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PHOTON ALBEDO FOR WATER, CONCRETE, AND IRON AT NORMAL INCIDENCE, AND DEPENDENCE ON THE THICKNESS OF REFLECTING MATERIAL

by

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Total number and angular albedo were calculated for commonly used shielding materials, water, concrete, and iron, for photons with initial energies from 10 keV up to 10 MeV and normal incident angle. Influence of material thickness on total number albedo was also investigated. Double differential albedo was determined from simulation of photon transport through materials by using PENELOPE and MCNP software. Backscattered photons were scored and grouped in equal intervals of energy and angle. Analytical expressions for angular and total number albedo as a function of initial energy were obtained. It was shown that angular albedo can be determined with the same formula for three examined materials. Corresponding analytical expressions for number albedo as a function of material thickness were presented in this paper.

Key words: albedo, radiation reflection, PENELOPE, MCNP

INTRODUCTION

Reflection of radiation is an important subject of investigation in radio-protection studies, because reflected radiation presents unknown secondary radiation source [1]. In reflected radiation significant number of photons can be found. In order to describe reflected radiation field, double differential albedo as a function of energy and angle was introduced [2]. This quantity enables determination of energy and angular distribution of reflected rays, and is defined as flow rate ratio of reflected and incident photons.

Photon reflection from shielding materials which are used in nuclear facilities must be determined because of the risk from irradiation. To take into account reflected radiation and prevent irradiation of surrounding, it is necessary to determinate energetic and angular distributions of reflected photons. Photon reflection is a complex process which is not restricted only to reflection from boundary surface of material. Entire process of photon penetration should be taken into account, starting from the entrance into a material up to the absorption, or leaving material system [2, 3]. Photons which are emitted backward, after entire transport process through some material, are considered as reflected radiation.

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The photon albedo is defined as the ratio of the flow rate of photons emitted from a unit area of the reflecting surface and the flow rate of primary photons incident upon that surface [2]. When photon with incident energy E_0 and direction $\vec{\Omega}(\theta_0, \varphi_0)$ enters boundary surface, it can be reflected by the target material with new energy E in direction $\vec{\Omega}(\theta, \varphi)$. θ and φ are polar and azimuth angles which define initial direction in respect to the perpendicular to the surface plane at the point where photons enter the surface (fig. 1).

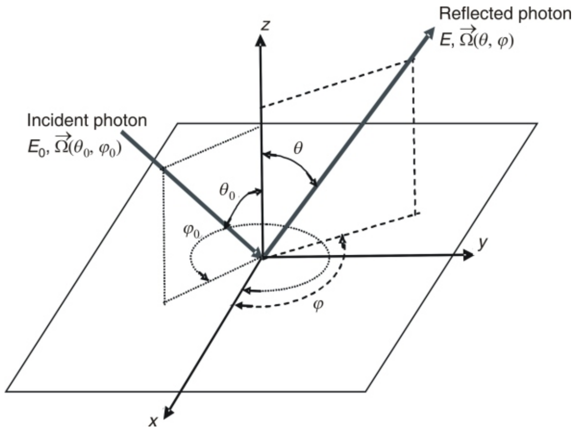

Figure 1. Geometry of photon reflection from boundary surface

The reflected photons flow rate, J, is defined as

$$J(E,\theta,\varphi) = J_0(E_0,\theta_0,\varphi_0)\,a(E_0,\theta_0,\varphi_0;E,\theta,\varphi) \quad (1)$$

where $J_0(E_0,\theta \ \ \varphi_0)$ is the flow rate of incident photons and $a(E_0, \theta_0, \varphi_0; E, \theta, \varphi)$ is double differential albedo over energy and angle. From eq. (1) double angular-energy differential number albedo is simply given as the ratio of photon flow rates [4]

$$a(E_0,\theta_0,\varphi_0;E,\theta,\varphi) = \frac{J(E,\theta,\varphi)}{J_0(E_0,\theta_0,\varphi_0)} \quad (2)$$

Double differential albedo defined in eq. (2) enables determination of angular, energy, and total albedo by corresponding integration.

Angular number albedo, $a(E_0,\theta_0,\varphi_0;\theta,\varphi)$, is defined as integral of $a(E_0, \theta_0, \varphi_0; E, \theta, \varphi)$ over all energies

$$a(E_0,\theta_0,\varphi_0;\theta,\varphi) = \int_0^{E_0} a(E_0,\theta_0,\varphi_0;E,\theta,\varphi)\,\mathrm{d}E \quad (3)$$

and presents ratio of flow rates of all photons with direction of emergence $\vec{\Omega}(\theta,\varphi)$ from boundary surface (fig. 1) to flow rates of incident photons.

