuous, adherent and its thickness ranges between 0.7μm and 0.8μm. The oxide is uniform, with brown-red shadows and formed in continuous film on the samples surface. For the Incoloy-800 samples tested for 1200h in demineralised water with a pH=8.5 the result of the exposure was the formation of an oxide layer with a uniform thickness of 1.2μm. In this case the oxide uniformity is noticed. The aspect of the oxide layer existing on the samples tested 1416h is shown that the film thickness on these samples is about 0.8μm. The surface morphology for the samples exposed for 1416h has a uniform aspect.

The aspect of the oxide layer existing on the surface of samples tested for 1656h in demineralised water with pH=8.5 is uniform, continuous and adherent. The uniformity and continuity of the oxide film is observed and the surface morphology for the samples exposed for 1656h in demineralised water with pH=8.5. The oxide film is uniform, continuous, adherent and has a thickness smaller than 2.6μm for a sample exposed for 1824h in demineralised water with a pH=8.5 in conditions specific to the operation of the secondary circuit.

The aspect of the oxide layer on the surface of samples tested for 2064h in demineralised water with a pH=8.5 is uniform, continuous and adherent. The uniformity and continuity of the oxide layer can be noticed by the surface morphology of samples exposed for 3600h in demineralised water with a pH=8.5, Fig.3. The oxide layer is uniform, continuous and adherent and has a thickness smaller than 3.5μm. The aspect of the oxide layer and the surface morphology, respectively, for a sample exposed for 3192h in demineralised water at a pH=9.5 under operating conditions specific to the secondary circuit are presented in Fig.4.

4.1 Comparison of outputs of tests performed at pH=7.5, pH=8.5 and pH=9.5

After autoclaving operation the samples were descaled in two stage alkaline permanganate – citrox, (Taylor, 1977). Fig.5 ÷ Fig.11 comparatively present the corrosion kinetics for: metal loss by corrosion; corrosion rate; totally formed corrosion products; adherent corrosion products, released corrosion products; corrosion products release, and the release rate of

metal at a pH=7.5, pH=8.5 and pH=9.5, respectively. The Table 1 presents the equations for the corrosion kinetics. For the weight loss due to corrosion and corrosion rate it is noticed that, in the case of a pH=9.5 these have the smallest values (Fig.5 and Fig.6), (Lucan et al., 1998; Lucan et al., 2001; Lucan et al., 2003; Lucan et al., 2005; Cojan et al., 2008). The results are confirmed by the experiments presented in articles from specialty journals, (Taylor, 1977; Stellwag, 1998; Iglesias & Calderon, 2003).

No.	Parameter	pH=7.5	pH=8.5	pH=9.5
1	*Loss of metal by corrosion*	$y=0.1249\ln(x)+0.0337$	$y=0.2201x^{0.2705}$	$y=0.10501x^{0.277}$
2	*Corrosion rate*	$y=0.2275x^{-0.831}$	$y=0.3439x^{-0.8377}$	$y=0.2579x^{-0.8434}$
3	*Total corrosion products*	$y=0.1626\ln(x)+0.1055$	$y=0.2417\ln(x)-0.0648$	$y=0.0973\ln x+0.2721$
4	*Adherent corrosion products*	$y=0.2924x^{0.142}$	$y=0.2962x^{0.2602}$	$y=0.0757\ln x+0.2827$
5	*Released corrosion products*	$y=0.051\ln(x)-0.0328$	$y=0.0296\ln(x)-0.0461$	$y=0.0216\ln x-0.0106$
6	*Release rate of corrosion products*	$y=0.0206x^{-0.4336}$	$y=0.0217x^{-0.6715}$	$y=0.0168x^{-0.6354}$
7	*Release rate of metal*	$y=0.0031x^{-0.6542}$	$y=0.0174x^{-0.7571}$	$y=0.0031x^{-0.6715}$

