LESSONS LEARNED FROM THE EXPERIENCE OF CANDU STEAM GENERATORS APPLICABLE TO SMR

DOINITA CIURCU [1], DUMITRA LUCAN [2], AUREL DAVID [1], VALENTIN LAUTARU [1]

[1] Institute for Nuclear Research (RATEN ICN) Pitești, Romania
[2] Technical Sciences Academy of Romania ASTR, Bucharest, Romania

e-mail: doinita.ciurcu@nuclear.ro

Abstract

In recent years, the international nuclear industry has learnt from the experience of large-scale commercial power plants and has consistently shared this knowledge so that others can benefit from it. The need to learn from the others' experiences has been evident since the beginning of the nuclear industry. Corrosion difficulties common in water-cooled reactors forced the expansion of this collaborative process to include research and development initiatives for GEN IV concepts, or in the case of small modular reactors (SMRs). Thus, the knowledge and skills of the CANDU PHWR domain can be applied to the research and development of new small modular reactors. This work presents a comparison of the steam generators used for a CANDU nuclear power plant with those for a NuScale reactor. The study discusses the degradation processes of the structural materials in the CANDU steam generator, as well as the degradation mechanisms that may affect the NuScale steam generators. One of these processes is fouling, and the research describes methods for characterizing the deposits formed in the secondary circuit of the CANDU steam generators that can be used to NuScale steam generators. Thus, it is proved that the knowledge gained via experience in the research activities of structural materials degradation may be applied to small modular reactors.

Keywords: *CANDU, NuScale, Steam generator, Alloy 800, Alloy 690*

Introduction

The basic design principle of CANDU is similar to that of other water-cooled nuclear reactors; in the reactor core, the role of fission reactions is to heat pressurized water in a cooling loop. Generally, the commercial water-cooled reactors use light water as moderator. Since the CANDU reactors operate with natural uranium, to enable operation with this type of fuel, heavy water is used instead of "light" water in the CANDU design.

The heat is transferred with the steam generators' help, in a secondary cooling loop, which drives a steam turbine with an electric generator attached. After that, the steam released by the turbines is cooled, condensed and returned to the steam generators as feed water [1].

After a long period of focus on the development of large nuclear power plants (NPPs), there is a renewed interest in small and modular reactors (SMRs) development. Small modular reactors are advanced nuclear reactors with installed capacities of up to 300 MWe per unit. This type of reactor has many advantages, including: relatively small footprints, lower capital investment, possibility to be sited in areas not accessible for larger NPPs, distinct safeguards, security and nonproliferation. Romania has the potential to implement small modular reactors and, in this regard, Nuclearelectrica and NuScale Power have signed an agreement to advance the implementation of NuScale's innovative SMR technology. The NuScale Power Module™ (NPM) is a small, modular pressurized water reactor (PWR) used for electrical power generation and non-electrical process heat applications. It has a reactor power of 250 MWt/module and an electric output of 77 MWe/module, which can be used in plants of 4, 6 or 12 modules, as needed [2, 3]. The reference facility size for design and licensing activities consists of twelve modules, each of which operates independently of the others in a complex configuration. The location of such reactor in Romania was chosen because here there are nearly 30 years of experience in successfully operating one of the highest-performing power plants in the world (CANDU reactor), a team of skilled engineers, and a huge supply chain.

Mainly, a NuScale reactor consists in three parts: a reactor pressure vessel with the nuclear core, a helical coil steam generator, and a pressurizer. The reactor core is made up of a series of LWR fuel assemblies (with reduced height in comparison with PWR standard fuel assembly) and control rods at standard enrichments. The helical coil steam generator consists of two independent sets of tube bundles with separate inlet lines for feed water and steam exhaust. The feed water is fed into tubes where it boils and turns into superheated steam. A set of pressure heaters in the upper part of the vessel keeps the pressure under control.