For a photon with initial direction perpendicular to the reflecting surface (θ), double differential albedo, $a_n(E_0; E, \theta)$, does not depend on azimuth angle φ, it depends on incident and reflected photon energies, reflected polar angle θ and atomic number of target material [5]. In this case, the angle φ_0 does not influence on albedo and it is removed from notation. Double differential number albedo does not depend on φ and after integration over the angle φ, factor 2 will appear in eq

$$\int_0^{2\pi} a(E_0,\theta_0 = 0;E,\theta,\varphi)\,\mathrm{d}\varphi = 2\pi a_n(E_0;E,\theta) \quad (4)$$

Angular number albedo is obtained by integration of right side of eq. (4) over all energies as

$$a_n(E_0;\theta) = 2\pi \int_0^{E_0} a_n(E_0;E,\theta)\,\mathrm{d}E \quad (5)$$

Total number albedo, a_n is obtained as integration of $a_n(E_0; \theta)$ over all angles

$$a_n(E_0) = 2\pi \int_0^{\pi/2} a_n(E_0;\theta)\sin\theta\,\mathrm{d}\theta \quad (6)$$

In this paper, angular and total number albedo, defined by eqs. (5) and (6), have been calculated for water, concrete, and iron, for initial photon energies from 10 keV to 10 MeV. This work extends on authors previous studies on this subject in [6- 8]. These materials are the most commonly used for shielding in nuclear facilities and places where protection from radiation is needed. For this purpose PENELOPE code [9] and MCNP5/X software [10] were used to simulate photon propagation through materials. Simulated data were processed and analytical expressions for total and angular albedo were obtained using iterative method.

In literature, albedo is defined for reflecting material of infinitive thickness and this assumption was adopted in present work to determine total and angular number albedo. Real materials are not infinitely thick, but they can be treated like that, if the thickness is larger than the two mean free paths of initial photons. In the second part of the work, the influence of material thickness on albedo has also been investigated using PENELOPE code. Dependence of albedo on material thickness has been presented for three of the most often used materials in shielding.

The main purpose of this work is to calculate albedo values under perpendicular incidence for the above mentioned materials and to find approximate analytical formulae which describe the dependence on the reflected polar angle, initial energy and the thickness.

METHODOLOGY

PENELOPE code and MCNP software

The FORTRAN 77 subroutine package PENELOPE [9], which performs Monte Carlo simulation of electron-photon showers in arbitrary materials, is used to determine photon albedo. The scattering model in PENELOPE gives a reliable description of radiation transport in the energy range from about 1 keV (100 eV for electrons and positrons) up to several 100 MeV. PENELOPE generates random electron-photon showers in complex material structures consisting of any number of distinct homogeneous regions (bodies) with different compositions. This simulation package incorporates a scattering model that combines numerical total cross-sections (or stopping cross-sections) with simple analytical differential cross-sections for the different interaction mechanisms.

PENELOPE is structured in such way that only one particle is simulated at the time. Generated photon is transported through material until it is absorbed, or reflected from the boundary surface. In interactions of the primary photon with a material, secondary particles can be produced and their characteristics are stored for later simulation after the simulation of primary photon was completed.

Since PENELOPE is subroutine package, main steering program must be developed by user which controls transport of particles, score relevant quantities and stores characteristics of secondary particles for latter simulation. In this paper the main program was developed for transporting particles through water, concrete, and iron. Cross-sections and relevant data about these materials were taken from PENELOPE material database, which is included in the code [9].

PENELOPE code was used for determination of the energy of photons reflected from material and for determination of polar angle of reflecting photons. Simulations were performed for histories of primary photons to ensure low statistical uncertainty. Initial photons, with energy E_0, were sampled from the source placed on the reflecting surface. The direction of initial photons is perpendicular to the surface ($\theta_0 = 0$). Sampled photon was "transported" through material by PENELOPE code and all backscattered photons and their quantities were scored. The angles and energies of reflecting photons were stored in data files.

