EVALUATION OF THE SECONDARY RADIATION IMPACT ON PERSONNEL DURING THE DISMANTLING OF CONTAMINATED NUCLEAR EQUIPMENT

by

Gediminas STANKUNAS**, Aurimas TONKUNAS, Raimondas PABARCIUS, and Rolandas URBONAS

Laboratory of Nuclear Installation Safety, Lithuanian Energy Institute, Kaunas, Lithuania

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The article contains a numerical analysis of the secondary radiation contribution to the total radiation affecting the operational personnel during the dismantling activities of the contaminated equipment at a nuclear power plant. This study considers a widely applicable Monte Carlo particle transport code MCNPX and real Ignalina nuclear power plant records. A simplified albedo method is investigated in order to analyse the selected geometrical design cases. Additionally, the impact of the secondary radiation on the personnel dose was analysed. The numerical MCNPX simulation allowed ascertaining the optimal distance between the source and the wall for the working personnel in closed rooms with contaminated equipment. The developed dose rate maps of the secondary radiation showed cross-sectional distribution of the dose rate inside the enclosed area.

Key words: radiation, albedo, dose, dismantling, Monte Carlo method

INTRODUCTION

The evaluation of safety for the planned decommissioning activities, including the calculation of effective doses for the most exposed individuals performing the work in the most hazardous areas of the nuclear installation, belongs to the standard activities in the selection of the optimal decommissioning scenario. According to the IAEA methodology for the evaluation of safety-related parameters [1], the exposure of people and the release of radioactive material is performed for different decommissioning activities, *i. e*. the hands-on decommissioning activities; work at radioactive waste processing facilities; and periodical supporting activities (surveillance, maintenance, technical support).

From the point of view of dose evaluation, the critical decommissioning activities are the dismantling activities where the working personnel are closely present to the contaminated equipment. In the dismantling stage of any nuclear facility, it is essential to take into account the radiation effect on the working personnel and equipment inside the facility. A considerable exposure can occur within relatively short period of time. Because it is impossible to completely avoid the unwanted exposure of personnel, it is, therefore, reasonable to limit the amount of radiation levels in the working areas. During the dismantling operations, the equipment will be cut, opened and incompletely isolated. Hence, it is not very clear how gamma radiation, neutrons and their associated dose rates will affect the working personnel, especially in the places where the equipment is dismantled.

It should be recognized that the working personnel is exposed in different ways in accordance with the type of work they perform. The working personnel who directly perform the dismantling activities is the most exposed to the dose rate of the dismantled equipment (direct radiation). For others, the average dose rate in the room is dominant. The dose rate in the background of the controlled area is a very important component, and is caused by the radiation reflection as well. Thus, the uncertainties in the dose estimation can arise from the fact that the radiation reflection, *i. e*. the particle scattering, can be generated by the floor, roof, walls or other objects, and make a significant contribution to the total dose rate. Such secondary radiation may occur in locations highly isolated from the primary radiation areas.

In order to execute the decommissioning economically and rationally, the engineering systems are being developed to create a dismantling plan using the state-of-the-art software. For instance, the decommis-

* Corresponding author; e-mail: gediminas@mail.lei.lt

sioning engineering support system OMEGA [2], VISIPLAN [3] and VRdose [4] are aimed at the simulation and planning of the dismantling work in an environment with the presence of radioactivity. Although such engineering systems provide comprehensive (all types of radiation are considered during dose evaluation, including the secondary ones) and detailed (real premises and contaminated objects are modelled) results, the development of such software and input data preparation process are very long and expensive. On the other hand, the inhomogeneous neutron-gamma field simulations are very time-consuming in order to obtain reliable results, because they require handling complex geometries and radiation sources [5].

Another field where the investigation and determination of dose caused by the secondary radiation are especially relevant is radiotherapy. The secondary radiation (bremsstrahlung, neutrons, scattered electrons, *etc*.) can create high dose rates over large areas of the accelerator workplace. In [6] a comprehensive guidance on the design and layout of radiotherapy facilities and methods for determining the necessary structural shielding for external beam units is presented, including the examples of basic shielding equations application for all types of radiation. In the situations where the barrier being assessed will be exposed to both the primary and secondary radiation, it should not be assumed that the primary radiation component will always dominate [7]. Due to the reflection from a surface, radiation dose is an example that arises in the treatment of streaming of radiation through ducts and passageways. In case of gamma particles dispersion from a point-isotropic source in straight concrete ducts, it was found that the secondary scattered radiation may play a significant role (up to 30%) in regard to the total dose [8].

