

NUMBER ALBEDO OF LOW-ENERGY PHOTONS FOR WATER, ALUMINUM, AND IRON

by

**Vladan LJUBENOV, Rodoljub SIMOVIĆ,
Srpk MARKOVIĆ, and Radovan D. ILIĆ**

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Number albedo of water, aluminum, and iron for incident photons in the energy range from 20 keV to 100 keV is presented in this paper. The results are obtained through Monte Carlo simulations of photon reflection by using MCNP-4C, FOTELP-2K3, and PENELOPE-2005 computer codes. The calculated values are compared with the classical data published by B. P. Bulatov and his collaborators. The influence of fluorescence yield to the photon number albedo of an iron target at the initial photon energies below 40 keV is detected and analyzed.

Key words: photon reflection, number albedo of photons, Monte Carlo simulation, water, aluminum, iron

INTRODUCTION

In studying radiation reflection from larger objects (such as walls, floors, *etc.*), the concept of radiation albedo originating in astrophysics is used [1]. In this case, reflection is not strictly defined as the reflection from a surface (surface backscattering), but as a complete process of radiation penetration into a target material, its scattering and absorption in the object, and finally, irradiation of a part of radiation from the boundary surface of the material, with the decreased energy and from a point on the surface dislocated regarding the point of the primary beam incidence. This concept includes several basic and quite acceptable simplifications of the physical problem, thus enabling spatial, energy, and angular distribution of reflected radiation to be determined in a simpler way than required originally by the totality of the transport task [2-4]. First, it is possible to consider the points of radiation incidence and of radiation reflection to be identical, which is quite correct for all reflecting surfaces of the dimensions bigger

than several mean free paths of the incident radiation being approximately of the constant intensity in the lateral direction. Then, regarding its lateral dimensions, a reflector is considered to be an infinite plate of infinite thickness. Thus, the problem of reflection is reduced to a model of radiation transport in a half-space, mathematically easier to solve, which is correct for all shields thicker than two mean free paths and for homogenous materials. Finally, the scattering in the air from a source to a boundary surface of a reflector, as well as from the surface to the detector position, is neglected. On the basis of these assumptions, it is possible to simplify the transport task and obtain, using numerical and semi-analytical methods, relevant reflection coefficients of the radiation shield [5-7].

The calculation of reflection by Monte Carlo method, *i. e.* by numerical simulation of reflection process, does not mean that the above mentioned simplifications are obligatory, but at least a part of them is used for simpler modeling of physical processes and for optimization of computer time needed for achieving the satisfactory accuracy of the obtained results [8-11]. Numerical simulation of the reflection problem enables solving more complicated tasks with the pronounced material inhomogeneity in two-dimensional or three-dimensional geometry, but it sets high demands regarding computer performances, values of the central processor unit time needed for simulations, and professional training of program users. Therefore, there is still a need for easily applicable semi-analytical formulae for determining reflection coefficients

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Authors' address:

VINČA Institute of Nuclear Sciences
P. O. Box 522, 11001 Belgrade, Serbia

E-mail address of corresponding author:

vladan@vin.bg.ac.yu (V. Ljubenov)

based on detailed angular-energy distributions of reflected photons obtained by Monte Carlo simulations of tasks simple in geometry and material. Calculation of the radiation reflection in the range of low initial photon energies, characteristic for medical application of radiation, has been performed by semi-analytical methods and Monte Carlo simulations, regarding dosimetric aspect, as a long-term study in the VINČA Institute of Nuclear Sciences [12-16].

In this paper the results for number albedo calculated by Monte Carlo simulations of photon reflection from homogeneous slab of the shielding materials for the incident photon energies from 20 keV to 100 keV are presented. Water, aluminum, and iron targets are treated. MCNP-4C [9], FOTELP-2K3 [10], and PENELOPE-2005 [11] computer codes have been used for the simulation of photon interactions. The obtained results have been compared mutually and with the referent data of B. P. Bulatov and collaborators [17]. The contribution of fluorescence photons to the total number albedo has been taken into account, which is significant for the iron shielding slab.