MCNP5/X software [10] is Monte Carlo program developed in Los Alamos laboratories in order to simulate the neutron transport and calculate the critical nuclear mass. Today it is wide used by physicists in various fields such as medical physics and radiation protection, nuclear physics, particle physics and other. MCNP is a general-purpose, continuous energy, generalized-geometry, time-dependent, coupled neutron, photon or electron Monte Carlo transport code. The user creates an input file that is subsequently read by MCNP. This file contains information about the problem such as: (1) the geometry specification, (2) the description of materials and selection of cross-section evaluations, (3) the location and characteristics of the source, (4) the type of answers or tallies desired, and (5) any variance reduction techniques used to improve the efficiency. The MCNP treats an arbitrary three-dimensional geometry of user-defined material cells bounded by the first and the second-degree surfaces and the fourth-degree elliptical tori [10]. The cells are defined by the intersections, unions, and complements of the regions bounded by the surfaces. Surfaces are defined by supplying coefficients to the analytic surface equations or, for certain types of surfaces, known points on the surfaces. The MCNP performs extensive internal checking to find input errors in the geometry. The tally cards are used to specify what type of information the user wants to obtain from the Monte Carlo calculation. That could be, for example, a current of particles across a surface, flux of particles at the point, energy deposited averaged over a cell, *etc*. All MCNP tallies are normalized per starting particle history and are printed in output with an estimated relative error of the tally corresponding to one standard deviation. In this work MCNP option-Tally F1:P which determines the surface photon current – the number of photons crossing the boundary surface, was used to determine photon albedo for 10^9 photon histories of normal incidence initial photons with starting energy E_0. The statistical uncertainty was less than 1% of the calculated value and the computer calculation time was about 100 minutes on the PC AMD Pentium II X4 3 GHz and 4 GB of the RAM memory.

Determination of double differential number albedo

The albedo defined in eq. (2) presents the ratio of the number of reflected photons to the number of initial photons. By scoring reflected photons with given angles, θ_i and energies, E_j, the double number albedo can be defined as

$$a_n(E_0;\, E_j, \theta_i) \quad \frac{1}{2\pi \sin\theta_i \Delta\theta \Delta E} \frac{N_{ij}}{N_{\mathrm{tot}}} \tag{7}$$

where $\Delta\theta$ and ΔE are polar and energetic segments; N_{ij} is the number of photons which are reflected from the boundary surface with energy ranging from E_j to $E_j + \Delta E$ and angle within θ_i and $\theta_i + \Delta\theta$; N_{tot} is the number of incident photons.

Total number albedo, $a_n(E_0)$, can be obtained by summing over all energies and angles of reflected photons

$$a_n(E_0) \quad 2\pi \sum_{i,j} a_n(E_0;\, E_j, \theta_i) \sin\theta_i \Delta\theta \Delta E \quad \frac{N_{\mathrm{ref}}}{N_{\mathrm{tot}}} \tag{8}$$

where N_{ref} is the total number of photons reflected from the boundary surface.

Angular number albedo can be determined by summation of double differential albedo number, $a_n(E_0;\, E_j, \theta_i)$, over all energy intervals

$$a_n(E_0;\, \theta_i) \quad 2\pi \sum_j a_n(E_0; E_j, \theta_i) \Delta E \tag{9}$$

From eqs. (7) and (9) angular albedo can be defined as ratio

$$a_n(E_0;\, \theta_i) \quad \frac{1}{\sin\theta_i \Delta\theta} \frac{N_i}{N_{\mathrm{tot}}} \tag{10}$$

where N_i is the number of reflected photons grouped in angle interval (θ_i, $\theta_i + \Delta\theta$).

Using eqs. (7) (8), and (10) double differential, total and angular number albedo can be obtained in a simple way from simulation by scoring relevant quantities and summation.

RESULTS AND DISCUSSION

Total number albedo

Total number albedo, $a_n(E_0)$, which is obtained using eq. (8) is presented in fig. 2 for water, concrete, and iron, as a function of initial photon energy. Total number albedo of used materials rises monotonically with increasing energy of the initial photon, until it reaches the maximum value. After the maximum, albedo monotonically decreases. $a_n(E_0)$ for all examined materials have maximum for certain initial energies which are about 160 keV, 250 keV, and 500 keV, for water, concrete, and iron, respectively.

Water has the smallest effective atomic number among the examined materials, but also has the largest total number albedo, $a_n(E_0)$. With increasing of atomic number of materials albedo decreases, and iron has the smallest total number albedo.