The Nuclear Steam Supply System (NSSS) is isolated in a steel tank measuring 24.6 m in length and 4.6 m in diameter. The high design pressure containment vessel with a small volume is a unique feature of the NuScale concept, contributing significantly to the plant's safety and durability. Multiple modules are installed in a single large pool contained within an aircraft-resistant reactor building. The reactor pool provides passive containment cooling and decay heat removal.

Some essential features of the NuScale plant include compact size, the nuclear core completely cooled by natural circulation, design based on well-established light water reactor technology and nuclear modularity [3-5].

A comparison of selected operating conditions for a PHWR, and the water cooled SMR NuScale is presented in Table 1, [6].

Table 1. Comparison of CANDU and NuScale SMR operating conditions [6]

	PHWR (CANDU 6)	**NuScale**
Gross thermal power	2064 MWt	250MWt
Gross electric power	735 MWe	77 MWe
Primary Side		
Flow direction	horizontal	vertical, upward
Reactor coolant	heavy water	light water
Circulation mode	forced	natural
Operating pressure	11.2 MPa	12.8 MPa
Core outlet temperature	310 °C	310 °C
Core inlet temperature	266 °C	258 °C
Total core flowrate	7700 kg/s	587 kg/s
Secondary Side		
Number of SG	4	2
Feedwater flow direction	upward	upward
SG tubes arrangement	inverted U-tube	helical coil
Number of tubes per SG	3550	690
Tube OD	15.9 mm	15.9 mm
Tube material	Alloy 800	Alloy 690
Steam outlet pressure	4.6 MPa	3.5 MPa
Steam outlet temperature	260 °C	300 °C
Steam inlet temperature	187 °C	149 °C
Feedwater flow per SG	262 kg/s	33.6 kg/s

CANDU steam generator vs NuScale steam generator

CANDU Model 6 has four steam generators (SG) represented by vertical recirculating heat exchangers made by Babcock & Wilcox Canada Ltd. The primary materials used for this equipment construction are: Incoloy 800 (tubes), SS-410 (intermediate supports and anti-vibration bars), SA-516 (shell), SA-508 (tubesheet) (AVB), as shown in Figure 1 [7]. In this type of generator, the primary coolant enters the tubes at 310 – 315 °C and exits at 270 – 280 °C after the heat is released [7].

The most important elements are the 3550 tubes, which are made of Incoloy 800, an austenitic alloy whose chemical composition is given in Table 2.

Table 2. Incoloy 800 limiting chemical composition, [%]

Component	***Composition (weight %)***
Nickel	30 - 35
Chromium	19 - 23
Iron	39.5
Carbon	< 0.1
Silicon	< 1
Manganese	< 1.5
Sulphur	< 0.015
Copper	< 0.75
Aluminium	0.15 - 0.6
Titanium	0.15 - 0.6