Thereby, it could be noted that in order to obtain accurate dose values, the secondary radiation needs to be considered. The aim of this article is to quantify the impact of the secondary radiation dose on the personnel during the dismantling of contaminated equipment. This study makes use of real data of the Ignalina nuclear power plant (NPP) decommissioning project, which is the first project in Lithuania designed for the decommissioning of NPP and the first attempt to dismantle equipment of a RBMK reactor worldwide [9]. It should be recognized that the engineering systems mentioned above and the associated software could calculate the impact of the secondary radiation relatively easy. However, in practice, especially during the primary estimation of personnel doses [10] and the preparation of alternatives for decommissioning activities, it is useful and advisable to estimate the proportion of the secondary radiation, which contributes to the total dose, beforehand. Such knowledge allows predicting the location of a worker in the room, and also provides assurance for complying with the regulatory requirements for accomplishing the required work with the resultant worker radiation exposures maintained as low as reasonably achievable (ALARA).

THEORETICAL BACKGROUND

In some cases, if only air separates a gamma ray or neutron source from a detector (worker, target, *etc*.), the interactions in the intervening air or in the ground/building walls are often negligible, and the radiation field at the detector is due almost entirely to the radiation coming directly from the source (direct radiation). If radiation is present in an attenuating medium, the dose D_0 caused by the direct radiation at a distance r from a point isotropic source emitting S_p particles (source) of energy E can be expressed as

$$D_0(r) = \frac{S_p C}{4\pi r^2} e^{-L} \tag{1}$$

where L is the total number of mean-free-path lengths of material, and C – the appropriate response function (the fluence to dose conversion factor) [11].

If one is dealing with shielding situations and the reflection is present, in many cases only scattered radiation may reach the detector. Frequently, the dose at some locations affected by the radiation reflected from walls and floors may be comparable to the dose caused by direct radiation. Such reflection processes are impossible to treat using elementary point-kernel methods, and very difficult and inefficient to treat using transport methods. When gamma rays or neutron fluence is present in the room, the particles penetrate the surface of a structural material (or shielding), scatter within the material, and then leave the material with reduced energy and at a location other than the point of entry. Radiation reflection may be described in terms of the geometry shown in fig. 1 (modified figure from [11]).

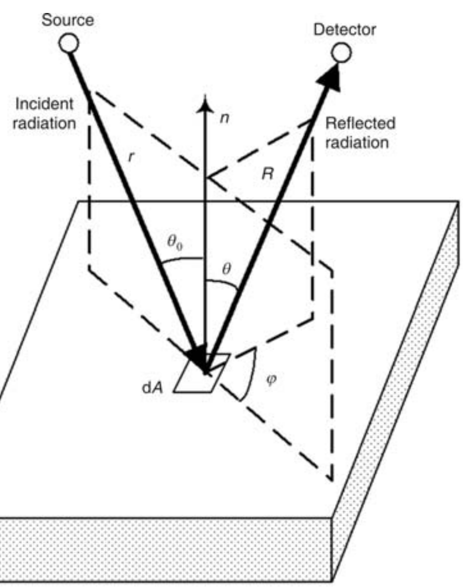

Figure 1. Angular relationship during reflection [11]

In such cases, a simplified method, called the albedo method, has come to be very useful in design and analysis. The albedo method is based on the following approximations: (1) the displacement between points of entry and emergence may be neglected, (2) the reflecting medium is effectively a half-space, a conservative approximation, and (3) scattering in air between a source and the reflecting surface and between the reflecting surface and the detector may be neglected. For practical purposes the dose albedo – the ratio of the emergent flow per steradian in dose units to that of the incident radiation – is commonly used

$$\alpha_D(E_0,\theta_0,\theta,\varphi) \quad \frac{\mathrm{d}EC(E)J_r(E,\theta,\varphi)}{C(E_0)J_0(E_0,\theta_0)} \tag{2}$$

where E_0 is the source energy, θ_0 and θ are polar angles of incidence and reflection (with respect to the wall normal), φ is the azimuthal shift of reflection flow; $J_0(E_0, \theta_0)$ and $J_r(E, \theta, \varphi)$ are incident and reflected flow, and $C(E)$ is the fluence to dose conversion factor.

Then the dose $\mathrm{d}D_r$ at the detector from particles reflected from area dA is

$$\mathrm{d}D_r \quad D_0\alpha_D \frac{\mathrm{d}A\cos\theta_0}{R^2} \tag{3}$$

where D_0 is the dose at area dA due to the incident particles, R – the distance from area dA [11] to detector.

The entire reflecting surface area should be integrated to calculate the total reflected dose D_r. This is not easy to achieve since the location on the surface as well as all the variables θ_0, θ, φ, r, and R change. Additionally, it is necessary to know the dose albedo $\alpha_D(E_0, \theta_0, \theta, \varphi)$ or, more usefully, to have some analytical approximation for the α_D so that the integration over all areas can be performed efficiently.