The results obtained here were compared with available data in fig. 2, [11, 12]. In [11] photon reflection was calculated with FOTELP [13] simulation software for energies up to 100 keV. It could be seen

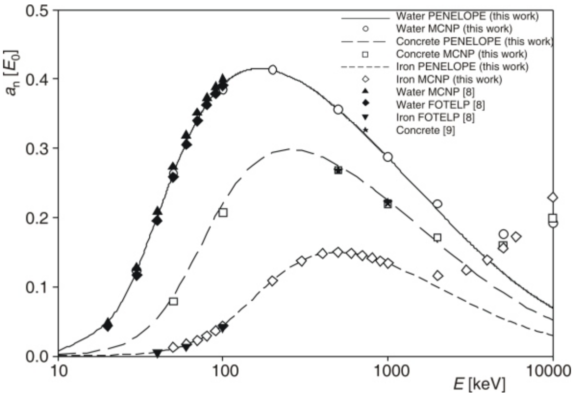

Figure 2. Total number albedo for water, concrete, and iron compared with available reference data

that there is a good agreement between results obtained here and the literature data for low energy photons. Albedo value calculated using PENELOPE code is between values calculated using MCNP and FOTELP [13]. MCNP gives a little bit larger values, while albedo calculated by FOTELP are smaller, which can be seen in fig. 2.

For photon energies greater than 1 MeV there is a big discrepancy between results obtained with PENELOPE and MCNP software. Albedo calculated with MCNP is rising with increasing initial photon energy from 1 MeV up to 10 MeV. This has no physical explanation since interaction cross-sections are decreasing with increasing energy. MCNP have recourse to multiple scattering theories which allow the simulation of the global effect of a large number of events in a track segment of a given length (step). These simulation procedures are referred to "condensed" Monte Carlo methods. The multiple scattering theories implemented in condensed simulation algorithms are only approximate and may lead to systematic errors [14]. This can be particularly expressed for low and especially high energy photons, where multiple scattering should be switched off and instead, track by track simulation procedure should be used, which will, on the other hand, unacceptably increase the computation time.

Curves in fig. 2 obtained with PENELOPE software were fitted, using iteration method of changing initial constants of probe function in order to get approximate analytical expressions. For that purpose SIGMAPLOT [15] software was used. Curves in fig. 2 can be presented by following equation with logarithmic x-scale

$$a_n(E_0) = \ln^6(aE_0)\exp[b - c\ln(E_0)] \quad (11)$$

The fitting constants are presented in tab. 1. Using eq. (11) total albedo can be analytically calculated for water, concrete and iron in the range of initial photon energies from 10 kev to 10 MeV.

Table 1. Total number albedo fitting constants from eq. (11)

Material	*a*	*b*	*c*
Water	0.625	16.88	0.116
Concrete	0.443	16.73	0.143
Iron	0.298	15.85	0.179

Total energy albedo

Total energy albedo is defined as ratio of photon energy emitted from the surface and total energy of incident particles on that surface. In other words, total energy albedo presents fraction of initial photon energy reflected from the surface. This ratio can be simply determined from simulation as

$$a_E(E_0) = \frac{\sum_i E_i}{N_{tot} E_0} \quad (12)$$

where $a_E(E_0)$ is the total energy albedo, N_{tot} – the total number of primary photons with energy E_0, and E_i – the energy of i-th photon backscattered from the boundary surface.

$a_E(E_0)$ calculated using eq. (12), are presented in fig. 3. Total energy albedo for examined materials behaves similarly as total number albedo, however with lower numerical values. This is quite expectable, because most of the particles reflected backward suffered one or more collisions in which they lost energy. Photons with larger initial energy have smaller energy albedo than those with lower initial energy. They are losing greater amount of energy as they are passing deeper in a material. Maximums of total energy albedo are little shifted to the lower energies in respect to the total number albedo. It could be seen that 25% of photon energy is reflected from water if energy of initial photons was about 90 keV. On the other side, larger part of photon energy is absorbed if the medium was concrete or iron.

Again discrepancies between PENELOPE and MCNP results for high energy photons are explained

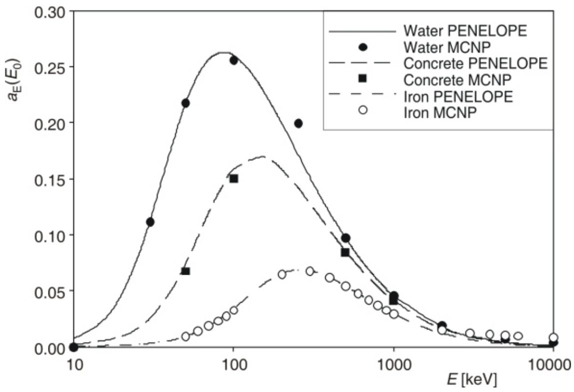

Figure 3. Total energy albedo for water, concrete, and iron

as for the discrepancies in total number albedo. Total and energy albedo were obtained from same simulations where for total albedo number of the reflected particles were scored and for energy albedo reflected particle energy was scored.

