

Modelling of the Radiological Contamination of the RBMK-1500 Reactor Control and Protection System Channels' Cooling Circuit

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Received 27 May 2015; accepted 15 October 2015; published 22 October 2015

Abstract

The article presents results of modelling and analysis of component contamination of the RBMK-1500 reactor Control and Protection System channels' Cooling Circuit (CPSCC) at Ignalina NPP Unit 1. The modelling was performed using a computer code LLWAA-DECOM (Tractebel Energy Engineering, Belgium), taking into consideration CPSCC components characteristics, parameters of the water flowing in the circuits, system work regimes, etc. During the modelling, results on activity of CPSCC components' deposits, nuclide composition of the deposits and dose rates after the final shutdown of the reactor, as well as activity decay of the most contaminated CPSCC components' deposits were obtained. Analysis showed that there is a significant difference in contamination levels between CPSCC components. The rundown header from the channels of the reactor's fast acting scram system is the most contaminated component, and contamination of the least contaminated component is only 0.27% compared to the activity of the most contaminated component. Corrosion nuclides are the nuclides that mostly contribute to contamination of the CPSCC deposits.

Keywords

Ignalina NPP, RBMK-1500 Reactor, Radiological Contamination

1. Introduction

On December 31, 2009, after the final shut-down of Unit 2 (Unit 1 was closed down on December 31, 2004), the Ignalina Nuclear Power Plant (INPP) terminated generation of electricity. After that, the decommissioning has been its main activity. In order to plan the dismantling process, data about contamination levels, nuclide composition, amount of the decommissioning radioactive waste, etc. are necessary. Contamination of the systems' components with radioactive particles is a result of the contaminated cooling water circulating within these systems during operation of the reactor.

There are several ways how the Control and Protection System channels' Cooling Circuit (CPSCC) water can be contaminated with activation products [1]. But usually corrosion of the components is the most important

problem. Intensity of corrosion in the reactor components depends on many factors, e.g., temperature, material of the components, operation duration, and coolant flow regime. Formation process of corrosion products and transfer mechanisms are described in detail in [2]-[5].

The corrosion products of the systems' components are transferred by the coolant to the reactor active zone. Here they form deposits on the surfaces of the equipment and are activated by high neutron fluxes. Due to erosion, these activated particles pass to the coolant and, due to its circulation, are deposited on the surfaces of the equipment located outside the reactor active zone. Corrosion particles may not deposit on the walls of the equipment in the active zone, but they are activated during circulation through the active zone and form a layer of contaminated deposits on the surfaces of the equipment located outside the boundaries of the active zone [6]. Corrosion and erosion products of the activated equipment located in the active zone are another source of equipment contamination. In case there are defects in fuel rods, fission products in the nuclear fuel can migrate through the damaged fuel claddings and pass to the coolant flowing in the main circulation circuit. Fission products are also additionally generated during the fission of "tramp" uranium, whose particles are deposited on the outside of the fuel components' claddings (contaminated during manufacturing of the fuel). During operation the coolant could be contaminated with these particles too [7]. Spectrum of the fission products of the "tramp" uranium is analogous to the spectrum of fission products in nuclear fuel. Radioactive contamination of the components is surface contamination since the activated particles deposit on the surfaces of the equipment.

The paper provides results of activity modelling and analysis of the CPSCC components at Ignalina NPP Unit 1 and nuclide composition of the deposits as well as variation of the deposits' activity and emitted dose rate of the most contaminated CPSCC components after the final shutdown of the reactor.

2. Control and Protection System Channels' Cooling Circuit (CPSCC)

The Control and Protection System (CPS) is an integrated system, which provides normal reactor control and power regulation, as well as automatic safety-related reactor shut-down when certain reactor operational limits are exceeded [8]. CPSCC provides cooling for Control Rod Channels (CRC), Fission Chamber Channels (FCC), Power Density Distribution Monitoring System Channels (PDDMSC), Fast Acting Scram System Channels (FASSC) and Reflector Cooling Channels (RCC). The flow in this circuit is gravity driven and is distributed in different ways for different channels to ensure that proper temperatures are reached. Numbering of the system components is shown in **Table 1**. CPSCC includes:

- CRC for control rods and safety instrumentation—187 in total;
- FCC for fission chamber cassettes which are inserted during reactor start-up (these chambers are removed during operation)—4 in total;
- PDDMSC for the in-core power density sensors of the axial monitoring—20 in total;
- RCC for graphite reflector cooling—156 in total;
- FASSC for fast acting scram system rods—24 in total.

