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ARTICLE

Prediction of radiation doses during the dismantling of a maintenance cooling reservoir of RBMK-1500 reactor

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Decommissioning of the Ignalina Nuclear Power Plant involves multiple problems. Personnel radiation safety during the dismantling activities is one of them. In order to assess the optimal personnel radiation safety, the modelling is performed by means of computer code "VISIPLAN 3D ALARA Planning tool" developed by SCK CEN (Belgium). In this paper it was used for the evaluation of direct gamma radiation from the radioactive equipment to personnel when carrying out dismantling activities and selection of gamma radiation shielding geometry (structure), shielding materials and positions. A modelling of radiation doses during the dismantling of the maintenance cooling reservoir (MCR) of RBMK-1500 reactor has been performed in this paper. The basic MCR model's development was based on internal contamination and the existing geometrical data. The assessment of workers exposure was performed to comply with ALARA. The effective doses to the workers were calculated for different strategies of reservoir dismantling. The impacts of dismantling tools, shielding types, variation of parameters such as shielding distance, shielding installation time and exhaust ventilation flow rate during the dismantling of reservoir on effective doses were analyzed. The total effective personnel doses were obtained by summarizing the effective personnel doses from various sources of exposure, i.e., direct radiation from radioactive equipment, internal radiation due to inhalation of radioactive aerosols, and direct radiation from radioactive aerosols arising during hot cutting in premises.

Keywords: RBMK-1500 reactor; decommissioning; dismantling activities; modelling of doses

1. Introduction

The Ignalina NPP Unit 1 was shutdown in 2004. In the early 2002, the Government of the Republic of Lithuania adopted the resolution on Unit 1 decommissioning by means of immediate dismantling in order to ensure that this process does not lead to serious social, economic, financial and environmental consequences. The first dismantling activities were related to the dismantling and decontamination of the Emergency Core Cooling System of reactor Unit 1 and these activities were completed in October 2011. After that the dismantling and decontamination of Turbine Hall equipment and of Building V1 will follow. In Building V1 the reactor auxiliary systems such as Maintenance Cooling Tanks System, Reactor Gas Circuit, Off-gas Clean-up System, Inlet and Exhaust Ventilation Systems of Building V1 are located. During the dismantling of any type of nuclear equipment, the most important requirement is to ensure safety of the personnel, population and the whole process. Radiation protection means should be established to protect the workers from the hazardous influence of ionizing radiation during such type of activities. Taking this into account, human exposure assessment must be performed in advance to comply with ALARA (as low as reasonably achievable) objectives.

Nowadays, due to enhancements in computer systems, the dismantling activities are planned using various software taking into account radiation fields. In 1999, SCK-SEN Laboratory in Belgium developed the computer code VISIPLAN [1] widely used to solve the radiation protection problems (for analysis of direct radiation) such as handling of fibre-reinforced concrete container with conditioned radioactive waste [2], using conditional release of materials in the form of steel railway tracks [3] or modelling of intrusion scenario in deep geological repository [4]. Using this computer code the radiation protection problems during dismantling of the maintenance cooling reservoir (MCR) located in Building V1 are analyzed in this paper. Furthermore other radiation sources (internal inhalation exposure and external radiation from radioactive aerosols) are analysed also in this paper.

The MCR is a stainless steel cylindrical tank with outside diameter – 1.575 m, height – 4 m and wall thickness – 0.008 m. It is intended for the heat rejection from the cooled reactor core in the mode of broken natural circulation of the coolant.

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2. Methodology of modelling

2.1. Direct radiation from equipment

As it was already indicated in this paper, the computer code VISIPLAN was used for gamma dose rate modelling. This code is intended for estimation of gamma radiation dose rates in simple and complex 3D geometries. In this code, the calculation of dose rate for radiation sources is based on "point kernel" method. The photon fluence rate at a dose point near a volume source can be determined by considering the volume source as consisting of a number of point sources [1].

$$\phi = \int_V \frac{S \cdot B \cdot e^{-b}}{4 \cdot \pi \cdot \rho^2} dV \qquad (1)$$

Where S - source strength representing the number of photons emitted by the source per unit time and volume, $n \cdot s^{-1} \cdot cm^{-3}$, B - built-up factor, b - the mean free paths (the attenuation effectiveness of a shield), ρ - distance from a point source, V - source volume.