Angular number albedo

To determine angular distribution or angular number albedo from eq. (10), reflected photons were grouped into equal intervals of polar angle $\Delta\theta$. Angular albedo is presented in figs. 4, 5, and 6, for water, concrete, and iron respectively, for initial photon energy as a parameter.

From figs. 4, 5, and 6 it could be seen that angular albedo decreases with scattering angle θ. Dependence of angular albedo on the initial photon energy is similar to the dependence of the number albedo on initial energy. As the initial energy of photons increases angular albedo also increases up to its maximum. With further increasing of energy angular number albedo is decreasing. For example, curves for water for energies of 500 keV, 1 MeV, 5 MeV, and 10 MeV are below the curve for 160 keV, which presets maximum. Maximums of angular number albedo for concrete and iron are about 250 keV and 500 keV, respectively, as it can be seen in figs. 4, 5, and 6. For all materials investigated in this work total number albedo achieves maximum at the same initial photon energies as angular albedo, which is expected.

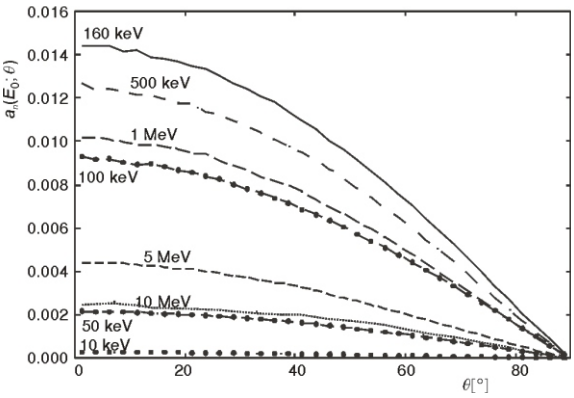

Figure 4. Angular number albedo for water determined using PENELOPE software, for some initial energies of incident photons, in the range from 10 keV to 10 MeV

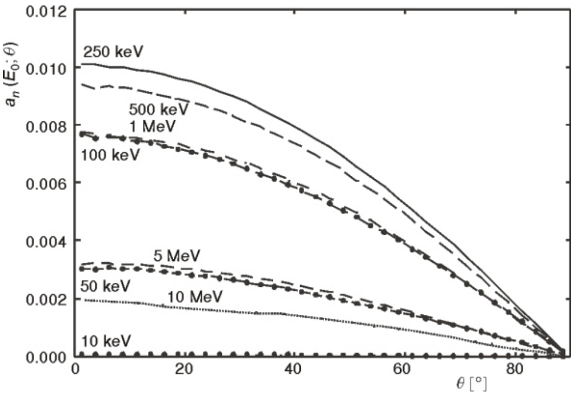

Figure 5. Angular number albedo for concrete determined using PENELOPE software, for some initial energies of incident photons, in the range from 10 keV to 10 MeV

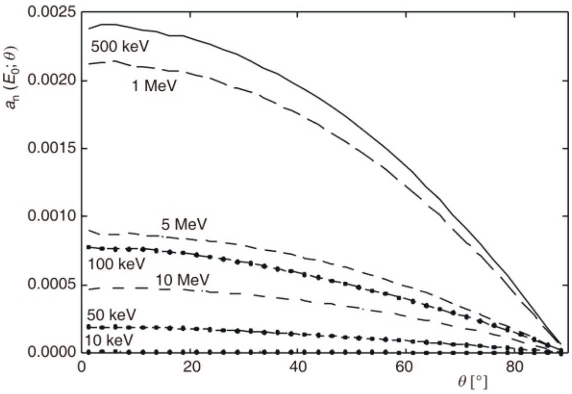

Figure 6. Angular number albedo for iron determined using PENELOPE software for some initial energies of incident photons in the range from 10 keV to 10 MeV

Several transformations were performed in order to determine probability function of photon reflection in angle between θ_i and $\theta_i + \Delta\theta$. Using eqs. (8) and (10), angular distribution can be normalized over all reflected photons

$$\frac{a_n(E_0;\theta_i)}{a_n(E_0)} \quad \frac{1}{\sin\theta_i\Delta\theta}\frac{N_i}{N_{\text{ref}}} \tag{13}$$

where N_i is the number of reflected photons in angle interval θ_i , $\theta_i + \Delta\theta$, and N_{ref} – the total number of reflected photons, as defined above.