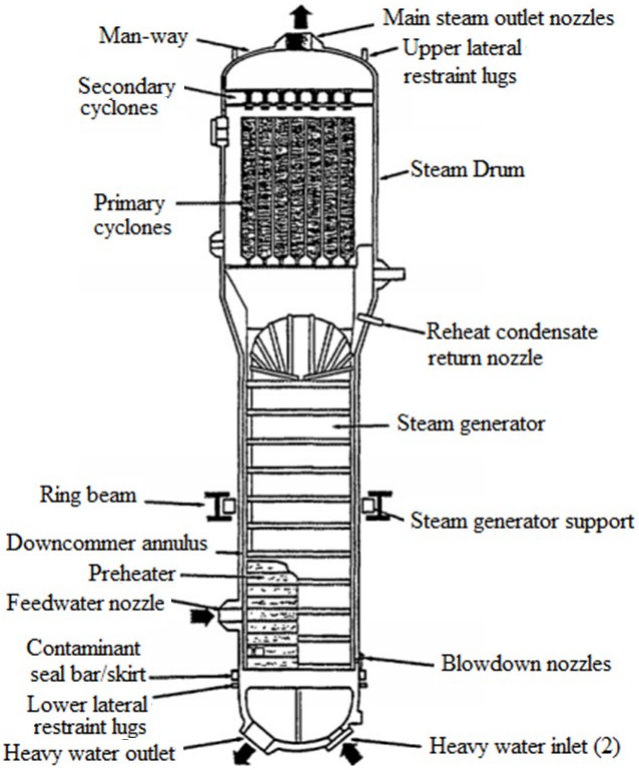
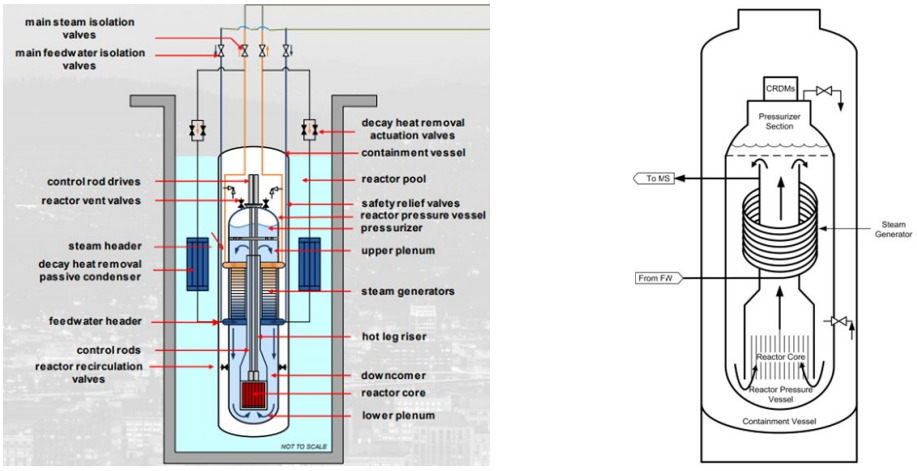


Fig. 1. CANDU Steam Generator [7]

The NuScale nuclear power module steam generator is built into the upper of reactor vessel structure. The helical coil steam generator design is unique, with steam generation inside the tubes and primary fluid outside the tubes [8]. Steam generators that use a helical tube array have the benefit of being compact while providing relatively high heat transfer efficiency. The advantage of using helical steam generators is the high heat transfer efficiency. Figure 2 depicts the design of a NuScale module [9] with the helical steam generator, the central element being the most important [10].

This element acts as a hot side, directing the flow of water exiting the reactor core area up through the central region of the vessel) where it is directed radially outward before passing down via the steam generator section.



a) NuScale module [9] b) Helical-coil steam generator [10]

Fig. 2. NuScale Small Modular Reactor:

In Figure 2, the reactor core is surrounded by the reactor vessel, which is surrounded by the containment vessel. In the reactor vessel, primary coolant (water or sodium), surrounds the reactor core, that is further located in a shroud which surrounds the reactor core on all sides. When the reactor core heats the coolant as the result of fission events, the primary coolant exits the shroud through a riser. This causes increased suction and heating of the primary coolant in the reactor core, drawing more primary coolant into the shroud. The water that is transported through the riser, is cooled down by the helical coil steam generator and directed towards the annulus, before returning to the bottom of the reactor vessel via natural circulation. The containment vessel is designed to prevent water or steam from escaping the reactor vessel into the surrounding environment.

The helical coil steam generator circulates feedwater and steam through the secondary cooling system to generate electricity via a turbine and generator. The feedwater passes through the heat exchanger and is superheated. The steam and feedwater in the secondary cooling system are isolated from the primary coolant so they do not mix or come into direct contact with one another. The primary coolant circulates through the reactor vessel as a result of temperature and pressure differentials that develop as a result of heat generation during reactor operation and through heat exchanger with the secondary cooling system [10].

The NuScale project specifies that the tubes will be hydraulically attached to the tubular plate, although the final design specifications have yet to be revealed. The thickness of the tube plate is significantly less than in previous models, requiring plating with an austenitic material, such as Alloy 52, or being constructed from Alloy 690. The tubes' connection with the tubesheet is carried out to determine whether the connection welds between the two can only be sealing welds or it is mandatory to provide a certain structural function. The NuScale project has a different design concept for the tube-to-tubesheet connection than the standard tube-to-tube plate connections based on the CANDU concept. If the tube sheet is made of low alloy, it requires a coating since the primary water flowing through the tubes' outer diameter contains boric acid. If the tubes are made of alloy 690, this will be a relatively new application of Alloy 690 in LWR.

