SPECTRAL ALBEDO OF PHOTONS OF INITIAL ENERGIES BELOW 100 keV

by

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Received on April 12, 2007; accepted on June 11, 2007

This paper shows the results of Monte Carlo simulations of the photon reflection from homogenous plates of the shield materials made of water, aluminum, and iron. Perpendicular incidence of a monoenergetic photon beam of the initial energy of 20 keV up to 100 keV is considered. The numerical experiments were performed using the verified Monte Carlo programs MCNP-4C, FOTELP-2K3, and PENELOPE-2005. As the result, the values of difference number albedo distributed in ten even intervals according to the energy and nine even intervals according to the polar angle of reflected photons were obtained. Out of these data, the spectral albedo coefficients for all three materials and three initial photon energies of 40 keV, 60 keV, and 100 keV were calculated, graphically presented, and analyzed. The values of the spectral albedo determined on the basis of MCNP-4C code were compared to the results of the early simulations of the photon reflection performed in Russia and in the USA. Also, with the help of MCNP-4C program, the yield of fluorescent photons to the spectrum of the reflected radiation was registered, which can be seen in the graphs in the form of the peak at the energy of 7.112 keV only at the shielding plates made of iron.

Key words: photon reflection, spectral albedo of photons, Monte Carlo method, water, aluminum, iron

INTRODUCTION

Research on the photon reflection from shielding materials was dealt with in the classic literature on radiation protection with the accent on the initial energies of photons of 100 keV up to 10 MeV as a consequence of the response of science on radiation to the requirements of the needs of that time appearing in construction and control of research and commercial nuclear reactors, and especially in military applications [1-3]. However, the experience gained in the civil usage of radiation in modern technologies, especially in medical diagnostics and treatment, points to the more consistent studies of the radiation interactions with the materials (nuclear processes, diffusion, slowing-down, and reflection) in which the initial photon energies are below 100 keV. In this energy range, values characteristic for photon reflection (differential albedo, number, spectral and dose albedos, as well as the total albedo coefficients) have not been systematically determined and numerically tabulated by all the materials characteristic for radiation protection and by the whole low-energy range of the initial photons. In literature, only unsystematic fragmentary results of the application of modern Monte Carlo codes for simulation of low-energy photon reflection, or particular, semi-analytical engineering formulae for some albedo coefficients can be found [4-7].

Long-term investigations of photon reflection conducted in the VINČA Institute of Nuclear Sciences by analytical and semi-analytical procedures for determining the characteristic albedo functions [8-10], as well as by the comparative Monte Carlo simulations of the transport process and photon reflection from the most typical shielding materials [11-13], have produced plenty of data referring to the characteristic re-

Scientific paper
UDC: 539.122:519.245
BIBLID: 1451-3994, *22* (2007), 1, pp. 40-47
DOI: 10.2298/NTRP0701040M

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flection coefficients: double differential albedo $a(E_0, \theta_0; E,\theta\ \varphi$, number albedo $a_N(E_0,\theta_0; \theta\ \varphi$, spectral albedo $a_N(E_0,\theta_0; E)$, energy albedo $a_E(E_0,\theta_0;\theta\ \varphi$ and dose albedo $a_D(E_0,\theta_0; \theta\ \varphi$, as well as the corresponding integral reflection coefficients – total number albedo $a_N(E_0,\theta_0)$, total energy albedo $a_E(E_0,\theta_0)$, and total dose albedo $a_D(E_0,\theta_0$. The aim of these investigations is (a) calculation of data on low-energy photon reflection collected on the basis of the Monte Carlo reflection simulations performed by verified domestic and foreign programs, more complete regarding energy and material, (b) perception of universal characteristics of the reflection phenomenon and their analytical description, and (c) practical insight significant to the industrial and medical application of radiation protection. The major part of this paper, a part of a doctoral dissertation of one of the authors [14], has been presented many times at expert and scientific conferences during past years [15, 16]. Collecting, final processing and publishing of the attained results is in progress.