Table 1. The equations for the kinetic corrosion specific parameters
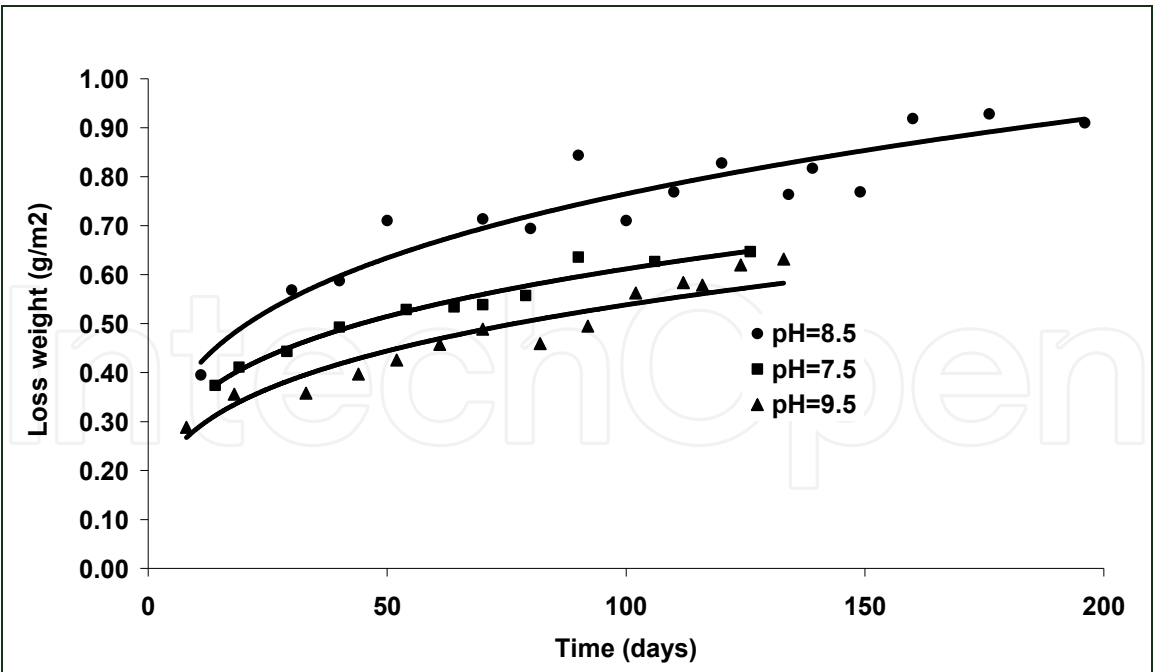
Fig. 5. Loss of metal by corrosion vs. time

Also, in the case of totally formed corrosion products the smallest values have been obtained in exposure in solution at a pH=9.5 (Fig.7). In the case of adherent corrosion products, the smallest values have been reached for the solution with a pH = 7.5 (Fig.8), but the values for