2.2. Internal radiation from inhaled radioactive aerosols

Cutting of contaminated equipment results in generation of radioactive aerosols. Inhalation of such aerosols causes the workers' internal exposure and presence in a radiological cloud results in the external exposure.

Based on IAEA Safety Guide [5], the inhalation effective dose to worker is calculated using the formula:

$$D_{inh} = INH \cdot t_{inh} \cdot \frac{1}{APF} \cdot \sum_i^n \left(DCF_{inh,i} \cdot \overline{C_i} \right) \qquad (2)$$

Where INH - the worker's breathing rate (according to [5], the standard worker's breathing rate is 1.2 $m^3 \cdot h^{-1}$), t_{inh} - time during which the worker is forced to breathe from the radioactive cloud, h, APF - assigned protection factor, $DCF_{inh,i}$ - effective dose coefficients for the i-th radionuclide [5], C_i - i-th radionuclide average volume activity in air, $Bq \cdot m^{-3}$.

2.3. External radiation from radioactive aerosols in premise

The external exposure effective dose due to the generated radioactive aerosols to worker is calculated using the formula:

$$D_{sub} = t_{sub} \cdot \sum_i^n \left(DCF_{sub,i} \cdot \overline{C_i} \right) \qquad (3)$$

Where t_{sub} - time during which the worker is exposed to ionizing radiation from the radioactive cloud, h, $DCF_{sub,i}$ - effective dose coefficients for the i-th radionuclide [6], C_i - i-th radionuclide volume activity in air, $Bq \cdot m^{-3}$.

3. Modelling of MCR dismantling

3.1. Designing of MCR basic model

Using the existing geometrical data, a basic 3D model of the MCR has been designed with VISIPLAN. During radiological characterization it was defined that the MCR internal surface is contaminated, particularly the bottom due to deposits. The bottom contamination is about 1000 $Bq \cdot cm^{-2}$ (Co-60 is the main radionuclide). The contamination of the lid is approximately 10 times lower and contamination of the wall is 4 times lower than the bottom's. Thus, for the modelling it is assumed that the MCR consists of three homogeneous contaminated surfaces. Using VISIPLAN the symmetrical dose rate map (isodoses) of the external MCR side is obtained and shown in **Figure 1**.

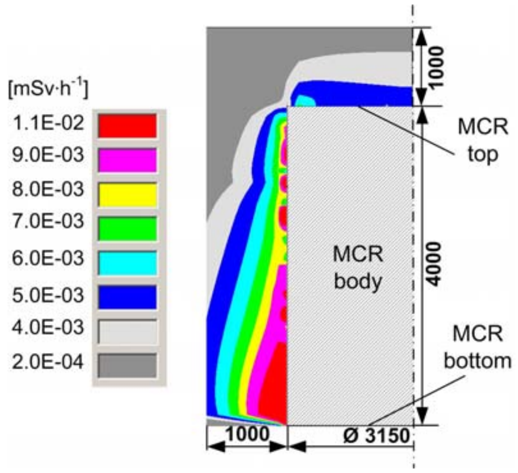

Figure 1. The MCR side-view of the dose rate map (isodoses) (dimensions are in mm).

For safe handling of the MCR will be cut into parts of ~1 m^2, i.e. the mass of each part will be 50–60 kg. The dismantling starts from the top to the bottom, using a hoist for the upper cut parts. In this way the MCR dismantling process is described by six computer models, i.e. one model for dismantling the upper MCR part, four models for dismantling the body and the last model for dismantling the bottom (in total 6 models).

3.2. Selection of cutting equipment

Taking into consideration the 0.008 m thick stainless steel wall, hot cutting technique (gas or plasma) may be used for the MCR dismantling. Mechanic cutting techniques may be used as well however the dismantling would be irrational. Since hot cutting may be controlled from a distance, therefore, in the MCR dismantling models manual and automatic cuttings are analyzed.

Cutting speed for such thickness of stainless steel plates by gas cutting equipment will be approximately 0.4 $m \cdot min^{-1}$ [7]. Using plasma cutting equipment, cutting speed will be approximately 1 $m \cdot min^{-1}$ [8].