This paper shows the values of spectral albedo $a_N(E_0,\theta_0; E)$ calculated on the basis of Monte Carlo simulations of the reflection initiated by a beam of monoenergetic photons of energies below 100 keV directed at the right angle onto the flat thick slab made of a homogenous material. Water, aluminum, and iron targets were treated because they correspond to the realistic diagnostic conditions in medical practice to the greatest extent. The verified Monte Carlo codes MCNP-4C [17], FOTELP-2K3 [18-20], and PENELOPE-2005 [21] were used. Their usage was coordinated regarding the geometrical and material data on the physical problem which was simulated, but the specifics of each program regarding the simulation technique and the data libraries used were taken *per se*, as if an average professional program user would do when designing, as an engineer, the radiation protection for the participants of a routine medical diagnostics or treatment. The values of spectral albedo, obtained by the three used codes, were compared to one another and analyzed, and the results of MCNP-4C program were additionally verified by data from classic literature on radiation protection [1, 2]. As a part of this research, the quantitative yield of fluorescent photons to spectral albedo was registered for each material using MCNP-4C [14]. The yield is in a shape of the second peak of the spectrum at the lower energy limit, which can be seen in the graphic presentation in the figures of this paper only for the iron shielding plates.

SPECTRAL ALBEDO OF PHOTONS

Functions characteristic for photon reflection are defined under assumption that a broad beam of directed and monoenergetic radiation, defined by the energy E_0 and polar angle θ_0, impinges the boundary surface of a material and that the photons are reflected with different energies E in different directions determined by the polar angle θ and the azimuthal angle φ. Thus defined albedo coefficients are equivalent to the albedo coefficients determined by the model of the directed narrow beam of the initial radiation [2, 10].

Determination of the reflection coefficient, such as number and spectral albedo, is based on the values of the double differential number albedo coefficient $a(E_0,\theta_0; E,\theta\ \varphi$, previously obtained by Monte Carlo simulations [10]. More precisely, the simulations are used to determine the difference number albedo $a_N^{ji}(E_0,\theta_0)$, the double integral of the previous coefficient

$$a_N^{ji}(E_0,\theta_0) \quad 2\pi \int_{\Delta E_j} \mathrm{d}E \int_{\Delta\theta_i} a(E_0,\theta_0;\ E,\theta,\varphi)\sin\theta \mathrm{d}\theta \quad (1)$$

In the expression (1), indexes j and i denote the energy and angular intervals which the reflected photons are grouped into.

Subsequently, using the values $a_N^{ji}(E_0,\theta_0)$ determined by the simulations, and the definition of spectral albedo [2]

$$a_N(E_0,\theta_0;\ E) \quad \int_0^{2\pi} \mathrm{d}\varphi \int_0^{\pi/2} a(E_0,\theta_0;\ E,\theta,\varphi)\sin\theta \mathrm{d}\theta \quad (2)$$

which represents the probability that a photon is reflected within the differential energy element dE around the energy E, the following expression is derived

$$a_N(E_0,\theta_0;\ E) \quad \sum_i a_N^{ji}(E_0,\theta_0) \quad (3)$$

Thus, by adding the values of the difference number albedo $a_N^{ji}(E_0,\theta_0)$ at all angular intervals i, the spectral albedo is obtained. It is understood that in the expression (3) the energy E belongs to the j energy interval.

MONTE CARLO SIMULATION OF PHOTON REFLEXION

The Monte Carlo simulations were performed by the standard programs MCNP-4C [17], FOTELP-2K3 [18], and PENELOPE-2005 [21]. It was assumed that a narrow photon beam impinged the flat target at the right angle ($\theta_0 = 0°$); upon that, the angular-energy distributions of the probability of the photon reflection from the target after one or more scattering were determined using the simulation results. In the simulations, the initial photon energies E_0 of 20 keV up to 100 keV in the intervals of 10 keV (MCNP-4C and FOTELP-2K3 programs) and the initial energies of 40 keV, 60 keV, and

100 keV (PENELOPE-2005 program) were assumed. The reflected photons were grouped into ten equal energy intervals identical to the one tenth of the initial energy, as well as in the nine identical intervals by the polar angle θ of the width of 10°.

Basic data on the Monte Carlo programs and their usage

MCNP-4C program

MCNP-4C is a version of the MCNP program, which has been developed for years in Los Alamos laboratories and which can be considered as the industrial standard beyond which there are 600 research years of developmental work. It is dedicated to physicists who work in the field of medical physics, ecology, and radiation protection, but also to those who deal with the problems of reactor physics and technology, calculations of nuclear criticality, particle transport, and new materials. It is available for portable and stationary computers.