It is evident that albedo depends on the source energy characteristics, nature and thickness of the structure material, the distance from the surface to the detector, and angular relationships during the reflection on the surface. The albedo increases with the reduction of source energy E_0 due to an increase of Compton scattering (an inelastic scattering of a photon by a free charged particle, usually an electron) [11]. The most part of backscattered particles are reflected in a thin near-surface layer. With an increase of thickness of the structure material (dispersive) the portion of albedo gradually increases according the *e* law. Reaching 1-2 mean-free-path lengths in a spreading direction of primary particles, the albedo reaches a constant value.

If an angle of incidence θ_0 increases, the albedo rises for any directions of the reflected particles, because with an increase of θ_0 the distance up to a reflecting surface for the backscattering particles decreases, the angle of scattering θ_S reduces and the probability of particles escaping from the surface increases (fig. 2) [11, 12].

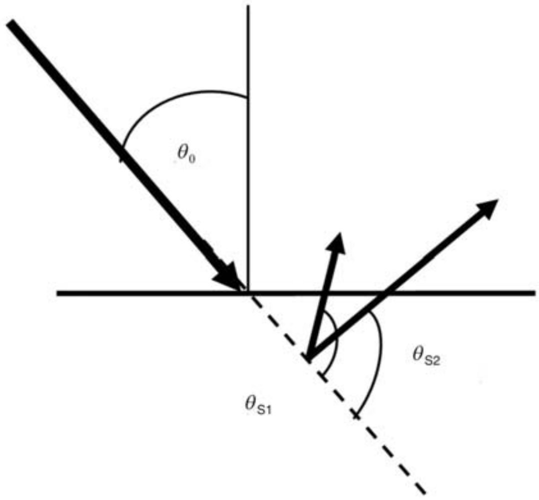

Figure 2. Angle of a scattered particle [13]

The albedo dependence on angle of reflection θ is defined by a competition of two processes. On one hand, for the given angle of incidence θ_0 the probability of particles scattering increases with a reduction of the angle of scattering θ_S (that conforms to an increase of angle of reflection θ); on the other hand, the path which particles should pass to leave the dispersive material increases in this case, and the probability of their absorption grows as well.

SIMULATION MODELS AND METHODOLOGY

In this study four cases were modelled (see fig. 3 for more details). The impact of the secondary radiation to assess the albedo depending on the distance (r) between the source and the walls was analysed for all four cases. Theoretical approach was employed by the first two simulation geometries:

– the two-wall case with perpendicular walls, composing a semi-enclosed space. For this situation, simulations were performed for several distances

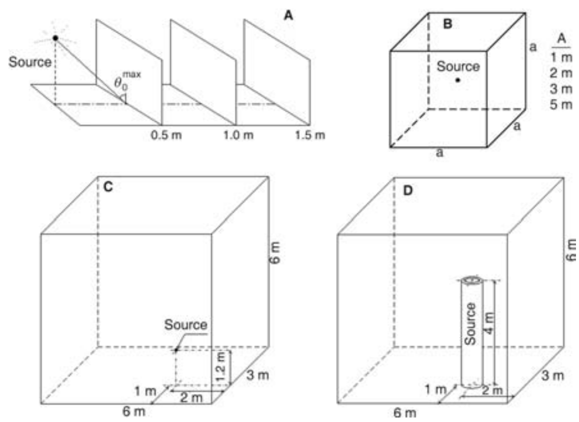

Figure 3. Simulation cases: (A) two-wall case, (B) cube case, (C) Ignalina NPP case with point-isotropic source, and (D) real case of Ignalina NPP

by moving one of the walls by 0.5 meters from the source up to the maximum distance of 1.5 meter in the analysed model, and
– the second set of calculations were made using a cube geometry for four different side lengths *a*, when the point source is situated in the centre of the cube.

Next two simulations cases were employed to assess the dose rate to a worker depending on the worker position *R*.

Dismantling of emergency core cooling system (ECCS) installed in the building No 117/1 of Ignalina NPP Unit 1 was used as a real example. Ignalina NPP Unit 1 was shutdown in 2004. A decision was taken to decommission this Unit by means of immediate dismantling in order to ensure that this process does not lead to serious social, economic, financial and environmental consequences. Thus, a real rectangular Ignalina NPP room (6 m × 3 m × 6 m) with concrete walls (thickness 30 cm) with contaminated equipment ready for dismantling inside was selected for the analysis of the third and the fourth simulation cases. They both differ in boundary conditions for source type and geometry in the room, *i. e*. the point-isotropic source for the former and the real case for contaminated tank with real length and geometry for the latter. The geometry of the simulation ECCS tank has the following parameters: outer radius – 40 cm, thickens of the pipe wall – 10 cm, its height – 4 m. The source was placed not in the centre of the room and this, in general, reflects the real condition of location of the contaminated equipment during the dismantling activities.