The risk of primary water stress-corrosion cracking (PWSCC) occurrence in the helical coil steam generator should be slightly reduced compared to high capacity advanced PWRs, since NuScale's operating temperatures are lower than the temperatures achieved in Generation II and advanced PWR models. The hot leg temperature for the NuScale design is around 310 °C, compared to hot leg temperatures at or above 315.5 °C for all Generation II and advanced PWR designs. The large radius of curvature of the helical coil is very effective in reducing the potential for high manufacturing-induced stresses, such as those caused by the recirculating U-shaped tubes used in the CANDU steam generator. However, it has not been established if the coil tubes would be heat treated after formation. As a result, the cold deformation of alloy 690 tubes must be considered in relation to the known data on the percentage rise of PWSCC in the cold-worked material.

The high level of Stress Corrosion Cracking (SCC) in Alloy 690 caused by the presence of concentrated impurities (e.g., lead) should be reduced since line-contact crevice on the inner diameter has been eliminated. In the case of steam generators of gas-cooled advanced reactors, where water from the secondary circuit is convert into steam and superheated on the ID tube, problems have arisen due to the concentration of impurities in the hot zone. The NuScale steam generator operates quite different. The SCC potential of Alloy 690 tubing will be thoroughly analyzed throughout the steam generator design modification. The composition of Alloy 690 is presented in Table 3 [11].

Table 3. Incoloy 690 limiting chemical composition, [%]

Component	***Composition (weight %)***
Nickel	58
Chromium	27 - 31
Iron	7 - 11
Carbon	0.05
Silicon	< 0.5
Manganese	< 0.5
Sulphur	< 0.015
Copper	< 0.5

The materials used for the tube supports have yet to be established, although they will most likely be stainless steel type 405, which has a passive, long-lasting structure within the primary system. Until now, 405 stainless steel was used to support the secondary side tubes, but not in the primary circuit. Advanced investigations are necessary to ensure that there are no vulnerabilities.

Carrying out the assessment of the steam generator, no material performance issues were identified. However, the NuScale steam generator design differs significantly from that used in PHWRs. The study conducted to reduce the risk of SCC in advanced large PHWRs cannot be applied to the NuScale project, but certain correlations can be drawn in the case of the tube-tubesheet joint. Additional material research and development is necessary to demonstrate long-term performance capability, which is applicable to the NuScale design [9, 10].

Degradation mechanisms of PHWR Steam Generators

The degradation processes with the highest incidence in CANDU steam generators are estimated to be especially generalized corrosion, localized corrosion under-deposits, SCC on the U-shaped upper region of Incoloy-800 tubes, fouling crevice corrosion and mechanical degradation including vibration-induced wear. Figure 3 shows corrosion mechanisms specifics to a PWR steam generator [11].

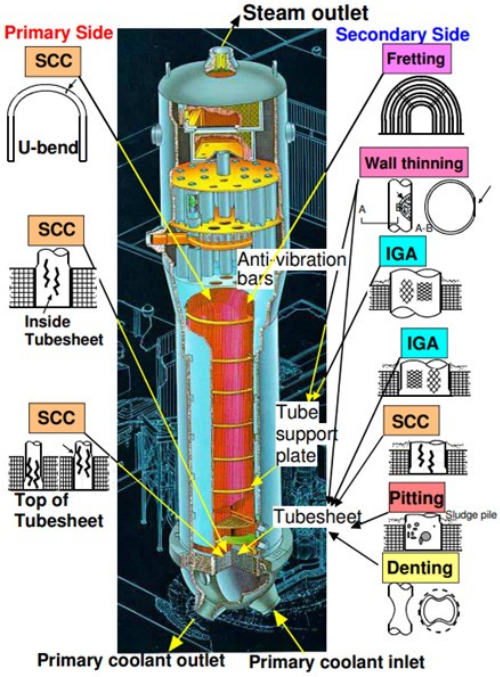


Fig. 3. The structure of Steam Generator and degradation mechanisms [11]

