UDC 535.361

V. V. Sobolev[1], Dr. Sc. (Tech.), Prof.,
orcid.org/0000-0003-1351-6674,
L. M. Shyman[2], Corresp. Member of the National Academy of Sciences of Ukraine, Dr. Sc. (Tech.),
M. M. Nalysko[3], Cand. Sc. (Tech.), Assoc. Prof.,
orcid.org/0000-0003-4039-1571,
O. L. Kyrychenko[2], Cand. Sc. (Tech.)

1 – National Mining University, Dnipro, Ukraine, e-mail: velo1947@ukr.net
2 – State Enterprise Research-Industrial Complex "Pavlohrad Chemical Plant", Pavlohrad, Ukraine, e-mail: dirphz@pkhz.dp.ua
3 – Prydniprovs'ka State Academy of Civil Engineering and Architecture, Dnipro, Ukraine, e-mail: 59568@i.ua

COMPUTATIONAL MODELING IN RESEARCH OF IGNITION MECHANISM OF EXPLOSIVES BY LASER RADIATION

В. В. Соболев[1], д-р техн. наук, проф.,
orcid.org/0000-0003-1351-6674,
Л. М. Шиман[2], чл.-кор. НАН України, д-р техн. наук,
М. М. Налисько[3], канд. техн. наук, доц.,
orcid.org/0000-0003-4039-1571,
О. Л. Кириченко[2], канд. техн. наук

1 – Державний вищий навчальний заклад „Національний гірничий університет", м. Дніпро, Україна, e-mail: velo1947@ ukr.net
2 – Державне підприємство „Науково-виробниче об'єднання „Павлоградський хімічний завод", м. Павлоград, Україна, e-mail: dirphz@pkhz.dp.ua
3 – Державний вищий навчальний заклад „Придніпровська державна академія будівництва і архітектури", м. Дніпро, Україна; e-mail: 59568@i.ua

ЧИСЕЛЬНЕ МОДЕЛЮВАННЯ В ДОСЛІДЖЕННЯХ МЕХАНІЗМУ ЗАПАЛЮВАННЯ ВИБУХОВИХ РЕЧОВИН ЛАЗЕРНИМ ВИПРОМІНЮВАННЯМ

Purpose. To give a theoretical description of laser propagation in energy-saturated photosensitive composites as in diffuse scattering media with close packed scatterers.

Methodology. Analysis and generalization of theoretical research. The Monte Carlo method of direct statistical modeling has been applied. A computational study of the process of scattering of photons in photosensitive energy-saturated composites has been carried out, the results of the computational study have been analyzed.

Findings. The results of computation of the illuminance for diffuse scattering media (DSM) by the Monte Carlo method have been presented. In particular, it has been determined that the initiation of highly sensitive explosives and photosensitive composites can not be explained based on the concepts of a multiple increase in volumetric illumination within a diffuse scattering medium with respect to the surface one, since such an increase is unfeasible. However, the light regime in a diffuse scattering medium is one of the determining factors for the ignition of explosives by laser radiation.

Originality. The diffuse reflection factor of DSM mainly depends on the photon survival rate and the refraction index. For each DSM there is a limiting value of the laser beam radius beginning with which the spatial illuminance does not change with the increase in the laser beam radius r. It is shown that with the increase in the bunch concentration in samples of photosensitive explosives (VS), the depth of the material layer with high values of illuminance increases. Moreover, the growth rate is inversely proportional to the beam radius. This regularity is well correlated with observed experimental dependence of VS sensitivity on the bunch concentration. Thus, in case of initiation of substance of VS2 grade with a 1.5 mm diameter laser beam, the sensitivity increased approximately by a factor of 2 with an increase in the bunch concentration from 10 to 20–30 %, while for a 4.5 mm diameter beam the sensitivity growth was ~ 13 %.

Practical value. The results of theoretical research were used when making laboratory samples of the optical detonator and during the research on actuation of optical detonators depending on the energetic and geometric characteristics of the laser beam.

Keywords: *Monte Carlo method, numerical computation, diffuse scattering medium, laser, radiation, scattering, photons, explosives*

Introduction. The up-to-date requirements for safe and accurate carrying out of blasting operations in various branches of industry show a clear need for development of new systems for initiation of explosive charges. Improvement of methods for blasting operations in the field of material processing, rock destruction and carrying out of special blasting operations using laser propagation energy requires the development of new means of initiation and, accordingly, new primary initiating explosives with high sensitivity to laser radiation [1].