NUMBER ALBEDO – ANGULAR DISTRIBUTION OF REFLECTED PHOTONS

The photon albedo coefficient is defined on the assumption that a broad beam of parallel and monoenergetic photons, described by energy E_0 and polar angle θ_0 , reaches the boundary surface of the plane target, and that the reflected photons come out from the surface with different energies E , and different directions defined by the polar angles θ and the azimuthal angles φ [14, 17]. The incident polar angle θ_0 is measured with respect to the surface inward normal, while the exit polar angle θ is determined with respect to the outward normal. As for the value of the photon albedo, there is equivalence between the two similar monoenergetic reflection problems: one induced by a broad parallel beam of the initial photons and the other produced by the monodirectional narrow beam.

The double differential number albedo coefficient is defined as a ratio between photon number flow rates [17]

$$a(E_0, \theta_0; E, \theta, \varphi) = \frac{J_1(E, \theta, \varphi)}{J_0(E_0, \theta_0)} \quad (1)$$

where J_0 and J_1 stand for the incident and outgoing flow rates of photons.

This coefficient is obtained by numerical simulations of the photon reflection. In fact, the Monte Carlo simulations give the values for difference number albedo $a_N^{ji}(E_0, \theta_0)$ which is a double integral of the previous coefficient

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

Indexes j and i in eq. (2) are related to the energy and angular intervals in which reflected photons are collected.

Based on computed values of $a_N^{ji}(E_0, \theta_0)$ and the definition of the number albedo [17]

$$a_N(E_0, \theta_0; \theta, \varphi) = \int_0^{E_0} a(E_0, \theta_0; E, \theta, \varphi) dE \quad (3)$$

which represents the probability for photon reflection inside the solid angle $d\Omega = 2\pi \sin \theta d\theta$, one can find

$$a_N(E_0, \theta_0; \theta) = a_N(E_0, \theta_0; \bar{\theta}_i) \frac{a_N^{ji}(E_0, \theta_0)}{\sin \bar{\theta}_i} \quad (4)$$

Variable φ in the arguments of quantities in eq. (4) is omitted as only a perpendicular beam of incident photons is considered when isotropy of albedo coefficients is present along the azimuthal angle. The sign $\bar{\theta}_i$ denotes the value of the polar angle at the middle of i -th interval, while $\sin \bar{\theta}_i$ appears in the denominator of the right side term of eq. (4) due to conversion of the distribution function – from polar angle distribution to distribution over cosine of the polar angle.

RESULTS AND DISCUSSION

Values for the number albedo of photon current calculated from the Monte Carlo simulations of photon reflection from water, aluminum, and iron are presented in this paper. The initial photon energies were chosen in the range from 20 keV to 100 keV. Reflected photons were collected in ten energy intervals of equal width of $E_0/10$ and nine equal intervals of the polar angle of width of 10° . Detailed information about Monte Carlo simulations performed by MCNP-4C, FOTELP-2K3, and PENELOPE-2005 codes are given in previous papers [18, 19].

Figure 1 shows the values of number albedo $a_N(E_0, \theta_0 = 0; \theta)$ calculated from the simulations performed by MCNP code. Number albedo coefficients for water and aluminum rise monotonically with the increase of the initial photon energy E_0 from 20 keV to 100 keV. This rise is about ten times for water and thirty times for aluminum. For the iron target there is a characteristic inversion in changes of number albedo values for low energies of the incident photons: with rise of the initial energy E_0 from 20 keV to 40 keV, number albedo decreases more than twice. Further growth of the initial energy from 40 keV to 100 keV causes the constant rise of number albedo for the iron target. The explanation of this phenomenon is in photon absorption by K shell electron of an iron atom which occurs at the photon en-

ergy of 7.112 keV and is followed by the emission of characteristic fluorescent radiation of the almost same energy [20]. The contribution of the fluorescent radiation to the total albedo is particularly significant for low initial photon energies bellow 40 keV. For initial energies above 40 keV this contribution is insignificant because only small fraction of the primary photon beam will reach the energy of 7.112 keV through the slowing-down, diffusion and absorption processes in the target material, *i. e.*, there is a small number of emitted fluorescent photons. Figure 1 also shows that photon reflection is higher for light materials, *i. e.*, photon absorption is lower in such materials. Rough estimation can be done that for initial photon energies of 100 keV number albedo for water is almost twice higher than albedo for aluminum. For lower initial photon energies this ratio rises up to the value of seven. Comparing the number albedo for water and iron targets, ratio of 20 is found at the initial photon energy of 50 keV and it decreases to the value of 10 for the initial photon energy of 100 keV. Due to the fluorescence effect at low photon energies, this tendency has significant irregularities for the iron target.