3.3. Shielding selection

During the operation, the MCR was filled with water. Therefore during the dismantling, it can also be filled with water, which in this case will function as a shielding against the direct radiation from the opposite contaminated side of the MCR and against the MCR bottom. During the dismantling of the MCR, the water level is reduced to the lower cut line. In this case, four additional computer models of the dismantling the MCR top and body with water are designed.

During the dismantling of the lower wall of the MCR, a 1×1 m lead shield was modelled, which adheres to the inner wall of the MCR in order not to hinder the personnel performing cutting operations from the outside of the MCR. This shield is directed perpendicularly to the workers' position.

During the dismantling of the MCR bottom, a lead shield 3×1 m was also modelled. It was placed in the centre of the MCR bottom vertically or horizontally.

3.4. Manpower selection

It is assumed that the dismantling of the MCR will be performed by two workers: a cutter and an assistant.

Before cutting, these workers will perform preparation works. In the case of using manual cutting equipment, preparation works would comprise of the cutting line marking and cutting equipment preparation. In the case of using automatic cutting equipment with the cutter distance control, preparation works would comprise of the cutting line marking, mounting of cutting track on the wall of MCR, and cutting equipment preparation. It is assumed that using manual cutting equipment duration of preparation for one cut will be about 30 s. In case of using automatic cutting equipment duration of preparation for one cut due to mounting of cutting track will be about 120 s.

4. Results and discussion

Modelling results show that using manual plasma cutting equipment time of the MCR dismantling will be 3 h. Using automatic gas cutting equipment dismantling time will be 3 times longer.

Using water as a shield, dose rate in the workers' cutting position may be minimized from 40 % (for wall cutting) to 60 % (for lid cutting). Therefore, the highest dose rates are during the dismantling of the lower part of the MCR wall and bottom. The comparison of dose rates during the dismantling of the lower part of the MCR wall using different thickness of lead shielding is presented in **Figure 2**. This figure demonstrates that the lead shielding should be as close as possible to the MCR wall and the lead shield thickness should be thicker as applicable.

During the dismantling of the MCR bottom and using lead shielding (3×1 m), it is demonstrated that position of lead shielding does not affect the workers collective doses. Of course the doses decrease if the thicknesses of the lead shield increases. When the thickness of the lead shielding increases from 0.005 m to 0.02 m, the dose rates in the workers' positions decrease by 28 %.

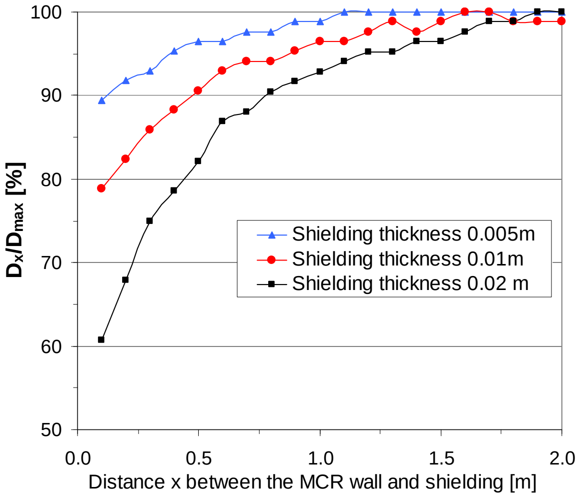

Figure 2. The comparison of dose rates during the lower MCR wall dismantling.

Installation time of the lead shielding should be very short to minimise the collective dose, i.e. <15 s using manual plasma cutting equipment and <20-35 s using manual or automatic gas cutting equipment or automatic plasma cutting equipment.