the tests at pH = 9.5 solution are similar, without significant differences between the two cases.
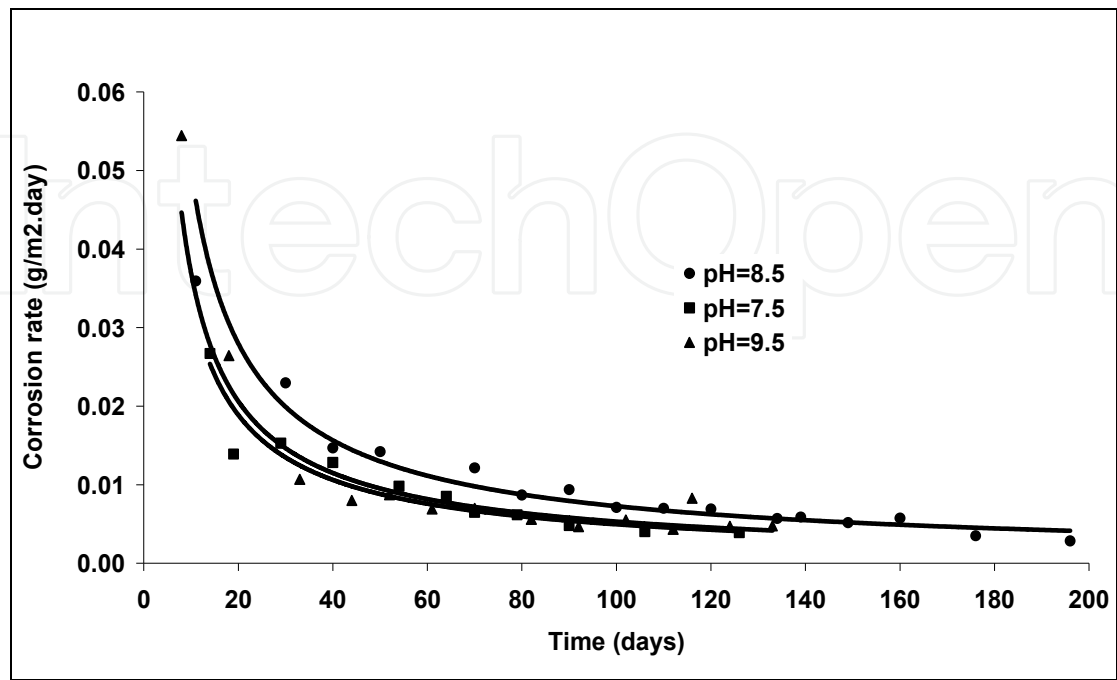
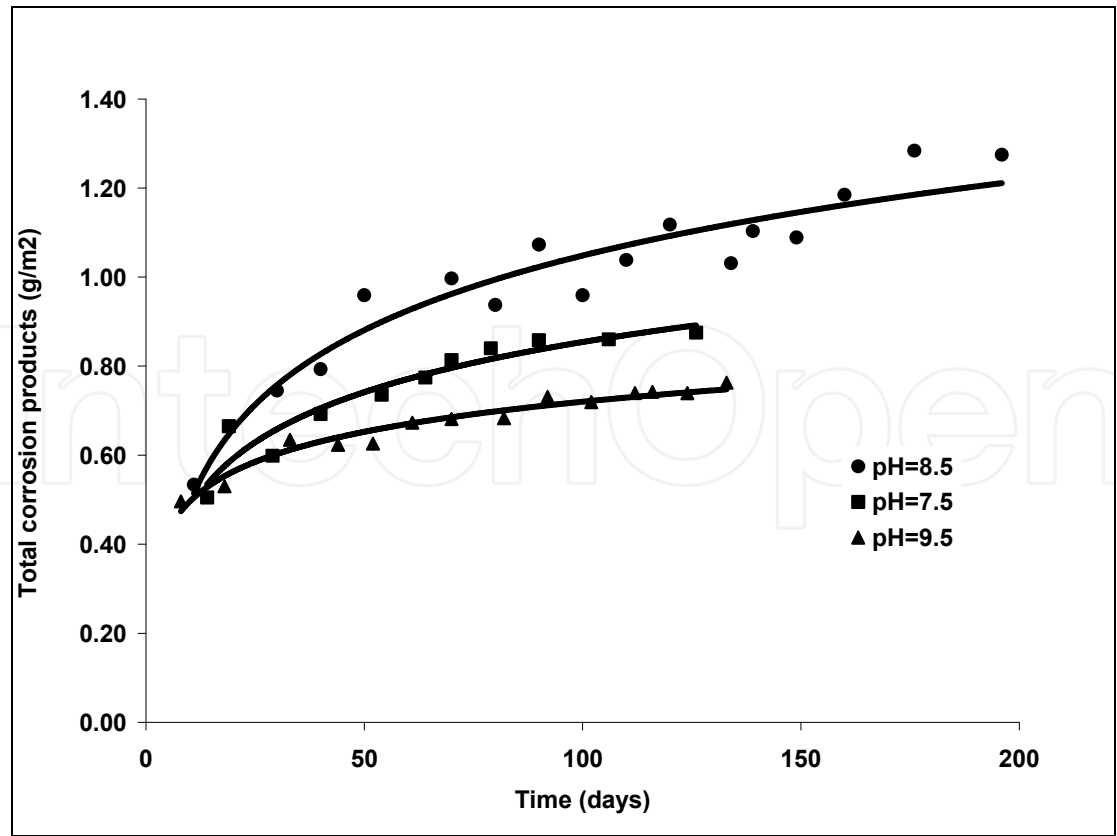Fig. 6. Corrosion rate vs. time