The degradation mechanisms in light-water SMR SGs are likely to be similar to those in CANDU steam generators, the higher-risk degradation mechanisms being: Fouling, Foreign Material Incursion, Stress-Corrosion Cracking, Crevice Corrosion, Vibration and Fretting Wear, and Denting [11]. However, the advanced SG designs with tubing made of either Alloy 800 (nuclear grade) or Alloy 690 TT (thermally treated) have shown relatively low degradation.

Corrosion behavior analysis of CANDU steam generator materials

In general, corrosion control of metallic materials in nuclear reactor cooling systems is kept to a minimum by closely monitoring of water chemistry to prevent solid deposits on the reactor core and steam generator tubes. However, after long periods of operation, many SGs in PHWR NPPs, experience the phenomenon of fouling. Based upon previous experience with fouling in the primary circuits of PWRs and PHWRs, a few points should be noted about water purification in the primary circuit of an SMR.

The flow rate of the reactor coolant purification system must be high enough to ensure that activation products are removed from the reactor coolant at a higher rate than that of deposition on out-of-core surfaces.

Fouling deposits are dangerous because they tend to increase the hydraulic roughness of surfaces, leading to reduced flow in a natural circulation system. Therefore, the effect of increasing the hydraulic roughness on the thermohydraulic conditions in the reactor cooling system must be assessed. In particular, an assessment must be conducted of how increasing hydraulic roughness impacts heat fluxes and corresponding corrosion product deposition rates on heat transfer surfaces in the reactor core and SG.

If magnetite deposits accumulate on the inside diameter of the tube walls, the tubes' inspectability with existing probes will most likely be compromised. Carbon steel, the most often used material in the PHWR feedwater system, is the primary source of magnetite. Using low alloy steels or stainless steels in the feedwater system would avoid magnetite formation, but the material cost would significantly increase.

Based on current research and operational experience, and with an iron oxide impurity concentration of 1 part per billion and a feedwater flow rate of 67.2 kg/s, a deposit buildup of 2.1 kg per year may be expected in the steam generator of a NuScale NPP.

The knowledge and skills gained from the operation of CANDU PHWR can be applied to SMR research activities. More research is needed to better understand, characterize, and manage service-induced degradation of steam generator components. Technology development must focus on the timely detection, mitigation, and prevention of significant long-term effects of ageing, such as degradations caused by fouling of heat transfer surfaces, [12-22].

The presence of deposits into the secondary side of these vertical heat exchangers is a significant element in the maintenance cost of CANDU steam generators. These deposits are formed when feedwater containing hard impurities, metals and oxides (corrosion products), and foreign materials enters the secondary circuit of this equipment. The penetration of the deposits into the secondary side of the steam generators comes via different tubes corrosion processes. Thus, small amounts of chemical species can be concentrated inside the deposits formed on the tubesheet or on the intermediate tubes supports, increasing the corrosive attack of the tubing or other metallic components.

Furthermore, fouling penetration in the crevices contributes to the concentration of aggressive chemical species within these crevices, which in time corrodes metals, limiting the life of the steam generator.

In recent years, a new phenomenon has been reported regarding the presence of deposits in the SG's secondary side. This refers to the heat transfer performance reduction caused by the deposition of sludge on outside surface of the tubes, which is shown by the drop in the generated steam pressure operating on the turbines. The effect of this phenomenon is to reduce the amount of energy generated. A 1% decrease in the electricity generation capacity equate to a loss of $ 2.5 million.

The effects of deposits on thermohydraulic performance also led to a reduction in the power of PHWRs. In this case, deposits in the zones with restrictive circulation where the tubes pass through intermediate supports (plate) restrict the upward flow of the biphasic steam - water mixture over the intermediate supports, causing the level of the cooling water inside the SG to oscillate. Continued operation under these conditions may cause power to decrease.