Rearranging eq. (13), the following expression can be obtained

$$a_n(E_0;\theta_i) \quad a_n(E_0)\frac{\phi(\theta_i)}{\sin\theta_i} \tag{14}$$

where

$$\phi(\theta_i)\Delta\theta \quad \frac{N_i}{N_{\text{ref}}} \tag{15}$$

is the probability for a photon to be reflected into angle interval θ_i, $\theta_i + \Delta\theta$. New introduced function $\phi(\theta_i)$, probability density, is presented in the fig. 7 for three materials and initial photon energy as a parameter.

From fig. 7, the following conclusions can be derived:

(a) function $\phi(\theta_i)$ does not depend on material and initial photon energy, and
(b) the most probable reflecting angle is 45° for all materials and energies.

The fact in (a) can be accepted as a quite good approximation because of the following: discrepancies in values of functions $\phi(\theta_i)$ for different initial

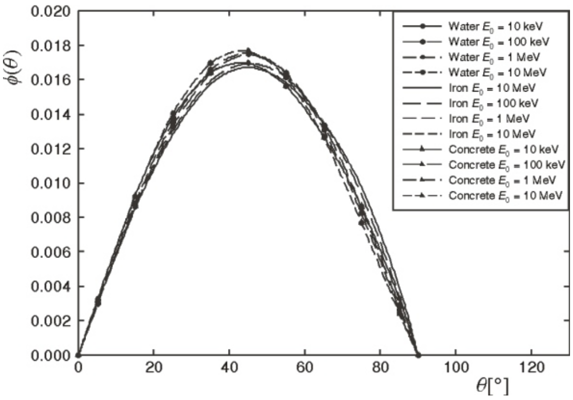

Figure 7. Probability density, $\phi(\theta)$, for water, concrete and iron, for initial photon energies from 10 keV to 10 MeV

photon energies and materials are less than 6%. The curve for water and 100 keV of initial photon energy is in the middle of all curves presented in fig. 7. The discrepancy of other curves from this middle curve is less than 3%, which can be considered quite acceptable, and all curves could be represented with the same function.

Function $\phi(\theta)$ can be presented by polynomial of the second order [16] over θ as

$$\phi(\theta) \quad \sum_{i\ 0}^{2} a_i \theta^i \tag{16}$$

where azimuth variable θ is the measured in radians and a_i are coefficients. The constants in eq. (16) were obtained by fitting of curve $\phi(\theta)$ for water with 100 keV initial photon energy, using software SIGMA PLOT [15]. Values of these coefficients are $a_0 = -0.065$, $a_1 = 2.66$, and $a_2 = -1.7$. From eqs. (14 and 16) angular albedo is expressed as

$$a_n(E_0;\, \theta) \quad a_n(E_0) \frac{0.065 \quad 2.66\theta \quad 1.7\theta^2}{\sin\theta} \tag{17}$$

In this way angular number albedo is represented as a product of two factors. The first one, $a_n(E_0)$, is total number albedo which depends on initial photon energy. Second term depends on scattering angle, θ.

Dependence of total number albedo on thickness of the material

The total number albedo, as a function of initial energy, and angular albedo as a function of energy and reflecting angle, were examined above from simulation in which infinite thickness of the material was considered. Real materials can be treated as infinitively thick if thickness of the material is larger than two mean free paths of photons with initial energy E_0 [2]. Results derived above can be used in calculations if the material satisfies this condition. Otherwise, when the material has smaller thickness, the effects of final dimensions must be taken into account. In the following, dependence of total number albedo on material thickness was investigated in simulations with PENELOPE code.

If material with thickness d is irradiated with N_{tot} photons with initial energy E_0, and the number of all backscattered photons is N_d, then total number albedo can be calculated as

$$a_n(E_0; d) \quad \frac{N_d}{N_{tot}} \tag{18}$$

The albedo defined in this way was determined for water, iron, and concrete for various thicknesses of material. Obtained results for water are presented in figs. 8, 9, and 10 for different photon initial energies as a parameter. Values of two mean free paths are marked with black points on curves in figs. 8, 9, and 10, and they present minimal thickness which is needed to consider material as infinitely thick. With increasing the thickness, total number albedo also increases and at around these points comes to saturation. With further increasing of thickness, total number albedo remains constant. If the thickness is larger than saturation one, the assumption of infinite thick material is correct and results derived above can be applied.