Fig. 7. Total corrosion products vs. time

In the case of released corrosion products, the release rate for products and metal the highest values are obtained for the samples tested in the solution with a pH=7.5 (Fig.9÷Fig.11). This can be explained by the fact that magnetite solubility has higher values for solutions with a smaller pH.
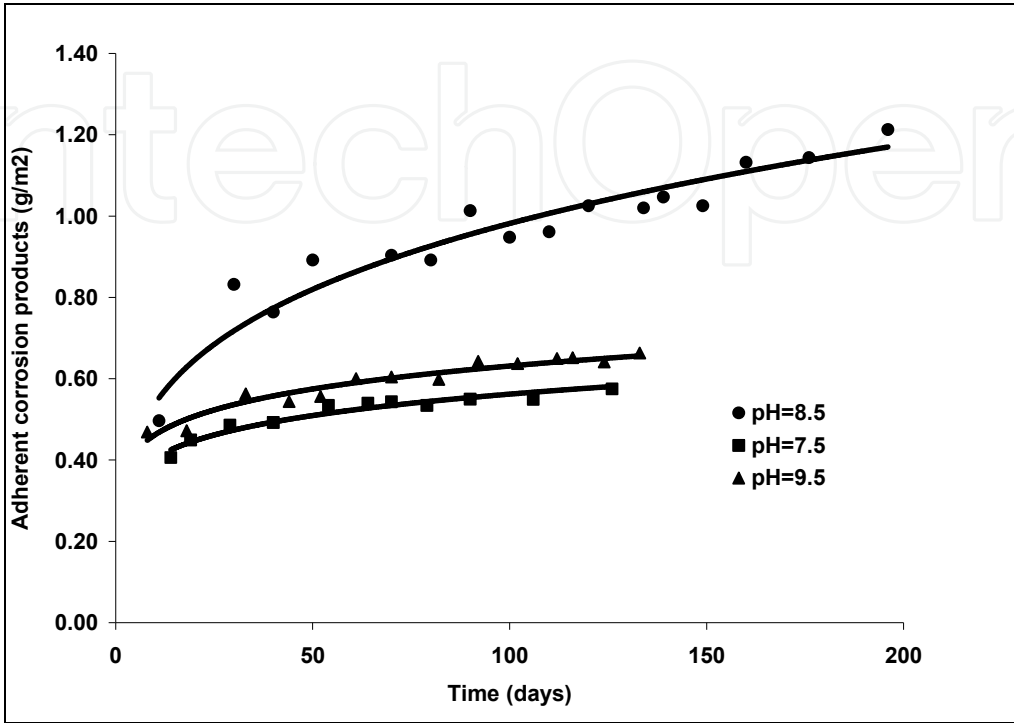