MCNP-4C is a Monte Carlo program for simulation of the coupled neutron, photon, and electron transport. It is of general applicability, with continuous energy presentation and generalized geometry. It treats materials with an arbitrary three-dimensional configuration arranged in the cells limited by the surfaces of the first and second order and by some special surfaces of the fourth order. The cross-sections are used in the pointwise continuous-energy presentation, as well as in a multigroup shape. During the photon transport, the incoherent and coherent scattering is included into calculation, with and without the electron correlation effects, with the possibility of examining the fluorescent emission which follows photoelectric absorption, as well as the annihilation absorption with pair production and local emission of annihilating radiation. The program is designed to be suitable for the general source structure and to offer the choice of six shapes of the output values (tally), with the extensive statistical convergence analysis. Fast convergence is provided by different methods of variance reduction. For photons and electrons, the energy interval is from 1 keV up to 1 GeV.

The calculation of the photon reflection from water, aluminum, and iron was performed using the MCPLIB2 standard data library and the program option – tally F1:P which determined the surface photon current – the number of photons crossing the boundary surface. In this case, $3 \cdot 10^8$ photon histories per calculating experiment were followed, which provided the statistical uncertainty of 1% of the calculated value in each angular-energy interval. In order to verify the simulation, in some cases the number of histories was increased to $1\ 10^9$. The duration of the simulation depends extensively on the material, initial energy, lower cut-off energy, and greatly on the structure of angular-energy groups. The simulations performed at the Intel processor 4, central processor unit (CPU) 1.8 GHz with 300 million initial photons, cut-off energy of 1 keV, ten energy and nine angular groups, for the selected tally F1:P, last in the interval of half an hour to four and half hours (tab. 1).

Table 1. Duration of photon reflection simulation – MCNP-4C program, Intel Pentium 4, CPU 1.8 GHz processor

E_0 [keV]	CPU time [min]		
	Water	Aluminum	Iron
20	45	28	42
60	261	70	54
100	275	118	60

FOTELP-2K3 program

FOTELP-2K3 program is a new compact version of the previous programs FOTELP-PEN and FOTELP-2KG, originally planned for Monte Carlo calculation of three-dimensional transport of photons, electrons and positrons through different materials. The most complete cross-sections available for the interaction are used in the program and complete physical models for description of particle transport and simulation of photon, electron and positron cascades within the range of 1 keV to 100 MeV are represented in it. It is dedicated to Monte Carlo numerical experiments in dosimetry, radiation therapy, radiation damage studies and other applications.

While forming a photon history, the trajectory is created by following a photon from one collision to another, using the corresponding inverse distribution between the collisions, through the process of which the dependency on the type of target, type of collision, and type of secondary radiation, its energy and angle are registered. The following interactions are included: photoelectric absorption, coherent and incoherent scattering, and pair production. Secondary photon histories assume backscattering radiation and positron-electron annihilating radiation. In its newest version, the program allows a very complex target structure with the possibility of defining up to 850 surfaces and bodies. Time of calculation depends on the number of simulated histories, initial photon energy and lower energy cut-off , as well as on the complexity of the geometry in question. Table 2 gives values of CPU time needed for performing computer simulations of the photon reflection when the number of initial photons is $1\ 10^8$, and the lower energy limit for the photons is 2.5 keV.

PENELOPE-2005 program

PENELOPE-2005 program enables a Monte Carlo simulation of the coupled electron and photon

Table 2. Duration of photon reflection simulation – FOTELP-2K3 program, Intel Pentium 4, CPU 1.8 GHz processor

E_0 [keV]	CPU time [min]		
	Water	Aluminum	Iron
40	6.48	8.45	6.50
60	7.38	13.74	7.37
100	11.52	25.53	11.32

transport in arbitrary materials of complex geometry. Photon interactions (coherent and incoherent scattering, photoelectric effect, and electron-positron pair production), as well as positron annihilation, were simulated completely. The photon energies of 100 eV up to 1 GeV are allowed. The program has been realized in the form of packages of FORTRAN subroutines which are controlled via the main program organized by a user. Beside the routines which describe interactions and energy transport, the code is equipped with the PANGEA package, which simulates the spatial transport through complex materials made of homogenous bodies limited by parallelogram surfaces. The techniques of variance reduction (particle splitting, Russian roulette, and interaction forcing) are used routinely. Newer versions of the program include the main generic program PENMAIN, which is controlled via the input data without any special programming effort, thus enabling the simulation of various practical tasks. This program system has been thoroughly evaluated throughout numerous applications, benchmark comparisons of simulation results and experimental data.