The case scenario data taken from [14] were used as gamma radiation source from inner surface of the cylinder. The experimental data, taken from the performed direct measurements of the surface contamination, indicated that the surface contamination of ECCS tank internal surface was up to 54 Bq/cm^2 (maximum values at the bottom of the tank). The main contribution to the total activity was influenced by ^{60}Co, while the contribution of ^{54}Mn and ^{137}Cs radionuclide activity was low. Table 1 demonstrates the gamma energy spectrum of the ^{60}Co source used in the investigation and in MCNPX simulations to estimate the gamma dose rate. The influence of the source power and type was not examined in this study; thus, the same source characteristics were employed during all simulated cases whether the point source or real tank source was assumed during the simulations.

Over the years, the use of the deterministic-type code has been over-shadowed by the Monte Carlo-based codes, such as multi-particle transport code MCNPX. Such wide application possibilities demonstrated by the Monte Carlo code MCNPX 2.7.0 [16] were employed for the simulation of the radiation fields and the investigation of the secondary radiation in this study. The gamma transport calculations were performed by MCNPX for all non-void geometry cells. The MCNPX does not directly calculate the dose rate; however, it converts the estimated flux into dose rate, where flux is defined as the number of the integrated particles per unit area. The MCNPX mesh tally Type 1 (track averaged) was used as a particle flux at the point detector followed by the modification by a dose function to calculate gamma dose rate. The conversion factors from IRCP-75 [17] for the ambient dose equivalent, H*(10), from photon fluence were used in the calculations obtained by the energy and its corresponding dose function. In order to evaluate the gamma dose rate, as well as the contribution of the main radionuclides to the total emitted radioactivity, the nuclear data library ENDF/B-VII [18] was used during the investigation. The Monte Carlo transport code MCNPX cannot calculate the dose equivalent to the second radiation directly as well. The way to calculate the dose equivalent is to calculate the dose rate with the complete modelled geometry first and subtract the values from the unbounded volume (space) under the consideration. Thus, this study includes a quantitative assessment of the secondary radiation in relative units, expressed as the dose albedo in percentage of the total radiation. The 3-D MCNPX model for basic ECCS tank room facility is presented in fig. 4.

Table 1. Gamma lines and emission probabilities [15]

^{60}Co	
Gamma line, E_g [keV]	Probability, I_g [%]
1173.237	99.974
1332.501	99.986

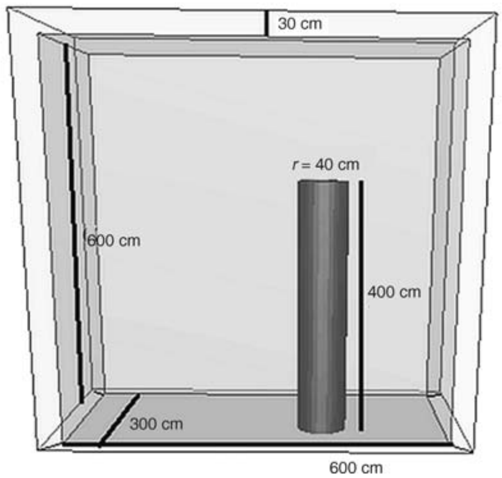

Figure 4. MCNPX model for ECCS tank (real case of Ignalina NPP)

SIMULATION RESULTS

Evaluation of the secondary radiation

Two-wall case

The secondary radiation was analysed in a semi-enclosed space at first. This theoretical case al-