To develop a technically effective laser method for initiating explosive charges, systematic research on the laser blasting of live initiating explosives and certain minerals began to be carried out in the 60's and 70's of the past century. The experiments conducted in the USSR, the USA and Japan unequivocally showed the futility of production on their basis of laser systems for initiating explosive charges, especially for carrying out mass explosions.

During the 80's–90's of the past century and at the beginning of this century the employees of Saint Petersburg State Institute of Technology (I. Tselinskiy, M. Ilyushin, I. Shugaley and others), the Institute of Mechanics of the National Academy of Sciences of Ukraine and the National Mining University (A. Baranovskyi, A. Chernai, V. Sobolev and others) carried out a number of joint studies on search, development and production of explosives, which are highly sensitive to laser radiation [2]. As a result of the conducted work, the photosensitive compositions with an assigned abbreviation VS were obtained, which were tested in detonators as primary explosives starting detonation in secondary explosives such as pentaerythrite tetranitrate and tetryl. Ignition of VS was carried out by transferring laser radiation through a light guide cord or through an air atmosphere. Favorable results of the experiments indicated that the success of the practical implementation of laser initiation systems depends directly on the development and production of new initiating explosives [3]. The photosensitivity of new initiating explosives to laser radiation should exceed the sensitivity of primary initiating explosives (mercury fulminate, lead and silver azides, leadtrinitroresorcinat) by two or three orders of magnitude, and the sensitivity to standard physical and mechanical effects should not exceed the sensitivity of secondary initiating explosives (pentaerythrite tetranitrate, tetryl, etc.).

So far, about ten different VS, which are the most suitable for solving practical problems, have been synthesized [4]. These VS are high energy systems consisting of a polymer matrix in which the microparticles of the explosive are distributed. VS, as a new class of primary initiating explosives, are intended for use in the initiating means as primary initiating charges or as a monocharge serving simultaneously as a primary and secondary explosive. In practice, we used some photosensitive explosives as the main charge [2], i.e. without the use of primary and secondary live explosives. Since the photosensitive explosive composites differ in physical and chemical properties and explosive characteristics, they are recommended for use in various fields of machine-building and mining and smelting industries.

Owing to the invention of photosensitive primary explosives at the National Mining University in 1995 with the use of production and technical facilities of the Institute of Mechanics of the National Academy of Sciences of Ukraine, the first in the world experimental model of the laser system of initiation of explosive charges, the OPCIN, was manufactured (V. Sobolev, A. Chernai, N. Studinskyi). The laser radiation used in the OPSIN is characterized by such parameters as wavelength of 1.06 μm, impulse duration of 10–11 ns, pulse energy of 100–200 mJ. The light pulse with similar parameters can be obtained only by means of an optical quantum generator (laser), but it cannot spontaneously arise in nature or in technology. This fact speaks well for increased safety conditions when working with OPSIN. It is also obvious that the effectiveness of the use of new photosensitive initiating explosives (VS) requires study and careful analysis of the peculiarities of the mechanism of explosives ignition by narrow laser beams.

To substantiate physical and chemical characteristics of photosensitive explosives and physical and technical parameters of optical detonators, the interaction of a photosensitive composition with a laser beam should be simulated.

Not only explosive and physical and chemical properties of a test sample, but also its component analysis, as well as geometric characteristics play an important role in the process of reliable VS ignition. In addition, the characteristics of a laser beam play an equally important role. Often the practice of transferring the studied regularities and established parameters during the study of any one type of photosensitive composition to another type appears to be improper [4]. Experimental research on the ignition mechanism and tryout of rational modes of VS initiation prove to be long-lasting and time-consuming.

Thus, a necessity for development of a physico-mathematical model connecting the light regime with the threshold energy of ignition of explosives and describing the behavior of photons in media with scatterers, which is a crucial scientific and practical task, arises during research.

Analysis of the recent research. The Monte Carlo method is widely used in modeling problems of the propagation of laser radiation in inhomogeneous media [5], for studying the patterns of photon propagation in multilayer materials [6]. This method is also used in the optical diagnostics of biological media [7], the passage of ultrashort laser pulses through an inhomogeneous medium with mobile scatterers [8]. The Monte Carlo method is indispensable in modeling the initiation of chemical reactions in condensed explosives [9] and primary initiating explosives [10]. Some of foreground tasks to be solved within the scope of these directions consist in analysis of processes of three-dimensional distribution of laser radiation in materials, computations of distribution of density of absorbed radiation energy, random photon motion path in a material (on the basis of geometry and optical properties), scattered radiation intensity (at any given sample geometry), etc. During research on energy-saturated materials, which are potentially capable of phase and chemical transformations when the laser action energy is relatively small, the regularities of initiating explosives ignition, the effect of absorbing impurities on the process, the regularities of explosives ignition due to duration and aperture of laser radiation with due regard for multiple scattering are particularly studied.