The photon number albedo values calculated from the simulation results obtained by MCNP-4C, FOTELP-2K3, and PENELOPE-2005 codes are presented graphically in fig. 2. Comparisons are shown for water and aluminum at the initial photon energies of 40 keV and 100 keV while the iron initial energy of 40 keV is replaced with the energy of 60 keV in order to enable better graphical presentation (the values are very low for the energy of 40 keV). It is obvious that in the wide energy range MCNP-4C and FOTELP-2K3 results are in very good agreement for water and aluminum (maximal relative discrepancy is bellow 5%), while the agreement of the results for iron is satisfactory (maximal relative discrepancy is up to 10%). Regarding the polar angle θ , the agreement is better for the photons reflected in the direction close to the boundary surface, *i. e.*, for the polar angle of $\theta = 0^\circ$. However, the discrepancies of the results obtained by PENELOPE-2005 code from two other data sets (MCNP-4C and FOTELP-2K3) are higher and there is an evident tendency to flatten the angular distribution of reflected photons. For example, discrepancy between the PENELOPE-2005 and MCNP-4C results for water is about 30% for the polar angle of $\theta = 0^\circ$, while the PENELOPE-2005 results are three times higher than the MCNP-4C results for the angle of $\theta = 85^\circ$. It is important to stress that these discrepancies between the results obtained by different codes for high values of the polar angle do not affect significantly the estimation of photon reflection because the number of photons reflected in this angular range (around $\theta = 85^\circ$) is ten times lower than the number of photons reflected near $\theta = 0^\circ$. In the more significant range of low angles the agree-

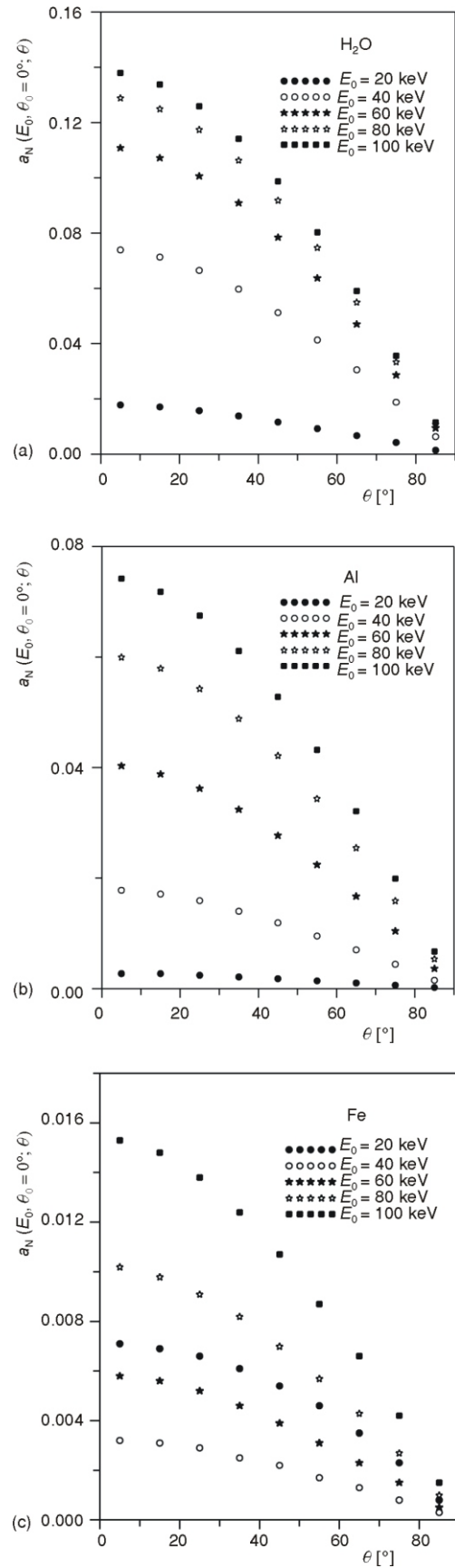


Figure 1. Number albedo – angular distribution of reflected photons for (a) water, (b) aluminum, and (c) iron. Calculation based on numerical simulations performed by MCNP-4C code