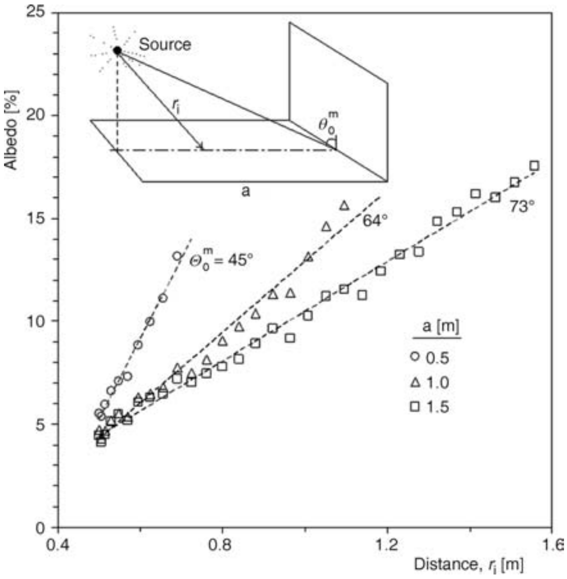

Figure 5. Albedo in a semi-enclosed space. Two-wall case

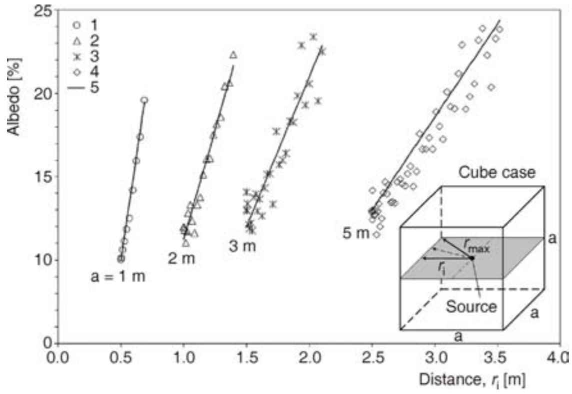

Figure 6. Albedo dependence *vs*. distance *r*. Cube case: *(1) volume 1 m^3; (2) 8 m^3; (3) 27 m^3, (4) 125 m^3; and (5) according formula (4)*

lows to quantify the dose albedo (hereinafter albedo) when the distance to the reflecting surface is increasing. Only one vertical wall and a horizontal surface (floor) were assumed during each separate simulation case. Figure 5 presents the simulation results of the three analysed cases. Note that the computer running time was chosen for all calculations in such a way that the statistical error of Monte Carlo simulation results was always less than 10%. The simulation results in the figure represent the reflection from the floor surface only. It is obviously that albedo dependence on the distance from the source to the surface *r* is linear and positive. If the vertical wall is moved forward (a = 0.5 m, 1.0 m, 1.5 m) and the distance *r* increases, the amount of the reflected particles increases as well. By approaching the junction point of both surfaces, the albedo achieves maximal values. Such distribution could be explained by the increase of the incidence angle and the contribution of the vertical wall (corner effect). As it was mentioned above, the albedo increases for any directions of the reflected particles, because with an increase of the incidence angle the angle of scattering reduces and the probability of particle escape from the wall rises. The maximal values of incidence angle for the modelled cases are 45°, 64°, 73° accordingly (fig. 5). Thus, even in a semi-enclosed space the dose caused by the secondary radiation may compose up to (13-17)% of the total radiation.

Cube case

The numerical modelling of the secondary radiation was carried out in an enclosed space, *i*. *e*. cubes of different sizes. Four cubes with the side length of 1 m, 2 m, 3 m, and 5 m were simulated. In this case, a source was placed in the centre of the cube. Figure 6 presents the simulation results showing the distribution of dose albedo throughout the distance from the source in the middle cross-section of the cube. Only 1/8 of the cross-section area was analysed because of the symmetry of the cube model. The simulation results confirm the linear dependence of albedo on the distance to the reflecting surface. The albedo could reach 20-24% of the total radiation in the cube case. It is clearly shown that by increasing the volume of a cube, the maximal values of albedo increase and its dependence on distance *r* changes. In order to find a simple and convenient solution as well as to get the possibility to quantify the secondary radiation effect approximately, all the obtained simulation results were described as a function of the cube volume V [m^3] and distance r [m]. The resumptive equation can be expressed as follows

$$\text{Albedo} \quad 50\frac{r_i}{V^{0.31}} \quad 15 \tag{4}$$

This equation describes the simulation results within average relative discrepancy less than 5%.

Ignalina NPP case with point-isotropic source

In this case a real rectangular room (6 m × 3 m × 6 m) at Ignalina NPP was modelled. The source point was located at the level of 1.2 m from the floor and was not placed in the centre of the room (in x-y plane) and this, in general, reflects the real condition of the location of the contaminated equipment during the dismantling activities. Hence, an appropriate cross-section was selected for the analysis and the secondary radiation reflected from the walls of the room. The simulation results for this case are presented in fig. 7, where albedos from all walls in the room for the selected cross-section area are shown. As it can be seen in the figure, albedo could reach 30-35% of the total radiation for this particular case. All simulation results could be described by some linear curve, where the albedo increases with the rise of the distance r_i (source-to-wall). Several points give higher values but it could be explained by the above-mentioned corner