The main regularities of the process of light scattering in diffuse scattering medium have been studied completely enough in A. P. Ivanov's monograph, but the issue of the spatial illuminance inside a layer has not been studied in detail. Nevertheless, the spatial illuminance represents a particular interest for practice of research on substance physicochemical transformation. However, obtaining a solution of a transformation equation in a general case (under conditions of a laser beam limited diameter, divergence of incident radiation, final absorption, beam oblique incidence, etc.) faces difficulties of a computation character. Therefore, E. I. Alexandrov, A. G. Vozniuk, V. P. Tsypilev computed the light field spatial illuminance in the quantity of explosives by the Monte Carlo method in their papers (1988, 1989). They showed that at some depth of the sample surface the illuminance reaches a maximum, the value of which depends on a laser beam radius, an average photon path length *t* sample diffuse reflection factor R, substance refraction index *n*. The character of dependencies indicates that with decrease in R and increase in τ (fixed laser beam radius *r*) the illuminance maximum decreases, which means that the critical density of ignition energy increases. In addition, as it appears from computations, for the purpose of an endlessly wide beam the spatial illuminance is greater than the surface one by a factor of $16\,n^3/(n+1)$ (n is the explosive refraction index). In view of the illuminance increase with this formula, the results of the experiments on initiation of heavy metal azides are in satisfactory agreement with theory. However, when studying separate monocrystals of β-lead azide representing plane-parallel plates with dimensions of $40\,\mu m \times 200\,\mu m \times 10\,mm$, J. T. Hagan and M. M. Chaundhri obtained anomalously high sensitivity of 1.5 mJ/cm^2. In this case there is no cause to speak about increase in the spatial illuminance. In this regard the doubts occur as to either local thermal process of ignition of explosives, which are highly sensitive to laser action, or correct computation of the spatial illuminance shown in papers written by E. I. Alexandrov, A. G. Vozniuk, V. P. Tsypilev.

After analyzing the results of computational modeling of scattering of photons in energy-saturated composites, which are transparent for laser radiation, the conclusions about the necessity to consider optical effects were drawn. Thus, the computational modeling with regard for the effect of photon multiple scattering have been conducted (V. Sobolev, A. Chernai, Ukraine, Report on research, state registration number 0100U001825). Similar tasks were also successfully solved during later research with the use of Monte Carlo modified models by specialists of a well-known school of Tomsk scholars [10]. A distinction between research carried out in the National Mining University and similar work performed by specialists of other scientific institutions consists in a study of synthesized photosensitive initiating VS of a new grade [2]. Physical and chemical and explosive properties of photosensitive VS differ fundamentally from those of live initiating explosives, moreover, some regularities of interaction of laser radiation and established optical properties are different.

Light propagation in scattering media has been a subject of research within several decades. In the time of the USSR this branch of science was developing the most intensively in Russia, Belarus and Ukraine. The Institute of Atmospheric Optics was founded in Russia (Tomsk). The main research line was connected with issues of optical detection, air pollution in industrial regions of the country, as well as in medicine. Also, similar issues were being solved in the USA and Western Europe countries. Most of the focus was on the issue of extinction of a light beam in turbid media (fog, polluted air, red blood cells, etc.) with a small concentration of scatterers. It was a small concentration of scatterers that allowed transferring a nonlinear equation of light propagation into a linear one.

The leading organizations dealing with issues of interaction of laser radiation with energy-saturated materials are Saint-Petersburg Technical University, research and development institutes of the Federal Nuclear Center, the Institute of Chemical Physics of the Russian Academy of Sciences (RAS), Tomsk Polytechnic University and others (Russia), Los Alamos Laboratory, the NASA universities (USA). In Ukraine the issues of laser initiation of explosives have been solved in the National Mining University, the Institute of Technical Mechanics of the National Academy of Sciences of Ukraine and other research and production establishments within last 30 years.

Objectives of the article. The Monte Carlo method is based on generation of a random value, namely: photon motion spatial characteristics, substance absorbing properties, etc. Up-to-date methods allow tracing behavior of each photon in a quantity of 10^5–10^6 photons. Averaging of their path is a basis for final conclusions on energy saturation of a volume of explosives, which determines the ignition process development and deflagration-to-detonation transition in optical detonators.