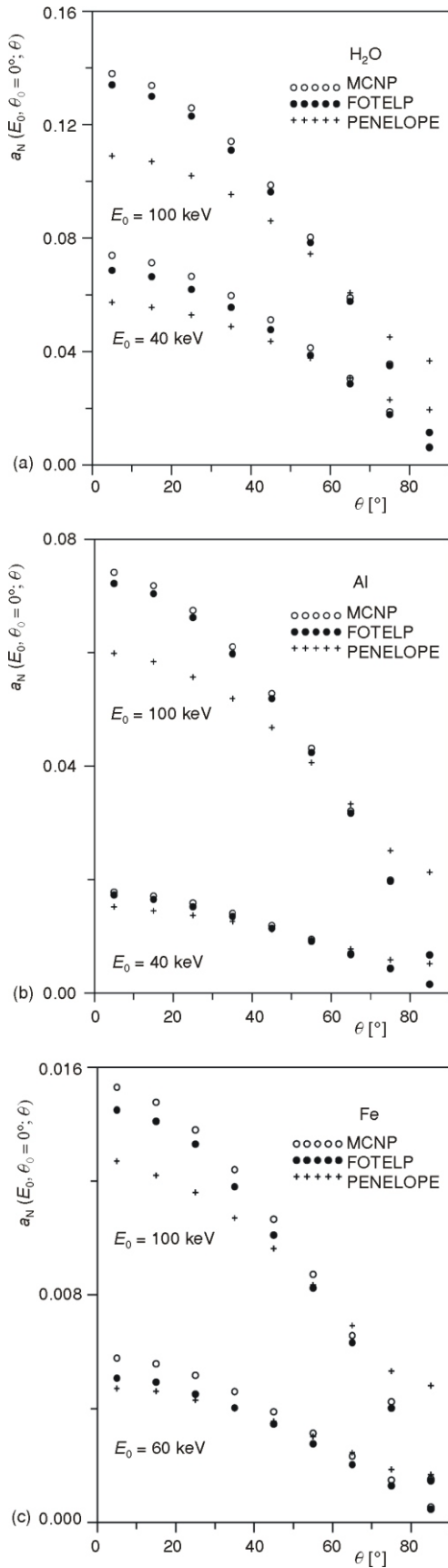


Figure 2. Number albedo of photons for (a) water, (b) aluminum, and (c) iron. Comparison of the results obtained by MCNP-4C, FOTELP-2K3, and PENELOPE-2005 codes

ment of the results is much better. The PENELOPE-2005 results are in better agreement with the FOTELP-2K3 results than with the values obtained by MCNP-4C code. As the angular distribution of reflected photons calculated by PENELOPE-2005 code is pretty flat, discrepancies from the results of two other codes are higher at the ends of the polar angle range, while in the middle of the polar angle range ($45^\circ < \theta < 55^\circ$) there is a good agreement between all three data sets. Exactly this range of polar angles is the most important one in radiation protection considerations for professionals performing medical diagnostic practice and being exposed to reflected photon radiation.

The values for photon number albedo obtained by MCNP-4C and FOTELP-2K3 codes have been compared with the results published by Bulatov and collaborators [17]. In fig. 3 the number albedo values for the initial photon energies of 60 keV and 100 keV are marked by different symbols. These energies have been chosen for graphical presentation and comparison because the energy of 60 keV was the lowest initial energy used in Bulatov's simulations of photon reflection. The MCNP-4C results are interpolated and presented by the solid line. The FOTELP-2K3 results are below the MCNP-4C results for all three materials and both initial photon energies, while the referent number albedo values for water and aluminum are below these two data sets. Bulatov's results for iron are higher than the corresponding MCNP-4C and FOTELP-2K3 results. The agreement between the MCNP-4C results and the literature data for water and $E_0 = 60$ keV is within 10% and even lower for the energy of 100 keV. For aluminum it is slightly better than for water. The discrepancies for iron at $E_0 = 60$ keV are about 20% and only few percent for the initial photon energy of 100 keV. In general, fig. 3 confirms good agreement between the results presented in this paper and the classic literature results of photon reflection simulation. Higher discrepancies noticed for the iron target and the initial photon energy of 60 keV can be explained by not so good statistics of Bulatov's simulation which was limited to only ten thousand photon histories and a small number of detected photons per one angular-energy interval. Usually, this number is below one hundred and in some intervals even below ten. Such unsatisfactory statistics was probably the main reason why the analyses in that first complete monography of photon reflection did not cover the initial photon energies below 60 keV.