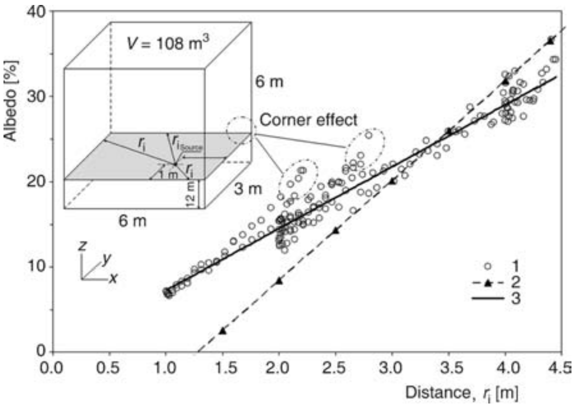

Figure 7. Albedo dependence *vs.* distance *r*. Ignalina NPP case with point source: *(1) simulation data, (2) according to formula (4), and (3) according to formula (5)*

effect. The albedo calculated by formula (4) for this particular case of the room with 108 m^3 volume does not suit the simulation results because of the non-symmetry of the room and source location (curve 2). To account for such non-symmetry, the correction coefficient r_i/r_{max} – where r_{max} is maximal distance from the source to the wall of the cube with appropriate volume was proposed (see fig. 6). This correction coefficient reflects the transformation of the symmetrical cube model to the rectangular room and accounts for the non-symmetry of the source positions in all x, y, z-directions. For the room with volume 108 m^3, the distance r_{max} is 3.37 m. Therefore, in this simulated rectangular room, albedo could be calculated by the following formula

$$\text{Albedo} \quad 50\frac{r_i}{V^{0.31}} \quad 15\frac{r_i}{r_{max}} \tag{5}$$

As it is shown in fig. 7, albedo calculated by formula (5) describes the simulation results fairly accurately since the average relative discrepancy is less than 7% (for all simulation points).

Real case of Ignalina NPP

During the simulation of the real case of Ignalina NPP (fig. 3), the dose caused by the secondary radiation to a worker (detector) standing in different distances from the reflection wall *R* was quantified (fig. 8) in four directions (west/east/south/north). It was assumed that a worker moves from the appropriate wall to the contaminated ECCS tank (source) in a normal direction towards the wall. Thus, $R = 0$ is the point on the perpendicular wall, and the maximal value *R* represents the close position near the source. Horizontal cross-section at level 1.2 m was analysed in this case as hereinbefore.

As fig. 8 suggests, the dose rate of the secondary radiation decreases with the distance *R*, and this dependence is quite linear. The principle of radiation protection states that increasing the distance from the

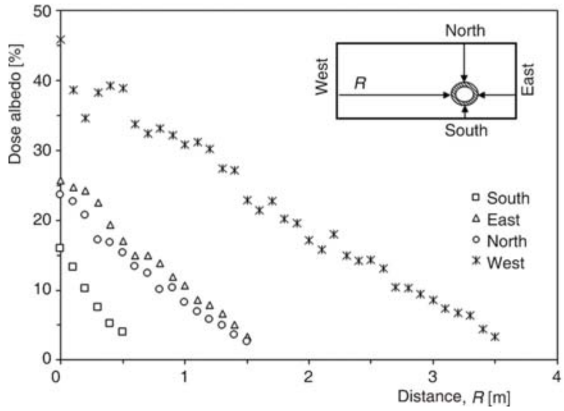

Figure 8. Dose albedo *vs.* distance *R* in different directions. Real case of Ignalina NPP

source to the detector reduces the total dose due to the inverse square law, see formula (3). Based on the gained simulation results, it is evident that the dose caused by the secondary radiation could be expressed by the direct linear law, if the reflecting wall is accessed as the source. The simulation results in fig. 8 demonstrate that the reflection from the farthest wall is the most intensive, and the dose albedo could comprise 35-45% of the total radiation.

Assessment of the secondary radiation to the personnel dose

Most of the residual nuclei produced via nuclear reaction at nuclear facilities are unstable. In order to return to the stability, they subsequently decay either via alpha, beta or gamma ray emission. The production of the secondary radiation usually results in a complex mixture of radiation, which can be problematic to radioactivity sensitive material and components and, especially, working personnel. Therefore, sufficient steps should be taken towards preventing the over-exposure of the personnel. As it was shown, the part of the secondary radiation in the total dose may exceed more than 1/3 in some cases.