The building of computational models is impossible without establishing a laser ignition mechanism. The illuminance in a volume of explosives plays a major role in the ignition process. Unfortunately, computation of the illuminance in explosives becomes more sophisticated as an explosive is a medium with a high density of scatterers, for which no analytical decisions have made up to this time.

The purpose is to give a theoretical description of laser propagation in energy-saturated photosensitive composites as in diffuse scattering media with close packed scatterers by the Monte Carlo method.

Presentation of the main research. The knowledge of regularities of initiation and build-up of detonation in photosensitive energy-saturated composites is required for the purpose of effective operation and the most complete use of a physical potential of the optical initiation system and their further improvement. Such necessity is based on at least several reasons. One of them is a fundamental distinction of an ignition mechanism from an overwhelming majority of chemical explosives. Other reasons include a necessity for a formulation selection rationale, development of a given texture, establishment of interdependence of laser radiation field with destabilization of crystal lattice of an explosive. To unlock the physicotechnical potential of laser ignition, the technique of prediction of a through scenario of chemical transformations development is required.

It was deduced from experiments that for detonation initiation, for example, in energy-saturated metal complexes a laser radiation was used with the following characteristics: wavelength – 1.06 μm, impulse duration – $(10–11)\cdot 10^{-9}$ s, pulse energy – 0.1–0.2 J. The light pulse with similar characteristics can be obtained by means of a laser (optical quantum generator). There is no hazard of unauthorized explosion from any external sources as the probability of spontaneous occurrence of radiance with such parameters in nature or technology is zero. This fact speaks well for maximum possible safety conditions when operating optical initiation system.

Primary initiating explosives used in optical detonators (OD) are pressed powders, which allows considering them as a diffuse scattering medium (DSM) with close packed scatterers from optical point of view. The presence of absorbing impurities, as well as scattering centers, affects the state of chemically active medium receiving laser radiation energy, so the correlation between absorption capacity and sensitivity of explosives to the light pulse effect should be expected.

In spite of the fact that basic regularities of light scattering process in a diffuse scattering medium have been studied completely enough, the issue of spatial illuminance in terms of such material has not been studied in detail. Nevertheless, the scattered light structure is of primary concern for practice of research on physicochemical transformations of a substance. Under conditions of limited laser beam diameter, incident radiation divergence at an angle, final absorption, etc., obtaining a solution of transfer equation generally faces computational difficulties. In general, the Monte Carlo method used particularly for determination of illuminance in DSM with close packed scatterers is the most versatile giving consistent results under various conditions of external illuminance of a medium under study. Unfortunately, the computational results according to the method by E. I. Alexandrov et al. can be verified only by development of one's own algorithm and computational program. On the other hand, the availability of such computational tool allows a correct statement of a problem of ignition of either high explosives, for which it is necessary to take into account the processes of gas-dynamic emission of decomposition products, or initiating explosives, when such processes are of minor importance.

The Monte Carlo method advantage over different analytical approaches consists in a possibility of computation of scattering intensity at almost any distances from a source as a scope of application of analytical approaches is quite limited.

The Monte Carlo method is based on direct finding of photon paths, where successive scattering events are considered as a sequence of random processes. The desired intensity is determined by a number of paths passing through the given space point.

When computing spatial illuminance, paths of $10^5 \div 10^6$ photons was computed. The beginning of a path is a point, which is at the DSM-environment boundary illuminated with a directive radiator. This area was simulated by an ellipse (in an individual case – by a circle). An angular coordinate of photon entry is a random value evenly distributed at angles from 0 to 2π and a radial coordinate is a random value determined by means of the Gaussian law.

The path length l was determined by generating a Poisson random variable. The path direction after entry into DSM was determined by refraction angle at the DSM-environment boundary. After computing the path end coordinates a random number is generated, which is compared with the photon survival index Λ, and this point is either the point of path interruption (the photon will be absorbed) or the point of the next path beginning. The direction of further paths is determined by generating scattering angles according to scattering indicatrix until the path exceeds the bounds of the sample or until the photon is absorbed.

The scattering probability at any space point is determined by the photon survival index Λ

$$\Lambda = \beta/(\alpha+\beta),$$

where α and β are absorption and scattering coefficients of elementary volume of a substance.

