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# Assessment of radioactive contamination in primary circuit of WWER-440 type reactors by computer code OSCAR for the decommissioning case

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ABSTRACT

The article presents the results of modeling of the contamination of primary circuit of WWER-440 type reactor. The modeling has been performed using the OSCAR computer code (Nuclear research Centre in Cadarache, CEA, France), version V1.3 for decommissioning of nuclear power plants, taking into account the peculiarities of the WWER-440 reactor primary circuit, such as geometry, volumes, operational regime, materials. The results have been analyzed in the light of the scaling factor approach with the aim to demonstrate the modeling capabilities to identify the possibility of scaling factor application and to reproduce the activity correlation between difficult to measure and key nuclides. Calculated scaling factors for corrosion products are comparable with the ones of other nuclear power plants. Calculation results of surface activity contamination confirmed the applicability of $^{60}$Co as a key radionuclide.

## 1. Introduction

Current situation of Nuclear Power Plants (NPPs) shows that a considerable part of nuclear reactors operating worldwide for electricity production are approaching to the mature stage of their operational lifetime. Currently more than a half of operating nuclear reactors are of the age over 30 years, i.e., in the next ten years they are approaching the end of their conventional design lifetime of 40 years (IAEA, 2015). Therefore the number of candidate reactors to be decommissioned is now increasing and this tendency will last the next decade or more, depending on the policy of reactor operation extension and other factors. Moreover, the enhanced safety requirements after Fukushima accident are also the factor which makes the lifetime extension more complicated.

In Eastern and Central Europe one of the most common reactor type is the WWER (Water-Water Energy Reactor) reactor designed by former Soviet Union. At the moment all 16 Units with WWER-440/230 (older design type) reactors are under decommissioning. Newer design WWER-440/213 reactors are still operating but also approaching the final shutdown as the design operational lifetime of the WWER plants is generally 30 years (exceptions are newer WWER-1000 units with 50 or 60 years operational lifetime). Therefore considerable part of all WWER-440 type reactors are candidates for decommissioning in the next decade (IAEA, 2015). However, the programs have been initiated to prolong the operation of these reactors therefore their decommissioning can be postponed.

For decommissioning of NPPs the radiological characterization of equipment to be dismantled is a key issue (IAEA, 1998). In particular, in order to plan the personnel exposure, necessary safety measures, radioactive waste mass-flow, and repositories for disposal of radioactive waste the radiological characterization is indispensable. One of the most common radiological characterization methods is the scaling factor approach (IAEA, 2009; Remeikis et al., 2007; Remeikis et al., 2009). It is based on the correlation of activities of nuclides, e. g., easy to measure nuclides ($^{60}$Co, $^{137}$Cs) and difficult to measure nuclides such as $^{36}$Cl, $^{55}$Fe, $^{63}$Ni, $^{90}$Sr, $^{99}$Tc, $^{129}$I, $^{135}$Cs, $^{235}$U, $^{238}$U, $^{238}$Pu, $^{239}$Pu, $^{240}$Pu, $^{241}$Pu, $^{242}$Pu, $^{241}$Am, $^{242}$Cm, $^{244}$Cm. To evaluate activities and correlations for this list of nuclides the sophisticated laboratory equipment is used: alpha, beta, gamma, liquid scintillation counting spectrometric tools. Determination of some nuclides, such as $^{129}$I or $^{135}$Cs, requires application of special laboratory preparation of samples and mass spectrometry equipment, such as accelerated mass spectrometry or inductively coupled plasma mass spectrometry. Moreover, time and cost consuming radiochemical procedures are necessary for preparation of

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samples practically for each nuclide or group of them (e. g. for alpha measurements of nuclides of one chemical element).

On the other hand, theoretical approach of the determination of the reactor equipment – pressure vessel and its internals, main piping, main circulation pumps, ion exchange resin filters – is possible and attempts of such characterization are known (IAEA, 2012). Historically many codes developed for the Reactor Coolant System (RCS) radiological characterization were oriented to the determination of the operational radiological characteristics. Internal surface activities were evaluated of relatively short lived beta and gamma emitting nuclides such as $^{51}$Cr, $^{54}$Mn, $^{59}$Fe, $^{58}$Co, $^{60}$Co. These nuclides are mainly of interest for the operating reactor characterization; however, many of them are not relevant if one considers decommissioning and disposal of resulting radioactive waste generated by the dismantling activities. The decommissioning requires information about the activities of long lived radionuclides which are important and their activities have to be declared and compared with the radioactive waste acceptance criteria of planned radioactive waste repositories.

Specific processes of equipment contamination with radioactive substances take place in the operating NPPs. These can be separated into two classes: contamination by Fission Products and Actinides (FPAs) and contamination by Corrosion Products (CPs). Such separation is done by taking into account the origin of generation: FPAs are mainly generated in nuclear fuel (additionally FPAs generation also takes place in tramp uranium), whereas the CPs are generated due to the interaction of reactor materials or deposits on them with neutron flux and production of these radionuclides by activation. Radionuclide composition of initial contamination is complicated by the transport of radioactive substances with the technological media of operating NPPs: reactor coolant, technological gasses (Remeikis et al., 2012; Jermolajev et al., 2014). Namely the transport processes introduce the change of initial ratios, i.e., of the scaling factors between initial activities of radionuclides which were generated at the place of origin. In reactor coolant the processes of the release from fuel cladding defects, transport with coolant, and sedimentation on particles in the coolant or internal surfaces of the RCS take place. In addition, the sediments can dissolve or erode from surfaces back to the coolant due to changing thermal-hydraulic conditions of the coolant.