Fig. 8. Adherent corrosion products vs. time
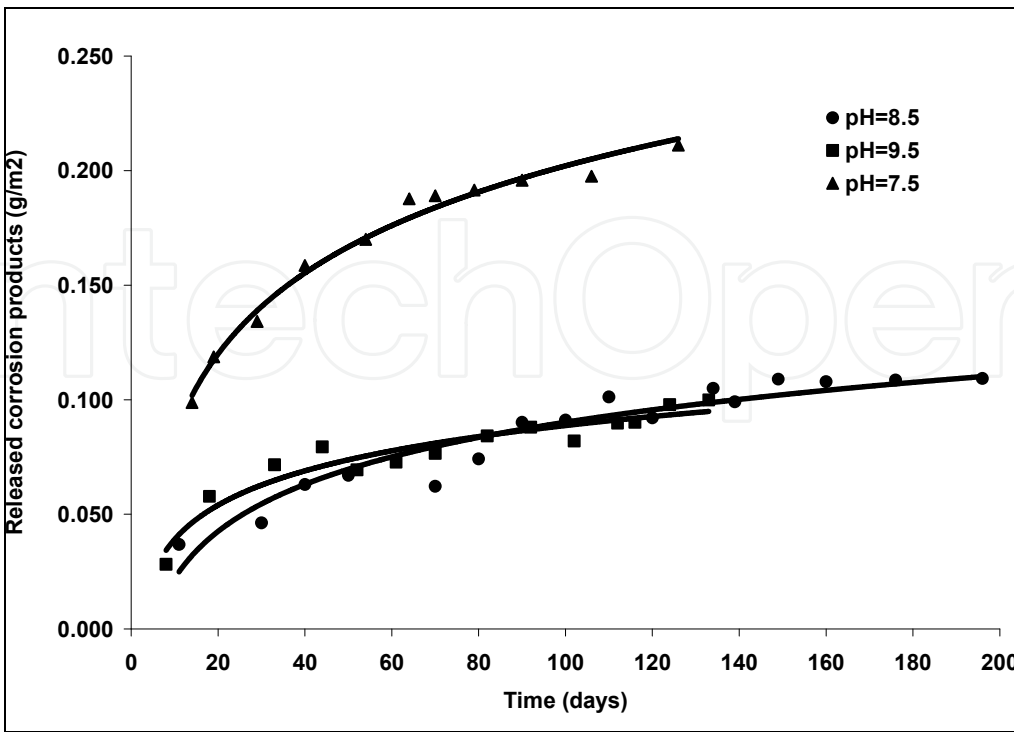
Fig. 9. Released corrosion products vs. time
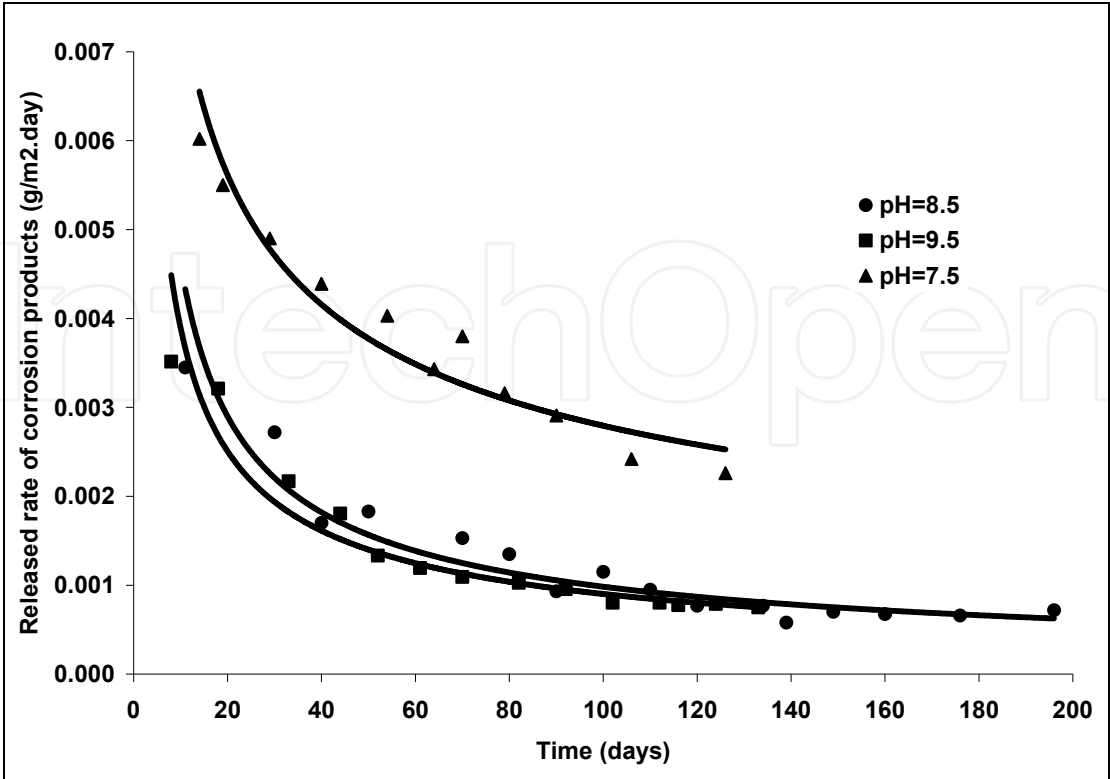
Fig. 10. Released rate of corrosion products vs. time
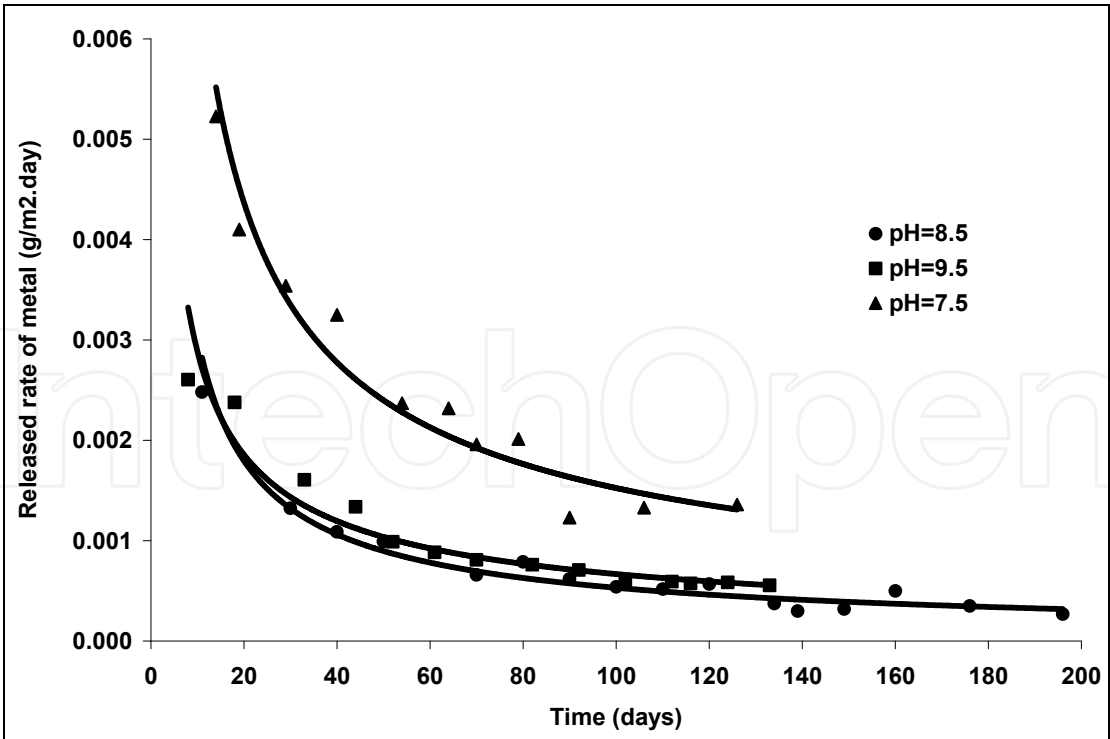
Fig. 11. Released rate of metal vs. time