Two of four circulation pumps (CPSCC-3) are on stand-by mode or can be serviced (repaired). In order to facilitate determination of the circulation pumps' radioactive contamination, a conservative assumption was made presuming that two of the pumps work all the time during INPP operational time and the contamination of the remaining items is the same.

3. Methodology

A computer code LLWAA-DECOM (Tractebel Energy Engineering, Belgium) was used for modelling of radioactive contamination of PCS components. LLWAA-DECOM validation results are presented in paper [9]. It is demonstrated that there is a rather good correlation between predicted and measured dose rates and deposited activities' results. When performing modeling, the following input data are necessary:

- Operation characteristics of the system (number of operating cycles, duration of operating cycles).
- Circulating water parameters (water pH, temperature, average rate, volumetric activity).
- Characteristics of contamination particles (density, diameter, solubility).
- Design parameters of the system components (design materials, geometric dimensions of the component, roughness of the walls), etc.

Nuclide activity variation of the deposits on the walls of the system components is described using the following Equation (1) [9]:

Table 1. Main CPSCC components.

Name of the component	Marking	Name of the component	Marking
Suction header from service tank	CPSCC-1	Channel of fast acting scram system within the core	CPSCC-23
Pipes between suction and pressure headers	CPSCC-2	Channel of fast acting scram system below the core	CPSCC-24
Circulation pumps	CPSCC-3	Pipes from reflector cooling channels	CPSCC-25
Prescreen (D300)	CPSCC-4	Rundown pipelines from reflector cooling channels	CPSCC-26
Pressure pipe	CPSCC-5	Rundown header from reflector cooling channels	CPSCC-27
Pressure pipe to service tanks	CPSCC-6	Rundown header from reflector cooling channels	CPSCC-28
Upper (service) tanks	CPSCC-7	Rundown pipelines from CRC FCC PDDMSC	CPSCC-29
Pipe between service tanks	CPSCC-8	Rundown header from CRC FCC PDDMSC	CPSCC-30
Overflow conduit	CPSCC-9	Rundown header from CRC FCC PDDMSC	CPSCC-31
Pressure pipes from service tanks	CPSCC-10	Rundown pipelines from channels of reactor fast acting scram system	CPSCC-32
Pressure pipes from service tanks	CPSCC-11	Rundown header from channels of reactor fast acting scram system	CPSCC-33
Prescreen (D400)	CPSCC-12	Rundown header	CPSCC-34
Pressure header	CPSCC-13	Pipes from rundown header to heat exchanger	CPSCC-35
Pressure header	CPSCC-14	Heat exchanger 1200TNG-1-10-B2/20G-6-1 (inner surface of vessel)	CPSCC-36
Pressure pipes to reflector cooling channels	CPSCC-15	Heat exchanger 1200TNG-1-10-B2/20G-6-1 (inner surface of pipes)	CPSCC-37
Pressure pipes to channel of fast acting scram system	CPSCC-16	Heat exchanger 1200TNG-1-10-B2/20G-6-1 (outer surface of pipes)	CPSCC-38
Pressure pipes to CRC FCC PDDMSC	CPSCC-17	Pipes from heat exchangers to the rundown header	CPSCC-39
Reflector cooling channel	CPSCC-18	Rundown header	CPSCC-40
Channel of reactor CRC FCC PDDMSC above the core	CPSCC-19	Lower tank	CPSCC-41
Channel of reactor CRC FCC PDDMSC within the core	CPSCC-20	Pipe for emptying the lower tank	CPSCC-42
Channel of reactor CRC FCC PDDMSC below the core	CPSCC-21	Filter	CPSCC-43
Channel of fast acting scram system above the core	CPSCC-22	Pump for emptying the lower tank	CPSCC-44

$$\frac{dW_i}{dt} = K_d * C_{v_i} * (1 - frspr_i) - W_i * (K_r + \lambda_i) \quad (1)$$