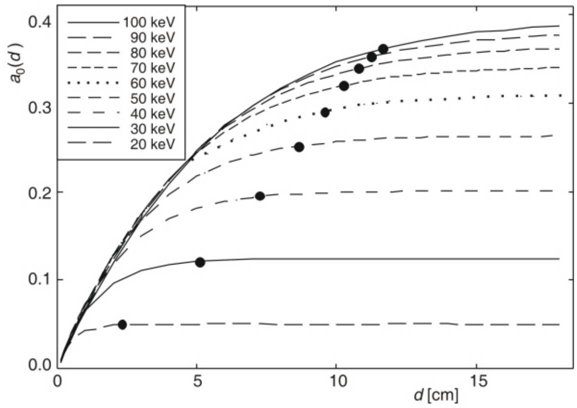

Figure 8. Dependence of total number albedo on thickness of water for initial photon energies from 20 keV to 100 keV

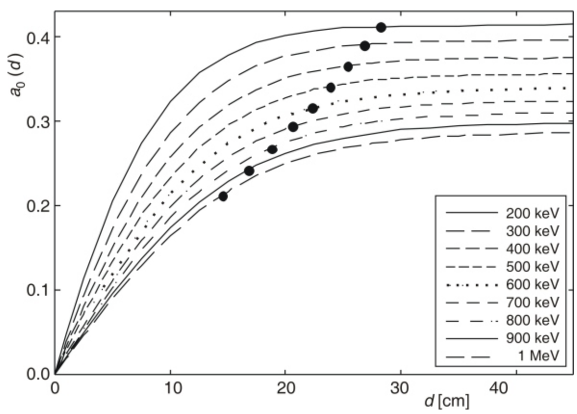

Figure 9. Dependence of total number albedo on thickness of water for initial photon energies from 200 keV to 1 MeV

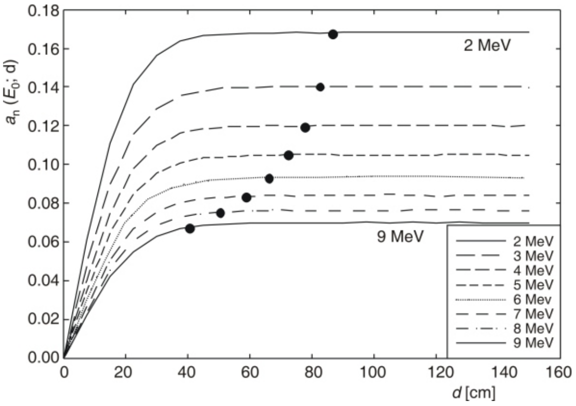

Figure 10. Dependence of total number albedo on thickness of water for initial photon energies from 2 MeV to 9 MeV

The total number albedo as a function of thickness d for concrete and iron is presented in figs. 11 and 12 for several initial energies. Shapes of curves for total number albedo are similar to those presented in figs. 8-10 and everything written for water is applied to concrete and iron. Due to the same behavior, only several curves in figs. 11 and 12 are presented.

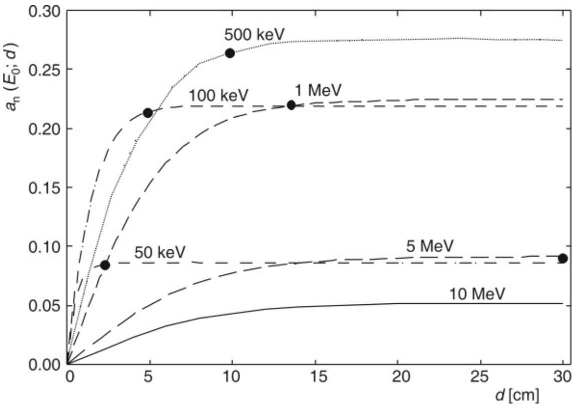

Figure 11. Dependence of total number albedo on thickness of concrete for initial photon energies from 50 keV to 10 MeV