Table 3 shows values of CPU time spent for the calculation simulation of the reflection from the selected materials, with the initial number of photons of 1 10^8. The lower energy limit for photons is 2.5 keV.

Table 3. Duration of photon reflection simulation – PENELOPE-2005 program, Intel Pentium 4, CPU 1.8 GHz processor

E_0 [keV]	CPU time [min]		
	Water	Aluminum	Iron
40	40	19	30
60	43	24	42
100	49	33	54

Comparison of maximal values of difference number albedos obtained by simulations

The ref. 14 gives the details of Monte Carlo simulations determining the values of difference albedo coefficients $a_N^{ji}(E_0,\theta_0)$ for water, aluminum, and iron. A set of values of difference albedo coefficients $a_N^{ji}(E_0,\theta_0)$ determined by simulations (tables A1-A9 of the ref. 14) is given for nine even angular intervals of the polar angle θ, width of 10°, and for ten even energy intervals whose width corresponds to one tenth of the energy of initial photons. Values $a_N^{ji}(E_0,\theta_0)$ present the basis for calculation of other differential, integral, and mean albedo values characteristic for the low-energy photon reflection. We will give here only one comparison of the maximal values of differential number albedo of photons obtained by the reflection simulations performed with the programs mentioned above (tab. 4).

Table 4 shows that the values for water, obtained by MCNP-4C and FOTELP-2K3 programs, diverge for less than 3% for $E_0 = 100$ keV up to 10% for $E_0 = 40$ keV. The differences of these programs for materials with the bigger atomic number are 10-20%. The discrepancies of the values obtained by PENELOPE-2005 program are even bigger compared to those obtained by the simulation performed by MCNP-4C code, while the values obtained by FOTLEP-2K3 program are always between the other two programs.

The agreement of the maximal values of difference number albedo obtained by these programs, though rough, is quite satisfactory because the issue is the energy angular distribution, *i. e.*, double-differential distribution. Even drastic discrepancy of the corresponding values of difference number albedo which exist when these values are very small (above all, at the furthest boundaries of the energy range, just below the initial energy E_0 and just above the lower limit of the whole energy range) do not distract significantly the acceptable agreement of all other characteristic values of photon reflection generated out of this basic set. Mostly, the discrepancies of the results can be attributed to the uneven number of simulations per one numerical experiment: the number of histories followed by MCNP-4C program was 3 10^8 (in some cases it was 1 10^9), while the simulations by FOTLEP-2K3 and PENELOPE-2005 programs were performed with 1 10^8 initial photons. Also, some values of difference number albedo are below the limits of the statistical uncertainty which the programs predict for the selected number of simulations.

Table 4. Maximal values of difference number albedo of photons $a_N^{ji}(E_0,\theta_0)$

Material	E_0 [keV]	MCNP	FOTELP	PENELOPE
Water	40	0.0306	0.0271	0.0245
	60	0.0330	0.0315	0.0282
	100	0.0348	0.0340	0.0306
Aluminum	40	0.00805	0.00631	0.00584
	60	0.0166	0.0148	0.0133
	100	0.0265	0.0249	0.0225
Iron	40	0.000930	0.000701	0.000653
	60	0.00250	0.00207	0.00190
	100	0.00698	0.00583	0.00535

SPECTRAL ALBEDO CALCULATED ON THE BASIS OF MONTE CARLO SIMULATIONS

Comparison of results obtained by MCNP-4C, FOTELP-2K3, and PENELOPE-2005 programs

Figures 1-3 show the values of the spectral albedo of photons through the histograms for water, aluminum, and iron, with the initial photon energies of 40 keV, 60 keV, and 100 keV. For better picture clarity, the linear scale was used at the ordinate. The data for drawing the histogram were obtained by the reflection simulations performed by MCNP-4C, FOTLEP-2K3, and PENELOPE-2005 programs.