An example in this sense is the fact that, at 200°C the magnetite solubility is 2µg/kg for a solution with pH=9.5 while for a pH=8.5 the magnetite solubility increases, reaching

60µg/kg. It can be stated that corrosion kinetics for: metal loss by corrosion; corrosion rate; totally formed corrosion products; adherent corrosion products; released corrosion products and the metal release rate at a pH=7.5, pH=8.5 and pH=9.5, respectively, evolve following power-type or logarithmic laws: the smallest corrosion rates are obtained in the case of exposure in a pH=9.5 solution.

Fig.12 and Fig.13 show the results of electrochemical measurements performed by the potentiodynamic method. The electrochemical potential values measured in demineralised water at a pH=9.5 for samples tested by autoclaving at a pH=7.5: PD 35 – tested 10 days, PD 39 – tested 19 days and PD 33- initial status; and pH=8.5 for samples tested by autoclaving at a pH=8.5: PD 36 – tested 10 days, PD 37 – tested 47 days, PD 38 – tested 96 days and PD 34- initial status, show that the oxide films formed on the samples surface at higher exposure times provides them a relatively high corrosion resistance.
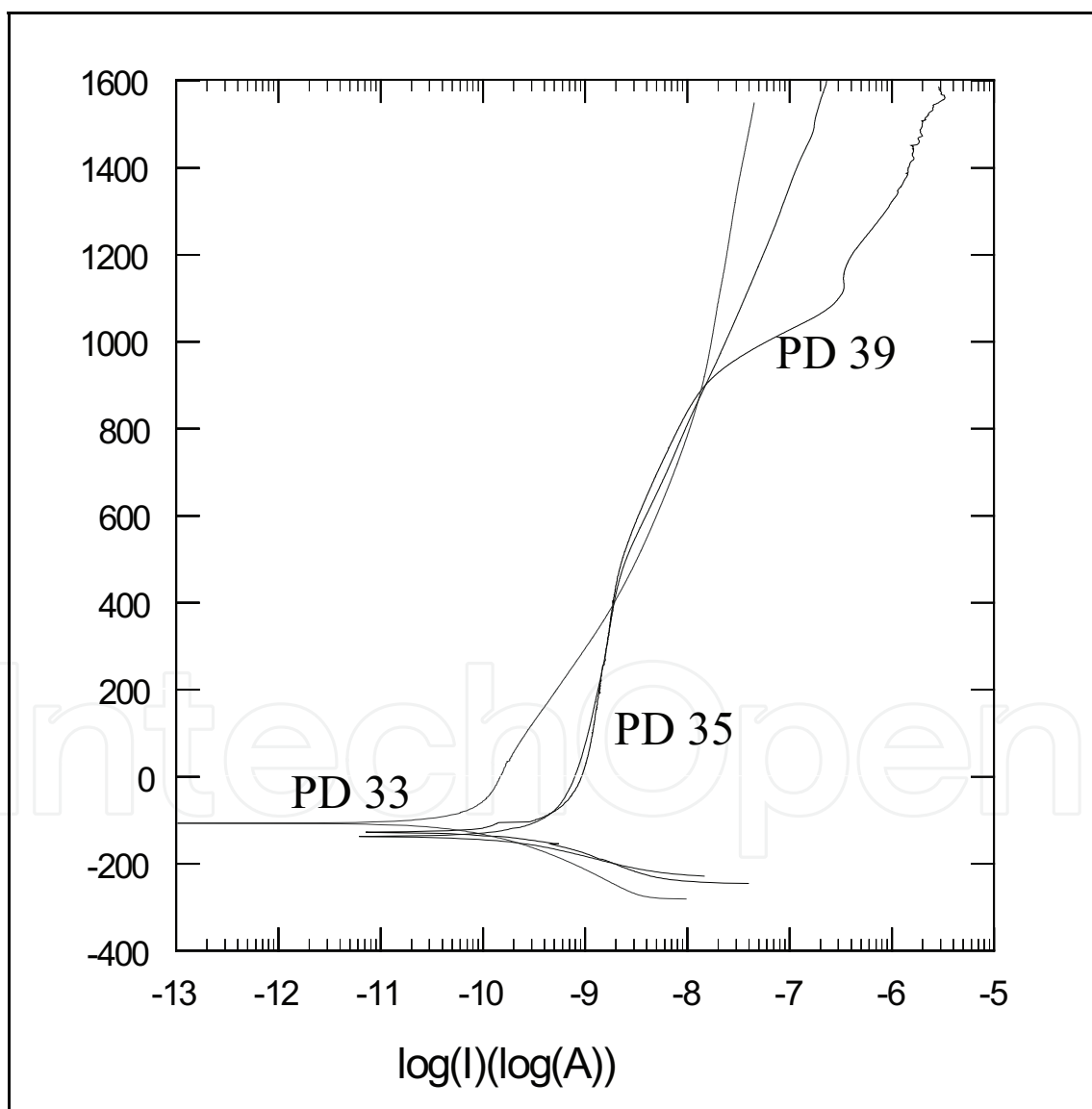
Fig. 12. Potentiodynamic curves Incoloy-800 tested pH=7.5: PD 33- as received; PD 35 – tested 10 days; PD 39 – tested 19 days
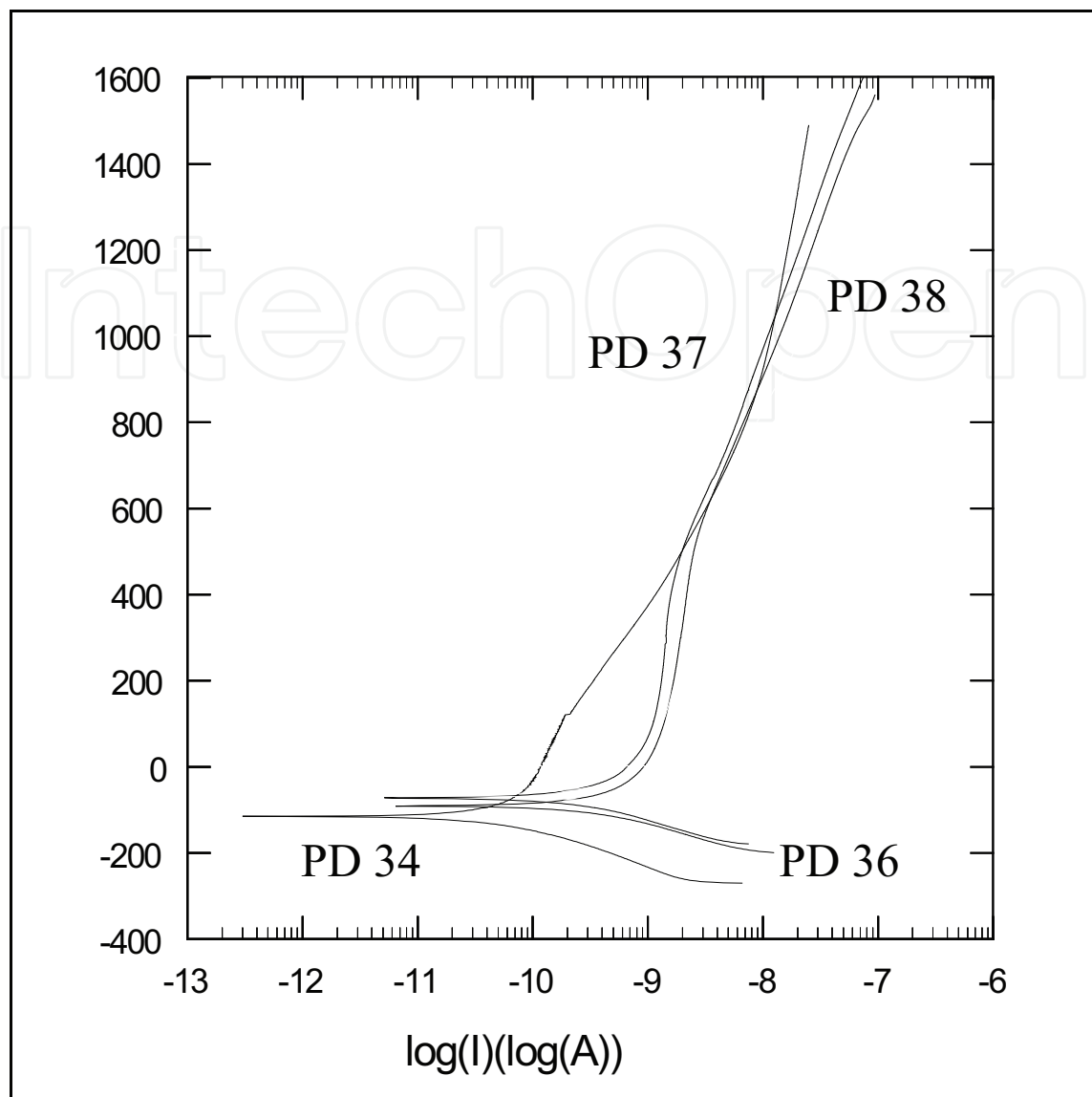
Fig. 13. Potentiodynamic curves Incoloy-800 tested pH=8.5: PD 34- as received; PD 36 –
tested 10 days; PD 37 –tested 47days; PD 38 – tested 76 days