Here: W_i is surface activity of i^{th} nuclide on the wall, Bq/m²; K_d is particle deposition rate, m/s; C_{v_i} is volumetric activity of i^{th} nuclide in the flux, Bq/m³; $frspr_i$ is soluble part of i^{th} nuclide in the circulating agent; K_r is particle relaxation coefficient, s⁻¹; λ_i is decay constant of i^{th} nuclide, s⁻¹; t is time. Deposition and relaxation coefficients (K_d , K_r) depend on coolant characteristics (flow rate, temperature, Reynolds number, etc.), characteristics of the system equipment (geometry, roughness of the inner walls, friction coefficient), and characteristics of radioactive particles (particle density in the coolant, diameter).

In LLWAA-Decom nuclide activity in the deposits and dose rate at the outer surface can be evaluated for one component during one calculation cycle. Based on CPSCC scheme, 44 components (**Table 1**) with different characteristics were chosen for evaluation.

4. Results

Analysis of contamination modelling result on CPSCC components shows that the rundown header from the

channels of the reactor fast acting scram system (CPSCC-33), the rundown pipelines from CRC/FCC/PDDMSC (CPSCC-29) and the rundown pipelines from the channels of the reactor fast acting scram system (CPSCC-32) are the most contaminated components (**Figure 1**).

As **Figure 1** demonstrates, there is a significant difference in contamination levels between CPSCC-33, CPSCC-29, CPSCC-32 and other CPSCC components. This is driven by different parameters in different components of the cooling circuit. Volumetric fluid activity is consistent in this coolant circuit, excluding CPSCC-37. CPSCC-37 is the inner surface of the heat exchanger pipes, therefore it is washed by non-contaminated water. Because there is no water purification equipment installed, the main drivers for surface contamination activity levels of other components are temperature and fluid velocity. Average fluid velocity passing through CPSCC-3 and CPSCC-4 components is high, but lower temperatures decrease overall activity levels compared to the most contaminated components. CPSCC-43 and CPSCC-44 components have even lower activity levels compared to the most contaminated components. This is because these components are only used when the cooling circuit must be drained for repairs, so the cycle length for these components is less than 1% of other components. CPSCC-7 and CPSCC-41 are the upper (service) and the lower tanks, which cannot be modelled by LLWAA-DECOM, so the contamination levels of these components are not indicated in **Figure 1**.

The nuclide composition of the deposits changes with time due to decay of different nuclides. **Figure 2(a)** demonstrates nuclide composition variation of the deposits on the walls of the most contaminated component of the CPSCC. After the final shutdown of the reactor, Fe-55, Co-60 and Mn-54 mostly determine contamination of the CPSCC. After 35 years, contamination of the CPSCC components is highly determined by a long-lived nuclide Ni-63 since short-lived nuclides decay in a short time (Fe-55, Co-60, Mn-54, Fe-59). The contribution of other long-lived nuclides to the total contamination increases also as their activity practically remains unchanged.

During dismantling, the most important nuclides are those that determine the dose rate by γ radiation from the contaminated components. Change of nuclide relative impact on the dose rate is shown in **Figure 2(b)**. After the

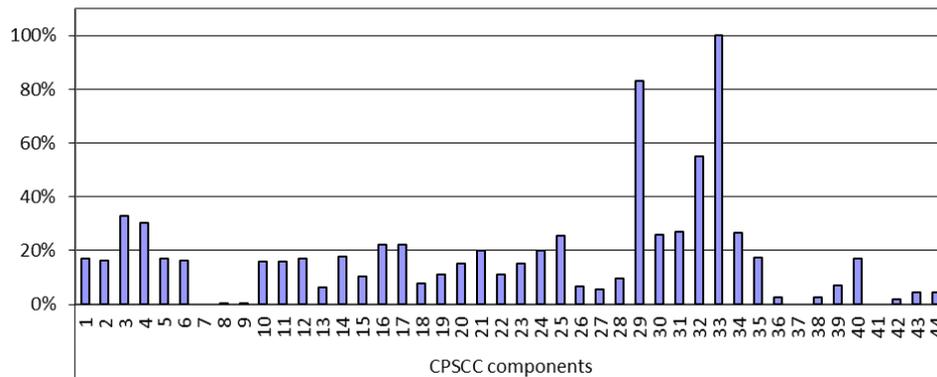


Figure 1. Relative activity of CPSCC components (CPSCC-1/44/CPSCC-33).