The figures clearly show that the spectral albedo coefficients of the photon current calculated by PHOTLEP-2K3 and PENELOPE-2005 programs

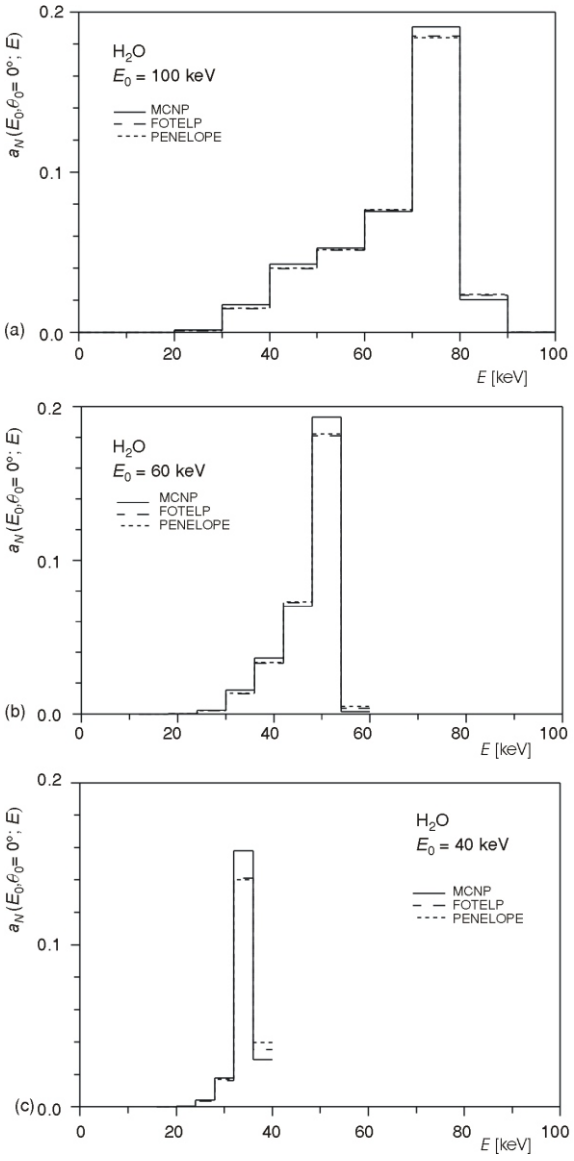

Figure 1. Spectral albedo of photons for water and initial photon energy of (a) 100 keV, (b) 60 keV, and (c) 40 keV

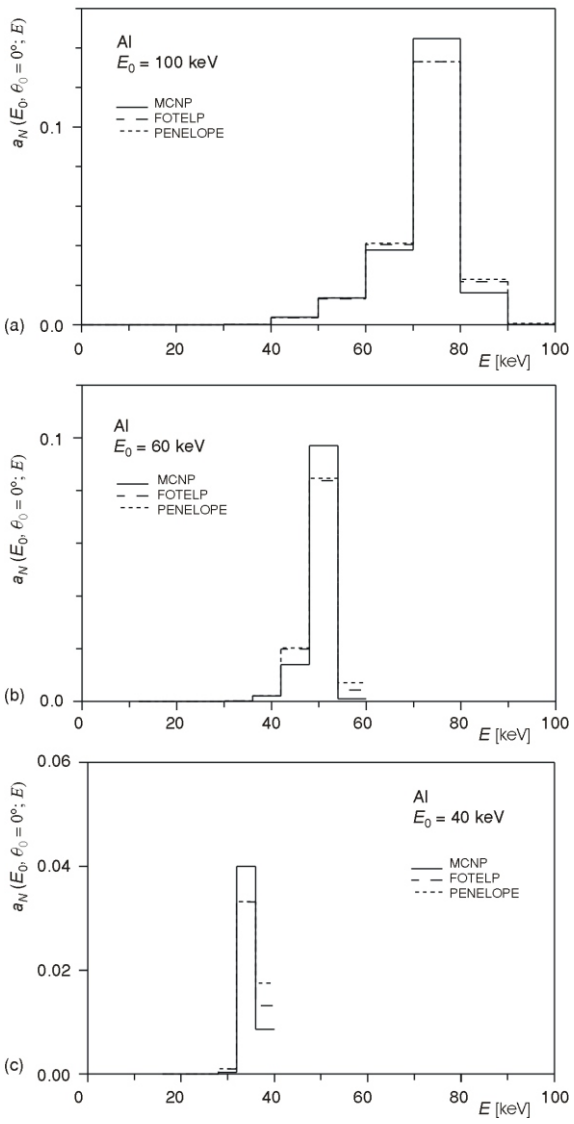

Figure 2. Spectral albedo of photons for aluminum and initial photon energy of (a) 100 keV, (b) 60 keV, and (c) 40 keV