Cernavoda NPP received the filtering elements that were used for retaining the deposits from the steam generator secondary side during a planned shutdown.

The sludge samples were collected by disassembling four filter elements, extracting the powder deposits on a filter paper, homogenizing them, and collecting them in lidded recipients. The amount of powder in each container was determined by the type of analysis used.

Characterization of deposits entails sampling, identification, laboratory analyses, and data interpretation, all of which are required to assess the effects of deposits on the SG's structural materials and to operate this key equipment. The main activity of deposit characterization consists in physical and chemical analysis, examination, and measurements performed in central or independent laboratories.

To characterize the sludges obtained after cleaning (pressure water lancing) of the steam generators secondary side from the CNE Cernavoda, the following analyses were performed: granulometric analysis, X - Ray Diffraction (XRD), X - Ray Fluorescence (XRF), Scanning Electron Microscopy (SEM), and Energy Dispersion X-Ray Spectroscopy (EDS).

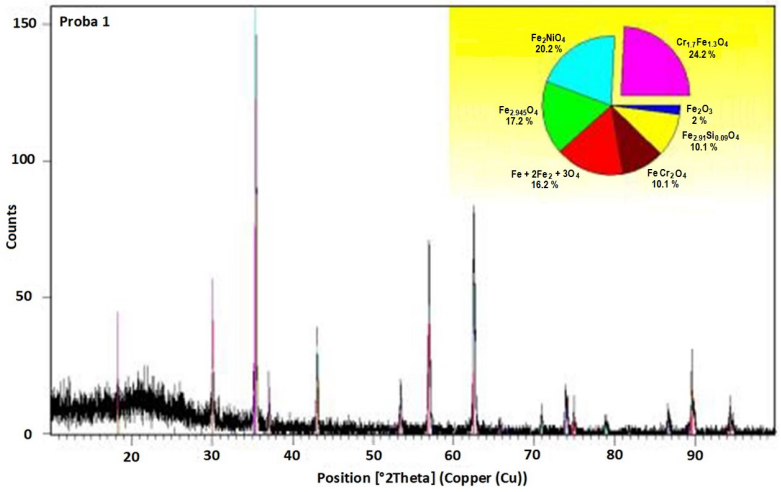
Granulometric analysis

Granulometric analysis was performed using a LA950V Horiba particle analyser. Granulometric examination revealed that for one sample had two fractions with approximate diameters of 10 μm and 100 μm, while the second sample was homogeneous at 10 μm.

X-ray diffraction analysis

X-ray diffraction analyses were performed using the X'Pert PRO MPD X-ray diffractometer, equipped with an X-ray tube (Line Fine Focus – 12 x 0.4 mm) with a Cu anode; the results of these investigations are shown in Figure 4.

X-ray diffraction revealed a high concentration of Fe_3O_4 (~ 16%), $Fe_{2.945}O_4$ (~17%), $FeCr_2O_4$ (~ 10%), Fe_2NiO_4 (~ 20%), and $Cr_{1.7}Fe_{1.3}O_4$ (~ 24%). Also, $Fe_{2.91}Si_{0.09}O_4$ was found to be about 10%. The deposit also contains a very small amount of hematite, Fe_2O_3 (~ 2%). X-ray fluorescence confirmed the presence of iron oxides.