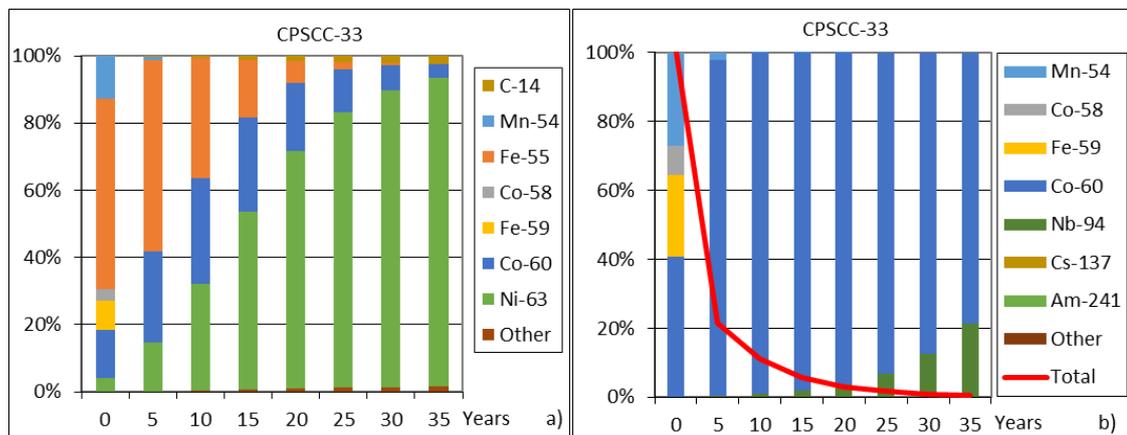


Figure 2. Change of relative nuclides activity (a) and dose rate (b) of CPSCC-33 component within time (other < 1%).

final shutdown of the reactor, γ radiation from the contaminated CPSCC components is mostly determined by Co-60, Fe-59, Mn-54 and Co-58. But five years after the shutdown, Co-60 starts to mostly contribute to the total dose rate. As it is shown in **Figure 2(b)**, the total dose rate decreases significantly (by ~80%) five years after the final shutdown of the reactor. This is caused by decay of short-lived radionuclides Fe-55, Co-58, and Mn-54. The CPSCC dismantling works will not start right after the final shutdown of Unit 1. Thus, such significant decrease of the dose rate will allow performing dismantling of the installations and radwaste management with lower radiation doses to the workers.

5. Conclusions

After analysis of contamination modelling result of the Control and Protection System channels' Cooling Circuit (CPSCC) components, the following conclusions have been drawn:

- 1) There is a significant difference in contamination levels between CPSCC-33, CPSCC-29, CPSCC-32 and other CPSCC components. This is mostly because the temperature and average fluid velocity in these components are higher than in other components.
- 2) After the final shutdown of the reactor, Fe-55, Co-60 and Mn-54 mostly determine contamination of the CPSCC. After 35 years, contamination of the CPSCC components is highly determined by a long-lived nuclide Ni-63 since short-lived nuclides decay in a short time (Fe-55, Co-60, Mn-54, Fe-59). The contribution of other long-lived nuclides to the total contamination also increases as their activity practically remains unchanged.
- 3) After the final shutdown of the reactor, γ radiation from the contaminated CPSCC components is mostly determined by Co-60, Fe-59, Mn-54 and Co-58. But five years after the shutdown, Co-60 becomes the nuclide that mostly contributes to the total dose rate. Due to decay of short-lived radionuclides, the dose rate decreases significantly over time.

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