were in very good agreement, except when the incident photon energy was 40 keV and the reflected photon energies were in the range of the first energy group below the initial energy (36 keV up to 40 keV). However, while determining the error, one should bear in mind that the number of photons reflected with the energies close to the initial energies is significantly smaller than the number of photons in the distribution peak, so that the discrepancy of the results in this range of reflected photon energies is less influential on determining the integral reflection coefficients or on the calculation of the characteristic mean values of the reflection.

The values for the spectral albedo obtained by MCNP-4C program differ to the greater extent from those obtained by the two other programs. The differences are the smallest for water, and the greatest for iron in the boundary energy ranges of the reflected

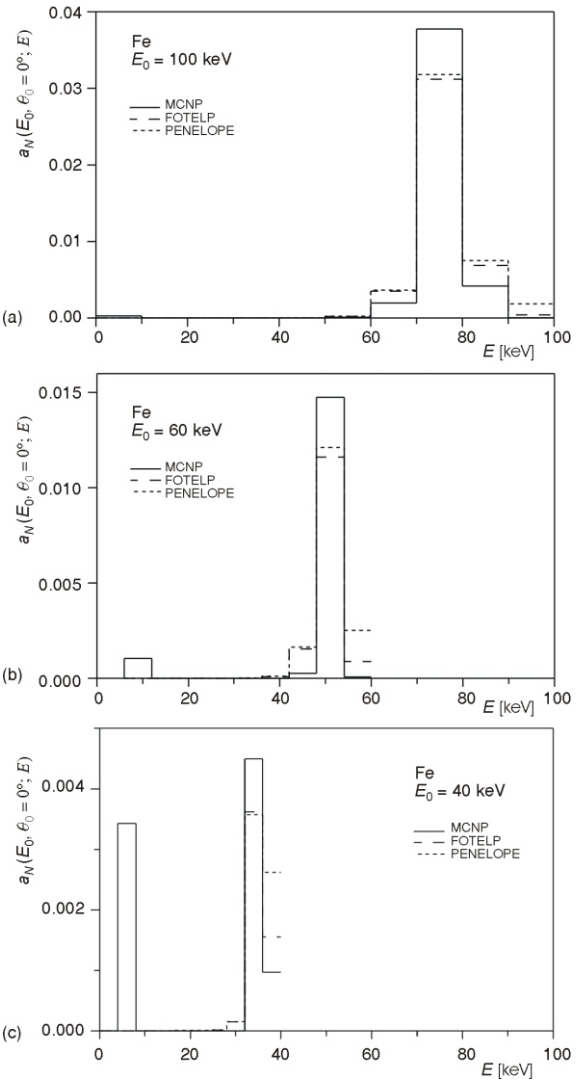

Figure 3. Spectral albedo of photons for iron and initial photon energy of (a) 100 keV, (b) 60 keV, and (c) 40 keV

photons. This indicates that there is a better agreement of the program results when the simulation process statistics is more reliable, thus making credible the values obtained by MCNP-4 program, which was used to simulate $3 \cdot 10^8$ photon histories, while in the other two programs the number of histories was three times smaller.

In the tables with the calculated values of spectral albedo given in the ref. 14 for aluminum and iron, one can see the reflected photon peaks in the low-energy part of the spectrum, which appear due to the absorption of photons by K electron, followed by the characteristic fluorescence photon emission. For aluminum, the peak is located in the energy range which includes the absorption K limit at 1.56 keV, and for iron in the energy range which includes the K absorption energy of 7.112 keV. For aluminum, the effect can be seen up to the initial photon energy of $E_0 = 30$ keV, and for iron up to the highest initial energy $E_0 = 100$ keV. The iron peak is more prominent than the aluminum peak because the fluorescent yield of iron ($\omega_K = 0.35$) is about nine times higher than the fluorescent yield of aluminum ($\omega_K = 0.04$) [22]. In fig. 3, which shows the spectral albedo of iron, the second peak can be detected in the distribution of low energies of the reflected photons. The peak is very prominent for the incident photon energy of $E_0 = 40$ keV, while it becomes barely observable for the energy of $E_0 = 100$ keV.