The absolute values for the secondary radiation dose rates for four different directions from the source to the walls are represented in fig. 9. Since the contamination of the source at Ignalina NPP was not hazardously strong and the estimation of dose rates does not require exact values, the simulation results are represented in order of magnitudes. Here, the most important is the comparison of the secondary dose rate trend in the dependency of the distance from the source on the edge of the modelled room. The results of these calculations could be used to determine the optimal distance between the source and the wall to achieve as low (ALARA principle) radiation from the contaminated object as possible taking into account the secondary radiation from the walls of the room as well. It is not difficult to notice (see fig. 9) that the secondary radiation is negligible at the short distances from the

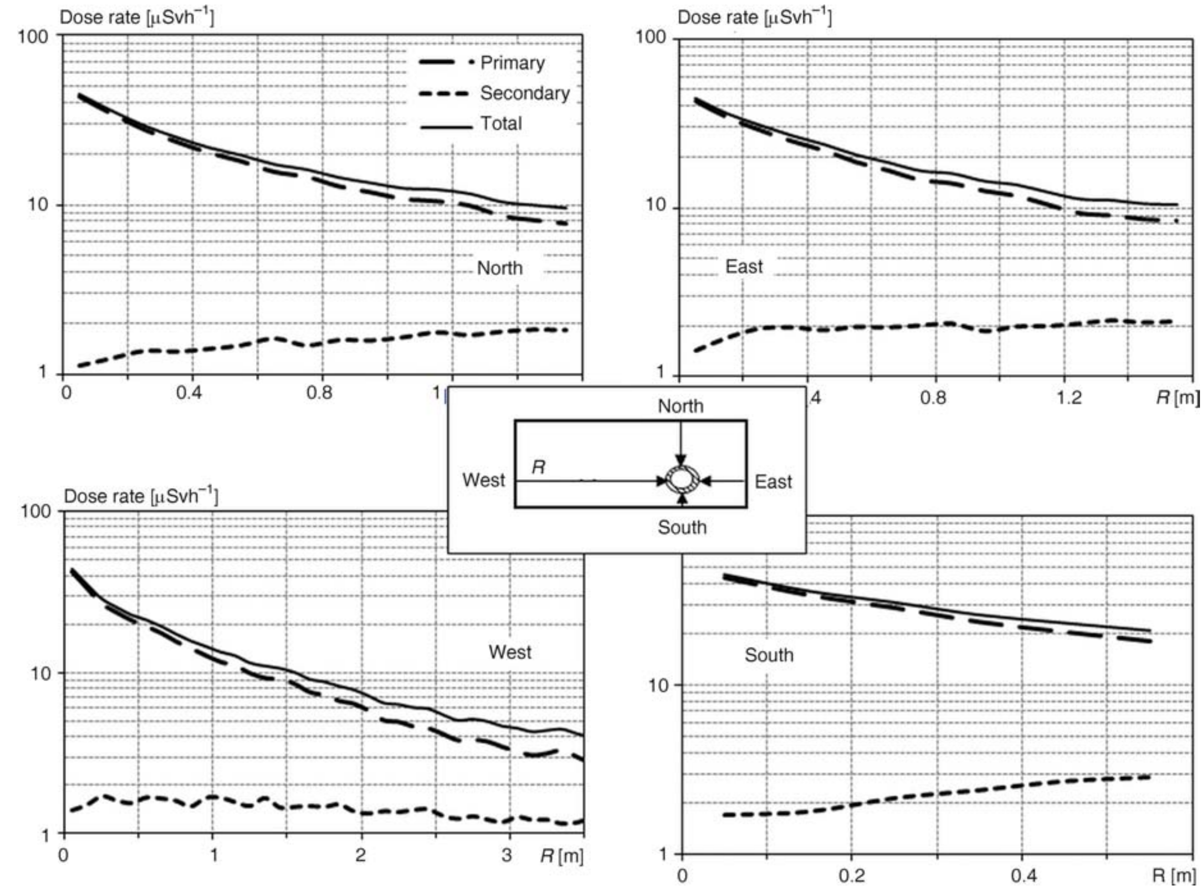

Figure 9. Comparison of dose rates; impact of scattering irradiation (real case of Ignalina NPP)

source, but it rises towards the walls where it becomes significant in comparison to the primary radiation. Therefore, one can assume that the optimal distance is 2/3 of the total distance from the source and 1/3 accordingly from the walls. This position can be clearly seen in fig. 9, where the curve representing the primary radiation starts to separate from the total radiation curve. This ratio of the distance is suitable for the most analysed cases.

Figure 10 represents the dose rate map of the simulated Ignalina NPP room (real case of Ignalina NPP), where the dismantling activities of ECCS tank are performed. These situations are important for the monitoring and planning of manpower dispositions around the contaminated object when the source is unshielded, or if a worker needs to enter the room to perform decontamination or other activities. In this way, personnel could escape excessive explosion and at the same time, the shielding arrangements could be properly set to reduce the secondary gamma activation near the walls and corner regions.