CPs are generated by the activation process, however due to corrosion of RCS equipment they are released to the coolant from firm metal basis and take place in the transport and contamination processes in the RCS. This implies that determination of the surface contamination of equipment cannot be done by neutronic codes only. This very approximate method can be improved if available experimental data is used with computer neutronic simulation codes. However, such approach provides only a very approximate understanding and estimation of the contamination processes of NPP equipment.

It has to be noted that radiological characterization and application of particular methods, such as scaling factor approach, or indirect assessment methods are only possible if all equipment to be characterized is still in place as it was operated. Only under this condition it is possible to apply special modeling tools, which take into account the information of the physical processes governing the generation of radioactive waste (Remeikis et al., 2012). After the equipment is dismantled and if information about its specific original place in the NPP is lost (or change of radioactive contamination occurred) the modeling is no more practicable as the information about contamination processes cannot be directly applied.

The aim of this paper is to present the results and benefits of application of computer simulation of the RCS internal surface contamination for a specific case – characterization of older type WWER-440/230 reactors. This type is selected as all these reactors are shutdown due to lack of safety features and decommissioning is ongoing in Central and Eastern European countries (Bulgaria, Germany and Slovakia). For this task the specialized computer code OSCAR, version V1.3 for decommissioning of NPP's, developed at Nuclear Research Centre in Cadarache by CEA has been used. This code is a unique modeling tool due to its development and extensive validation by using the data of French nuclear power plants.

## 2. Scaling factor approach for radioactive waste characterization

The results in the form of the surface activity ratio of some nuclides to the surface activity of $^{60}$Co can be treated as the scaling factors of this nuclide to the $^{60}$Co activity (ISO, 2007 Standard 21238, 2007). The reference nuclide which is easy measurable with conventional gamma spectroscopic equipment, in most cases $^{60}$Co, or also the $^{137}$Cs, is a so-called Key Nuclide (KN). Other nuclides, which cannot be directly measured and require laboratory separation procedures and specific alpha or beta counting equipment application, are called Difficult To Measure Nuclides (DTMN). In particular, scaling factor is a representative activity ratio of DTMN to KN. Moreover, this ratio has to be representative for the whole activity region of interest, e. g., activity interval of low and intermediate level waste. The representative activity ratio is usually determined by means of the correlation analysis of DTMN and KN activities in a particular system or a set of systems of NPP. This provides the possibility on the basis of the linear regression to evaluate the variability of the activity ratio in the primary system (RCS) or in an auxiliary system, e. g., the Chemical and Volume Control System (CVCS). In ideal case the activity ratio of a particular nuclide should remain constant for the system under consideration with some approximation, i.e., a good correlation of the DTMN and KN should be observed (Remeikis et al., 2009). In principal, the correlation coefficient value should be greater than 0.5 in order to be able to state, that there is a satisfactory correlation between DTMN and KN, or in other words, the activities of analyzed nuclides are moderately correlated, which is still enough for radiological characterization purposes. Therefore if one deals with systems which were contaminated by different physical processes (or different conditions governing the physical processes) it is natural to expect to have wider spread of activity ratio and correlation in this case is weaker.

The set of scaling factors for the selected group of DTMN nuclides and for a specific system of NPP is the so-called nuclide vector (Efraimsson, 2001). The validity of the nuclide vector is defined for a specific system and list of nuclides; also, the validity of the nuclide vector for relevant activity interval should be additionally justified either by measurements and/or theoretical considerations (IAEA, 2009; Efraimsson, 2001).

In case the correlation is unacceptably low for some nuclides in the foreseen waste flow, the introduction of additional nuclide vectors with different scaling factors for particular systems and waste flows could be considered as necessary. In case the scaling factors are being determined by theoretical calculations (e. g. calculations of RCS piping internal contamination; nuclear fuel composition calculations; material activation calculations), the comparison of theoretical scaling factors against the measured scaling factors plays an important role for validation purposes. In particular, for radioactive waste characterization the ratio of calculated and measured scaling factor should be not higher as several times for the relevant activity range in considered system (e. g., the RCS). This limit is set by the practical considerations and can be explained by the fact that waste with different nuclide vector has to be separated and treated individually as a separate waste stream. For practical reasons, it is desirable to have less waste streams in order to optimize the cost of waste management at NPP. However, reducing the amount of waste streams increases the conservatism of waste characterization and management: if lower activity waste is managed together with slightly higher activity waste (with increased amounts of radiotoxic nuclides) it leads to the overestimation of scaling factors and estimated activity of DTMN in the lower activity waste in the same waste stream. This finally results in the non-desirable overestimation of waste inventory leading to reduced quantities of waste which would be possible to dispose off in dedicated waste repositories. Therefore, waste