Comparison of MCNP-4C values with referent data

The values of spectral albedo calculated on the basis of photon reflection simulation using MCNP-4C program were compared to the data obtained by Bulatov and his collaborators [2] and by Berger and Raso [1]. The Bulatov's results were generated out of the original tables for double differential spectral albedo of the photon current by adding the tabular values for all the intervals of the solid angle; the results of Berger and Raso are given explicitly in their paper, but only for water and the incident photon energy of 100 keV. Thus, the result comparison is limited to only one material – water, and to only one initial photon energy of 100 keV.

Figure 4 presents the histograms of the spectral albedo with the exponential and linear scale at the ordinate. The differences in determining the energy distribution at the boundaries of the energy range can be observed better when the exponential scale is at the ordinate (fig. 4a), while the result discrepancies around the distribution peak can be seen more clearly with the linear scale (fig. 4b).

It can be noted that the results obtained using the MCNP-4C simulations are in excellent agreement with Berger and Raso's results. In both simulations, the same selection of collecting the reflected photons in the energy intervals of 10 keV width was performed, starting from the upper initial photon energy of 100 keV to the lower energy of 10 keV. Bulatov's results are also formed in ten energy intervals, with the lower energy of registered photons of 25 keV and the upper one of 81.2 keV, but with uneven group widths. The selection of these limits of the registered energies of reflected photons was conditioned by the limited total number of simulated photon histories and, as a consequence, by very reduced number of the reflected photons in the boundary energy ranges. Thus, Bulatov's results can be compared with the previous two results only to a certain extent; however, the satisfactory general agreement of the energy distribution was noted among the programs (fig. 4a).

For more precise result comparison, the numerical values of photon spectral albedo calculated on the basis of the simulations performed by MCNP-4C program and the published values of Berger and Raso are compared in tab. 5. Very good agreement of the results in a wide en-

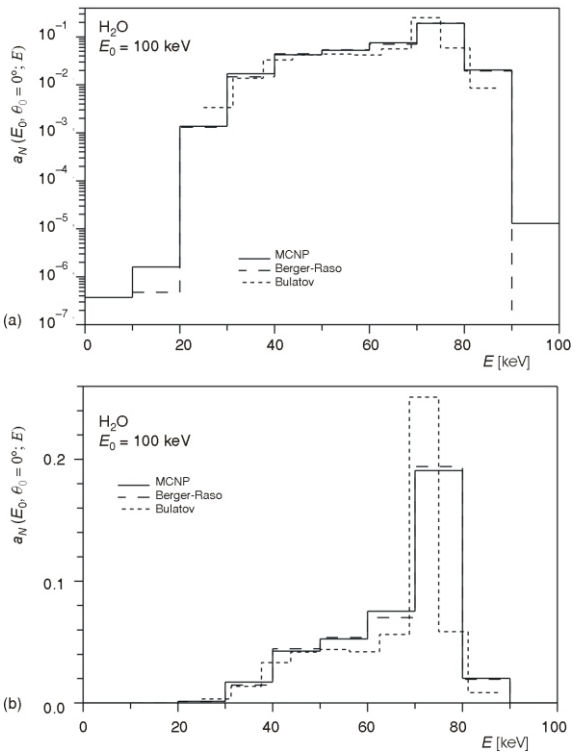

Figure 4. Comparison of values of spectral albedo for water and initial photon energy of 100 keV in (a) exponential and (b) linear scale

Table 5. Comparison of values of photon spectral albedo for water and initial energy of E_0 = 100 keV

Reflected photon energy [keV]	MCNP-4C code (from ref. [14])	Berger and Raso (ref. [1])
0-10	3.67-7*	–
10-20	1.61-6	4.77-7
20-30	1.36-3	1.31-3
30-40	1.72-2	1.47-2
40-50	4.26-2	4.46-2
50-60	5.26-2	5.36-2
60-70	7.54-2	7.00-2
70-80	1.91-1	1.94-1
80-90	2.03-2	1.95-1
90-100	1.30-5	0.0

*The designation 3.67-7 presents the value of $3.67 \cdot 10^{-7}$

ergy range of the reflected photons (20 keV up to 90 keV) is confirmed, for which the spectral albedo has the values of several hundredths up to several thousandths.