No.	Visible	Ref. Code	Compound Name	Chemical Formula	Score	Scale Factor	SemiQuant [%]
1	☑	00-019-0629	Magnetite, syn	Fe +2 Fe2 +3 O4	71	0.889	16
2	☑	01-072-6231	hematite HP, iron(III) oxide	Fe2 O3	13	0.090	2
3	☑	01-086-1360	magnetite high	Fe2.945 O4	74	0.940	17
4	☑	01-089-3855	iron dichromium oxide	Fe Cr2 O4	58	0.548	10
5	☑	04-005-7633	Trevorite, syn	Fe2 Ni O4	70	1.086	20
6	☑	04-005-8771	Chromium Iron Oxide	Cr1.7 Fe1.3 O4	51	0.783	24
7	☑	04-013-7315	Iron Silicon Oxide	Fe2.91 Si0.09 O4	60	0.560	10

Fig. 4. The diffraction spectrum for sample 1(up) and the list of compounds identified by X-ray diffraction (down)

X-ray fluorescence analysis

The X–ray fluorescence analysis was carried-out using the ADVANT'X device and the predefined method for He-UQ_Helium atmospheric assays. The semi-quantitative sample analysis is performed by scanning all elements using the OXSAS program and the UQ_Helium method. The scan data were processed using UniQuant software, which allows for unambiguous analysis of the samples. Table 4 contains the processed data along with their associated standard error. X-ray fluorescence confirmed the majority of iron oxides.

Table 4. Semiquantitative analysis results

Element	***% mass***	***STD error***
Fe	42.18	0.58
Rh	4.61	0.11
Zn	0.539	0.027
Mn	0.320	0.016
Cr	0.269	0.013
Ni	0.196	0.010
Ti	0.177	0.009
Al	0.0826	0.0041
Cu	0.0784	0.0039
Co	0.0725	0.0036
Si	0.0582	0.0029
Zr	0.0242	0.0012
Ca	0.0202	0.0010
La	0.0133	0.0011
Sn	0.0122	0.0008
Rest O	51.31	

Scanning Electron Microscopy, X-ray Dispersion Spectroscopy (EDS)

The deposits were analyzed using secondary electrons from topographic images obtained with a scanning electron microscope (SEM) type TESCAN VEGA II LMU. The images were acquired using a scintillation secondary electron detector, in the High Vacuum mode. The display mode of highest resolution and small depth of focus was used, with an acceleration voltage of 30 kV applied to the electron beam. Figure 5 shows the morphology of deposits determined by Scanning Electron Microscopy.

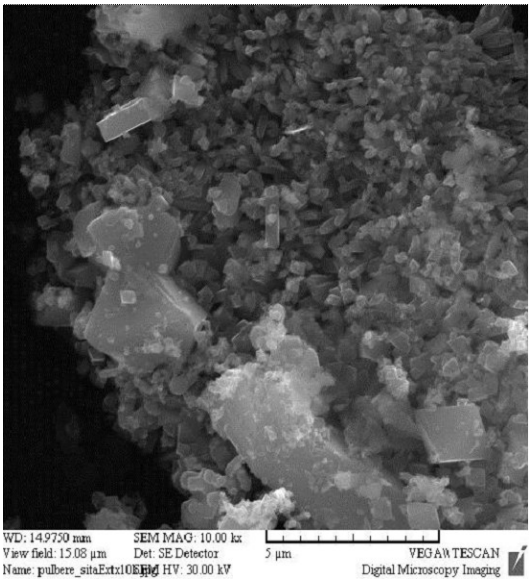
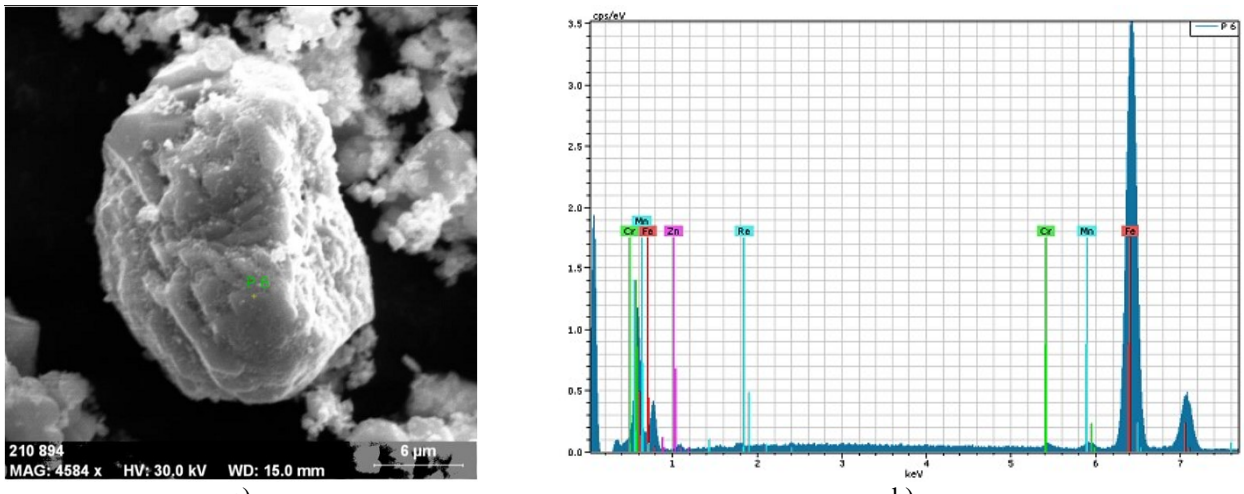