CONCLUDING DISCUSSIONS

Numerical calculations were performed to evaluate the impact of the secondary radiation to the personal during the dismantling activities of the contami-

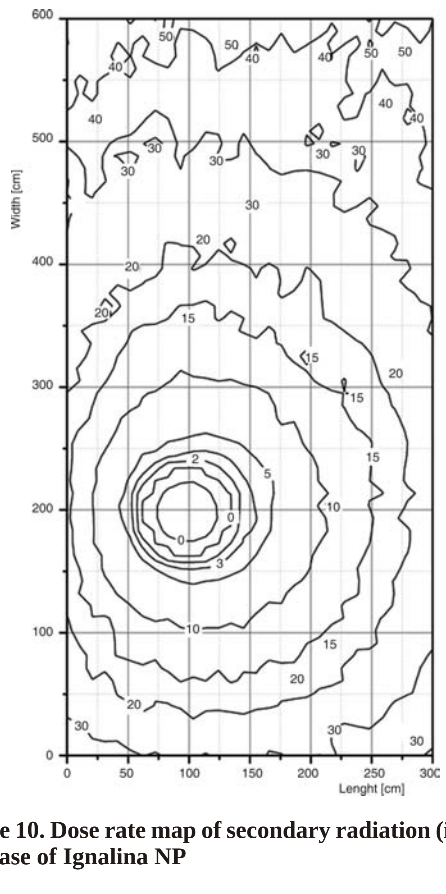

Figure 10. Dose rate map of secondary radiation (in %): real case of Ignalina NP

nated equipment at a nuclear power plant. This study employs a worldwide-accepted Monte Carlo particle transport code MCNPX and factual Ignalina NPP data. The results indicated that dose albedo is directly proportional to the distance from the source and it can reach up to 40% of the total radiation for particular cases. This concludes that the secondary radiation cannot be neglected while planning decommissioning activities in closed rooms. Based on the results obtained by the modelling cubes with various volumes, a formula which simply defines the secondary radiation as a function of a cube volume and the distance from the source was derived. In addition, the estimated correction coefficient allowed applying the derived equation for the determination of the secondary radiation at factual rectangular premises at Ignalina NPP, where the source was situated elsewhere than the centre. This equation can describe the simulation results with 4-7% average relative discrepancy. However, this investigation was limited only to the modelling of one non-symmetrical room (*i*. *e*. real case of Ignalina NPP), consequently, the derived equation with its correction coefficients is applicable only for this particular case. To succeed a universal equation, additional comprehensive investigation is required in the future.

Furthermore, the paper also carried out an assessment of the secondary radiation to personnel dose. A numerical Monte Carlo simulation allowed identifying the optimal distance from the source and the wall for the working personnel in closed premises with contaminated equipment inside. Differently from the albedo study results, the estimated ratio of the distances can be successfully applied for all cases analysed in this study and it can be treated as a general approach. The dose rate maps of the secondary radiation appeared to be valuable and will be used to observe the cross-sectional distribution of the dose rate inside the enclosed area by the NPP Safety Department to limit the amount of unnecessary exposed radiation to the operating personnel.

AUTHOR CONTRIBUTIONS

The theoretical analysis was carried out by R. Pabarcius and modelling was carried out by G. Stankunas and A. Tonkunas. All authors analysed and discussed the results. The manuscript was written by R. Pabarcius, G. Stankunas, and R. Urbonas and the figures were prepared by R. Pabarcius and G. Stankunas.

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**Гедиминас СТАНКУНАС, Ауримас ТОНКУНАС,
Рајмондас ПАБАРЧИЈУС, Роландас УРБОНАС**

ПРОЦЕНА УТИЦАЈА СЕКУНДАРНОГ ЗРАЧЕЊА НА РАДНО ОСОБЉЕ ТОКОМ РАСТАВЉАЊА КОНТАМИНИРАНЕ НУКЛЕАРНЕ ОПРЕМЕ

Овај рад садржи нумеричку анализу доприноса секундарног зрачења укупном зрачењу које делује на радно особље током растављања контаминиране опреме у нуклеарној електрани. У раду су коришћени опште прихваћен Монте Карло програмски пакет MCNPX за транспорт честица и прави подаци из нуклеарне електране Игналина. Примењена је поједностављена албедо метода како би се анализирала изабрана геометријска решења. Такође, анализиран је утицај секундарног зрачења на дозу за особље. Нумеричка симулација MCNPX програмом омогућила је утврђивање оптималног растојања између извора и зида за радно особље у затвореним просторијама са контаминираном опремом. Начињене мапе јачине дозе услед секундарног зрачења показују расподелу јачине дозе у зависности од нуклеарних пресека унутар затворене просторије.

Кључне речи: секундарно зрачење, албедо, доза, растављање реактора, Монте Карло метода