CONCLUSION

Systematic calculation of photon number albedo for slab shielding materials and perpendicular incidence of photons with the initial energies up to 100 keV has shown that the two sets of results obtained from the reflection simulation by MCNP-4C and FOTELP-2K3

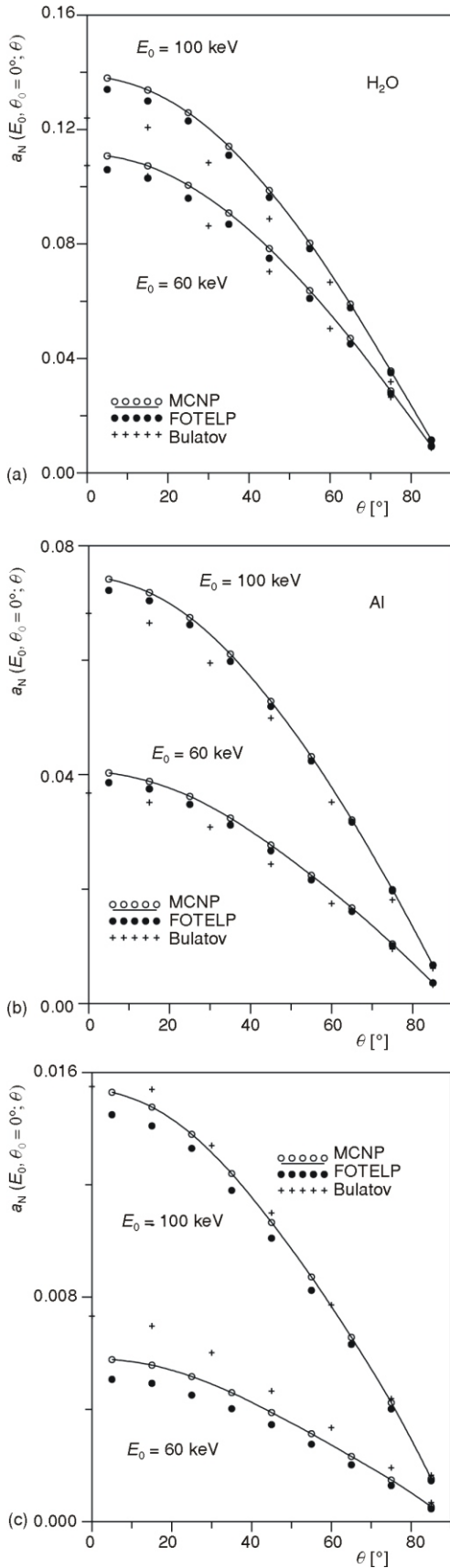


Figure 3. Number albedo of photons for (a) water, (b) aluminum, and (c) iron. Comparison of the results obtained by MCNP-4C and FOTELP-2K3 simulations with the results of Bulatov and collaborators [17]

codes are in very good mutual agreement, as well as in good agreement with the reference data sets. The results of PENELOPE-2005 code have shown the tendency to flatten the angular distribution and to have higher discrepancies from other data sets at the boundaries of the polar angle domain. The calculations for iron have indicated the anomaly of increased number albedo for the initial photon energies below 40 keV. This phenomenon is caused by photon absorption at the energy of 7.112 keV by K shell electron in an iron atom and the consequent emission of fluorescent radiation of the same energy and high yield.

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**Владан ЉУБЕНОВ, Родољуб СИМОВИЋ,
Српко МАРКОВИЋ, Радован Д. ИЛИЋ**

**БРОЈНИ АЛБЕДО НИСКОЕНЕРГЕТСКИХ ФОТОНА
ЗА ВОДУ АЛУМИНИЈУМ И ГВОЖЂЕ**

У раду је приказан бројни алbedo воде, алуминијума и гвожђа за енергије инцидентних фотона од 20 keV до 100 keV. Резултати су добијени на основу Монте Карло симулација фотонске рефлексије употребом програма MCNP-4C, FOTELP-2K3 и PENELOPE-2005. Израчунате вредности упоређене су са класичним подацима објављеним од стране Б. П. Булатова и његових сарадника. Уочен је и анализиран утицај флуоресценције на бројни алbedo фотона за мету од гвожђа и за енергије иницијалних фотона испод 40 keV.

Кључне речи: рефлексија фотона, бројни алbedo фотона, Монте Карло симулација, вода, алуминијум, гвожђе