Fig. 5. The deposits morphology determined by SEM

Point microanalysis was performed using Bruker AXS X-ray spectrometer and Quantax software. The chemical elements found in the powders were identified using both the automatic and the manual methods based on the spectra. Identification was performed using the PB-ZAF quantification method without standards (Figure 6). Table 5 contains the deposits quantitative composition.



a) b)

Fig. 6. Point microanalysis (a) and spectrum characterizing the deposits (b)

Table 5. Quantitative composition of deposits

Element	*P6 [%]*
Fe	85.63
Mn	10.15
Si	3.19
Cr	0.79
Zn	0.24

The magnetite crystals have rounded edges, which can be explained by the fact that they have been formed in the secondary circuit before being transported to the steam generator, and the edges have been rounded due to the flow. Particle sizes range from a few microns to tens of microns.

The point microanalysis and spectra from Figure 6, as well as the deposits' quantitative composition given in Table 5, show the presence of Fe - 85.63%, Mn - 10.15% (may come from the austenitic steels corrosion process) and Si - 3.19%. Silicon presence in deposits must be handled with extreme caution since it gives hard deposits that are more difficult or impossible to remove by simply washing with a pressure water jet.

Furthermore, the deposits' shape confirms the presence of magnetite (octahedral), hematite (rhombohedral) and, rarely, chromium compounds (oxides and carbides). There are several types of oxides that differ in their atomic structure and number [23, 24].

Conclusions

Based on PHWR experience with SG degradation and the materials, chemistry, design and operation/maintenance improvements achieved, corrosion degradation of the SMR SG tubing is not expected to significantly affect SMR SG life up to a typical PWR design life of 40 years.

The paper presents the results obtained following the characterization of the deposits removed from the tubular sheets of the Cernavodă NPP steam generators after a planned shutdown. Moreover, it summarizes the main information from the specialized literature regarding the degradation of the structural materials in the tube-tubular joint regions of the steam generators.

Knowing the composition of deposits can help to improve the control of cooling water, condensation and blowdown since these systems may contain different materials that are integrated into deposits and can be identified through laboratory analyses.

The deposit was characterized using several methods as follows: granulometric analysis, X-ray diffraction, X-ray fluorescence, scanning electron microscopy and energy dispersion X-ray spectrometry.

By comparing the results obtained in this work with public data provided by the operators of other similar NPPs, there are no significant differences regarding the chemical composition of the deposits removed from the steam generator secondary side.

The experimental data and expertise accumulated during the development of research activities in the frame of RATEN ICN Steam Generator R&D Program can be used to assess the types of degradations for NuScale structural materials.
According to present study, the knowledge obtained via research activity based on experience gained in the field of structural materials degradation in large PWRs can be applied to small modular reactors.

The objectives of the program for the NuScale steam generator could be as follows: identifying the relevant ageing degradation mechanisms and discussing the issues associated with continued safe and economic operation of this key equipment, summarizing the results of current research and development activities, and identifying future research needs.

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