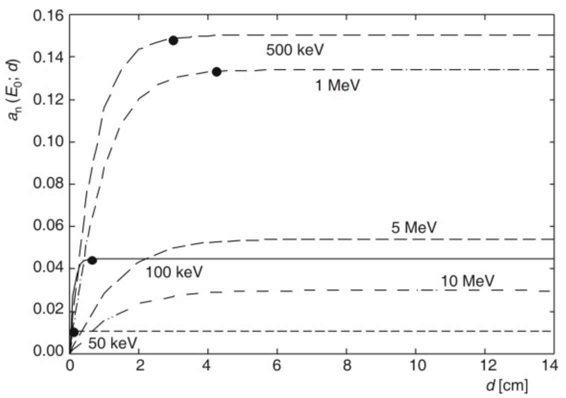

Figure 12. Dependence of total number albedo on thickness of iron for initial photon energies from 50 keV to 10 MeV

All curves in figs. 8-12 are increasing to maximum, and can be presented with following function

$$a_n(E_0; d) = a_n(E_0)(1 - e^{-\mu(E_0)d}) \qquad (19)$$

where, $\mu(E_0)$ is the new introduced function which depends on initial photon energy E_0. $a_n(E_0)$ is the total number albedo for material with infinite thickness, determined in eq. (11).

By fitting curves in figs. 8-12 with eq. (19), $\mu(E_0)$ was obtained for a large number of initial photon energies. Function $\mu(E_0)$ for three materials has the same shape, with different constants a and b

$$\mu(E_0) = \frac{1}{a + b \ln E_0} \qquad (20)$$

Constants a and b are numerically determined using SIGMA PLOT [15], and presented in tab. 2.

The eqs. (19) and (20) with data given in tab. 2, can be used to calculate total number albedo with reflecting material of final thickness, d.

Table 2. Constants for determining function $\mu(E_0)$, eq. (20)

Material	a	b
Water	–9.50	3.18
Concrete	–4.72	1.34
Iron	–0.55	0.15

CONCLUSIONS

In this work, total number energy albedo and angular photon albedo were determined in wide range of energies for three shielding materials using reliable simulation software PENELOPE and MCNP. Good mutual agreement was found comparing results obtained by using this Monte Carlo software's, as well as in good agreement with the reference data. There is a discrepancy of the results for high energy photons above 2 MeV. This disagreement was explained earlier in the text and it is the consequence of the methods used in MCNP calculations – multiple scattering. Other authors already compared software's PENELOPE, MCNP and FOTELP and also found good mutual agreement between results for low energy photons [17, 18].

The analytical expressions for total and angular number albedo were obtained and presented in eqs. (11) and (17). It was shown that angular albedo can be presented as a product of two factors with separated variables, eq. (17). I addition, the influence of material thickness on total number albedo was investigated. It was shown that material thickness influences significantly on total number albedo if the thickness is smaller than required to be treated as infinite. Analytical expressions for number albedo as a function of material thickness and initial energy are presented in eqs. (19) and (20).

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AUTHOR CONTRIBUTION

Theoretical analysis was carried out by V. M. Marković, D. Krstić and N. Stevanović. Literature research was carried out by D. R. Nikezić and V. M. Marković. Calculations were performed by V. M. Marković and D. Krstić. Figures were prepared by N. Stevanović and V. M. Marković. All authors discussed the result and participated in the writing of the manuscript.

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УКУПНИ БРОЈНИ И УГЛОВНИ АЛБЕДО ФОТОНА ЗА ВОДУ, БЕТОН И ГВОЖЂЕ ПОД НОРМАЛНИМ УПАДНИМ УГЛОМ И ЗАВИСНОСТ АЛБЕДА ОД ДЕБЉИНЕ РЕФЛЕКТУЈУЋЕГ МАТЕРИЈАЛА

Укупни бројни и угловни албедо су одређени за материјале који се често користе у заштити од зрачења: воду, бетон и гвожђе. Албедо је одређен за фотоне почетних енергија од 10 keV do 10 MeV-а при нормалном упадном углу. Двојни диференцијални албедо се одређује на основу резултата из симулације транспорта фотона кроз материјале помоћу PENELOPE и MCNP софтвера. Фотони који се рефлектују назад броје се и групишу у једнаке интервале енергија и углова. На основу тих резултата, испитан је утицај дебљине материјала на укупни бројни албедо и показано је да не постоји утицај, уколико је дебљина материјала већа од две средње слободне путање фотона. Одговарајући аналитички изрази за бројни албедо као функција дебљине материјала су одређени у овоме раду. Анализом резултата програма, показано је да се угловни албедо за три испитана материјала може одредити помоћу исте формуле.

Кључне речи: албедо, рефлексија зрачења, PENELOPE, MCNP