Based on [9], it is assumed that respirable mass (radioactive aerosols) for plasma cutter and gas cutter is 0.5 % and 4 % respectively of the cut-out mass. For models without exhaust ventilation, natural air flow was assumed to be 0.6 $m^3 \cdot h^{-1}$. Also it is assumed that during cutting with the manual cutting equipment, the distance between the worker and the cutting place will be approximately 0.3 m and the highest inhalation doses will be at this distance. When using automatic cutting equipment, the workers will be at 1.5 m distance from the cutting place. Thus, taking into account the linear volumetric dilution, the volumetric activity in their position will be approximately 130 times smaller. It was revealed that using plasma cutting equipment the worker will get 40 times smaller inhalation dose than using gas cutting equipment. Collective inhalation dose without exhaust ventilation for dismantling the MCR will be up to 5.24E-03 man-mSv. Using exhaust ventilation with air flow rate 2500 $m^3 \cdot h^{-1}$, the volumetric activity in place is drastically decreased and the collective inhalation dose will be decreased by four thousand times. The collective dose of direct radiation from radioactive aerosols is approximately 150 times smaller than the inhalation collective dose if gas cutting equipment is used, and approximately 370 times smaller if plasma cutting equipment is used.

Total effective personnel doses are obtained by summarizing effective personnel doses from various sources of exposure.

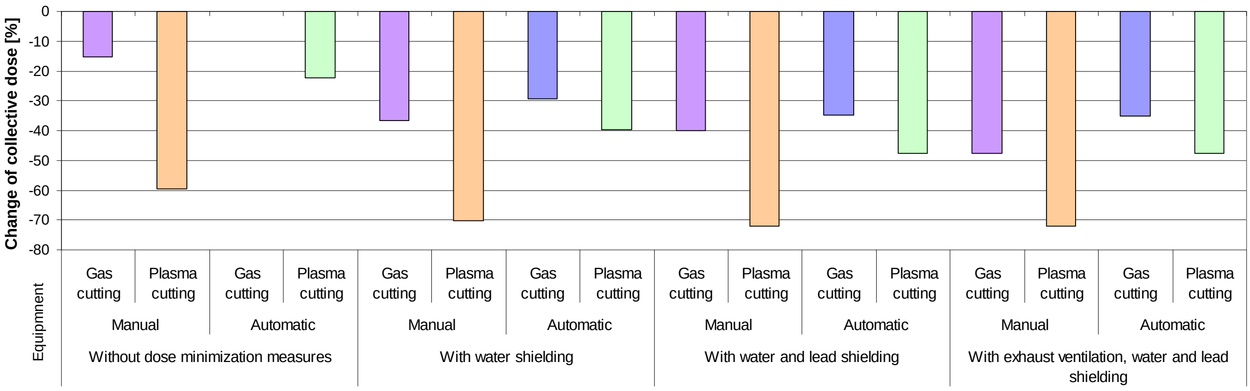

Figure 3. The collective effective doses vs the dismantling method of the MCR.

It was revealed that without dose minimization measures direct exposure from equipment contributes 91–99 %, internal exposure contributes 8–1 %, and direct exposure from radioactive aerosols contributes only <0.01 % to the total effective personnel dose.

When using exhaust ventilation, the internal exposure dose from radioactive aerosols is minimized and becomes negligible. Thus, personnel exposure from the radioactive aerosols is practically eliminated.

The comparison of the collective doses for each analysed case during the dismantling of the MCR is presented in **Figure 3**. This figure demonstrates that using manual plasma cutting equipment without shielding, due to the faster cutting speed and minor preparation time, the collective dose can be decreased by 59 % in comparison with automatic gas cutting. If water is filled in the MCR, the collective dose can be decreased by approximately 30 %. Using lead shielding with thickness 0.01 m and preparation time 20 s, the collective dose can be decreased by approximately 5 % if using slow cutting equipment. The collective dose may be decreased by approximately 72 % using manual plasma cutting equipment, exhaust ventilation, water and lead shielding.

5. Conclusions

After performing the investigation on minimization of the workers exposure during the dismantling of the maintenance cooling reservoir (MCR), the following conclusions have been drawn:

1. Without dose minimization measures direct exposure from equipment contributes 91–99 %, internal exposure contributes 1–8 %, and direct exposure from radioactive aerosols contributes only <0.01 % to the total effective personnel dose.
2. Collective dose can be decreased by approximately 30 % if water is filled in the MCR. Using lead shielding with thickness 0.01 m and preparation time 20 s, collective dose can be decreased by approximately 5 % if using slow cutting equipment.
3. Collective dose can be decreased by 59 % if faster cutting equipment (manual plasma cutter instead of gas cutting) is used.
4. Collective dose can be decreased by approximately 72 % when using manual plasma cutting equipment, exhaust ventilation, water and lead shielding.

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