CONCLUSION

The comparison of the values of photon spectral albedo (figs. 1-3) shows a very good mutual agreement of the results of FOTELP-2K3 and PENELOPE-2005 programs for all three materials, with the exception of the low energy of initial photons (E_0 = 40 keV) and one energy interval of the reflected photons just below the initial energy. At the same time, a certain discrepancy of the results of these two programs with the results of MCNP-4C code is observed, less prominent for water and more prominent for iron. On the other hand, the results of MCNP-4C code are in excellent agreement with the classic results of Berger and Raso and in quite satisfactory agreement with the results of Bulatov and his colaborators (bearing in mind that the Russian authors made a different selection of the energy intervals in which the reflected photons were collected – fig. 4). As the simulations with FOTELP-2K3 and PENELOPE-2005 programs were performed with the photon histories three times less in number than the photon histories simulated using MCNP-4C program, it appears that the discrepancies of the values of spectral albedo can be attributed to this fact in the first place, inasmuch as the agreement among the programs increases whenever the number of registered reflected photons in the angular-energy interval is higher, *i. e.*, when the simulation process is statistically more reliable.

The simulation of photon reflection from an iron target (fig. 3), performed by MCNP-4C program, points to the significant peak of the spectral distribution at the reflected photon energies below 10 keV. The same phenomenon is observed with water and aluminum, but in a very slight form which is registered only in the tabular presentations (in the ref. 14). It presents the contribution of the fluorescent photons to the exit spectrum which is the consequence of the photon absorption with K electron in the shielding material. The other two programs do not register this effect. As the fluorescent yield ω is directly dependent on the type of material, and the energy distribution of photons in the slowing down process determines the intensity of the low-energy photon absorption by K electrons, estimation of this effect is quantitatively connected also to the specific data libraries which are included into Monte Carlo programs, but with the precision of transport simulation and photon reflection as well.

After the comparison of the values of spectral albedos obtained by Monte Carlo reflection simulations, it can be concluded, from the point of view of MCNP-4C, FOTELP-2K3, and PENELOPE-2005 code users, that the complete agreement of the program input, especially the number of photon histories provided in sufficient quantities which guarantees the required data accuracy, is the necessary condition for satisfactory agreements of the results. However, in order to obtain the complete insight into the reliability of each Monte Carlo program, it is needed to include other albedo coefficients beside the spectral albedo, into the comparison.

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СПЕКТРАЛНИ АЛБЕДО ФОТОНА ИНИЦИЈАЛНИХ ЕНЕРГИЈА ИСПОД 100 keV

У раду су приказани резултати Монте Карло симулација рефлексије фотона од хомогених плоча заштитног материјала начињених од воде, алуминијума и гвожђа. Разматран је вертикалан упад моноенергетског снопа фотона иницијална енергија од 20 до 100 keV. Нумерички експерименти обављени су коришћењем верификованих Монте Карло програма MCNP-4C, FOTELP-2K3 и PENELOPE-2005. Као резултат добијене су вредности диференцног бројног албеда груписане у десет равномерних интервала по енергији и девет равномерних интервала по поларном углу излазних фотона. Из ових података израчунати су, графички приказани и анализирании спектрални албедо коефицијенти за сва три материјала и три иницијалне енергије фотона од 40 keV, 60 keV и 100 keV. Вредности спектралног албеда одређене на основу MCNP-4C кода упоређене су са резултатима раних симулација фотонске рефлексије совјетског и америчког порекла. Такође, програмом MCNP-4C регистрован је допринос флуоресцентних фотона спектру рефлектованог зрачења, који је у виду пика на енергији од 7.112 keV графички препознатљив само код заштитних плоча од гвожђа.

Кључне речи: рефлексија фотона, спектрални албедо фотона, Монте Карло метода, вода, алуминијум, гвожђе