5. Conclusions

This work presents in the first place the types of degradations specific to the steam
generators and in the second place the correlation between the nature of materials used for
the construction of the steam generator tubing, the chemical characteristics of the circulating
environment and the way in which certain of their pH values can lead to the development of
different types of oxide layers.

Corrosion testing has been performed for Incoloy-800 alloy samples for 3600h at a pH=7.5,
3600h at a pH=8.5 and 4800h at a pH=9.5.

By using gravimetric analysis and descaling of filmed samples assayed at certain intervals of
time, the corrosion kinetics of the Incoloy-800 alloy has been established.

The films formed on samples after autoclaving and the morphology of samples surfaces
have been assessed by metallographic microscopy.

In the case of samples tested in solution of pH=7.5 for 264h the thickness of the films is 0.6μm, this one increasing with the increase of the testing time, reaching 3μm after 1680h of testing.

For the samples tested in solution of a pH=8.5 for 240h thickness of the films is 1.9μm, this one increasing with the increase of the testing time, reaching 3.5μm after 3600h 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 work also presents the kinetic curves and the equations which describe these curves for the tests performed at the three values of the pH.

A comparison is presented between the corrosion kinetics for the normal value of the operation pH=9.5, and also for the values 7.5 and 8.5. For the corrosion-induced loss of weight and for the corrosion rate it is noticed that in the case of pH=9.5 solution these have the smallest values.

In the case of released corrosion products, their release rate and metal release rate, the highest values are obtained for the samples tested in a pH=7.5 solution. This can be explained by the fact that magnetite solubility has higher values for solutions with a smaller pH.

The work dones a correlation of the normal/abnormal chemical system of the steam generator secondary circuit with the corrosion of the tubing material exposed in respective environment.

The future research will have like objective experimental studies on the behaviour of the principal steam generator structural materials in the presence of the impurities and the synergetically effect of the simultaneosly presence of impurities especially in the regions with restrictive flow and/or in the presence of crevices.

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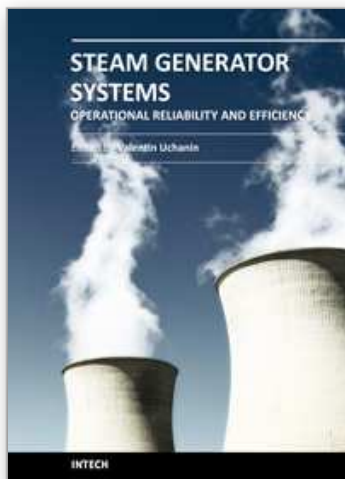
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The book is intended for practical engineers, researchers, students and other people dealing with the reviewed problems. We hope that the presented book will be beneficial to all readers and initiate further inquiry and development with aspiration for better future. The authors from different countries all over the world (Germany, France, Italy, Japan, Slovenia, Indonesia, Belgium, Romania, Lithuania, Russia, Spain, Sweden, Korea and Ukraine) prepared chapters for this book. Such a broad geography indicates a high significance of considered subjects.

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