When $\Lambda < \xi_1$ (ξ_1 are successive random numbers evenly distributed in the range from 0 to 1), the photon is considered to be scattered, otherwise it is absorbed. The direction of scattering is determined by scattering indicatrix. The azimuth angle of scattering is computed using formula $v = \arccos(1-2\xi_2)$ – for spherical scattering indicatrix and $v = \arccos(2\sqrt[3]{(1-\xi_3)}-1)$ – for stretched one. The free path length is computed using formula $\ell = -\tau\cdot\ln\xi_4$; $\tau = 1/(\alpha+\beta)$ is an average photon free path length. When the photon leaves the sample, its further behavior is determined by reflection coefficient R, which is calculated using well-known Fresnel's formulas. When $\xi_6 < R$ the photon is reflected from the boundary and returns into the sample, otherwise it leaves the layer and contributes to diffuse reflection characterized by diffuse reflection factor ρ.

To improve statistical validity of results of summing up paths of scattered photons, the averaging of results in terms of volume τ^3 was carried out.

For algorithm check-out and method verification the following was computed: coefficients of diffuse reflection of semi-infinite slab for the following values of photon survival index $\Lambda = \beta/(\alpha+\beta) = 0.999, 0.99, 0.9, 0.8$; parameters of elementary volume $\alpha\,(\text{cm}^{-1})$ and $\beta\,(\text{cm}^{-1})$: 99.9 and 0.1; 99 and 1; 90 and 10; 80 and 20 respectively. If the refraction index of the environment and DSM in the first case is taken as $n_1 = 1$, $n_2 = 1$, in the second case as $n_1 = 1$, $n_2 = 1.5$, i.e. the relative refraction index $n = n_2/n_1$ is respectively $n = 1$ and $n = 1.5$. The scattering indicatrix is spherical ($\chi = 1$) and stretched ($\chi = 1+\mu$) (Table).

In computations the behavior of $N_0 = 10^5$ photons, the distribution of which along the beam radius was described using Gaussian distribution, was traced. The diffuse reflection coefficient is a ratio of a number of photons left DSM due to Fresnel reflection and volume scattering to a total number of photons reaching the media boundary. Laser beam normal incidence was under re-view (angle of incidence $\theta = 0$).

As it can be seen from Table, the obtained results are in satisfactory agreements with the data from paper [5].

Some observed discrepancy (mainly for $\chi = 1$, $n = 1$) is probably due to the difference in the applied modeling algorithms. In addition, paper [5] dealt with laser beams with a rectangular energy density profile, and we analyzed Gaussian beams bounded by a diaphragm in terms of an intensity level of 0.8.

Initiation of highly sensitive explosives largely depends on volumetric illuminance of a substance. Whereas absorption of luminous energy in each cell of the sample is proportional to spatial illuminance, the latter was adopted as the main characteristic of light field. More precisely, the ratio of spatial illuminance E_0(x,y,z) to surface illuminance in the beam center $E(0)$ was taken as the main characteristic

$$F = \frac{E_0(r)}{E(0)}.$$

In terms of the Monte Carlo model, $E(0) = n(0)h\nu$ where $h\nu$ is photon energy, $n(0)$ is the density of particle current in the beam center.

Spatial illuminance, by definition, is the density of flux of energy entering an elementary volume of transparent medium from all sides

$$E_0 = \int_{4\pi} Id\Omega,$$

where I is radiation intensity (density of flow of luminous energy in a solid angle $d\Omega$).

In terms of the Monte Carlo model, $I = n \cdot h\nu$, where n is the density of photon flow in a unit solid angle $d\Omega$ In case of isotropic light field

$$E_0(\mathrm{r}) = 4\pi \cdot n(r) \cdot h\nu.$$

For isotropic light field it follows that $E_0 = 6 \cdot n(r) \cdot h\nu$. The value

Table

Reflection coefficients of a flat scattering layer

Photon survival index Λ	χ = 1		χ = 1+μ	
	MK_0^*	MK_1^*	MK_0^*	MK_1^*
	$n = 1$			
0.999	0.898	0.931	0.890	0.901
0.99	0.732	0.795	0.720	0.726
0.9	0.398	0.476	0.279	0.357
0.8	0.284	0.342	0.199	0.232
	$n = 1.5$			
0.999	0.827	0.851	0.811	0.791
0.99	0.604	0.620	0.522	0.522
0.9	0.258	0.289	0.206	0.186
0.8	0.172	0.189	0.107	0.107

MK_0 – results obtained by E. Alexandrov; MK_1 – results obtained in this paper

$$F = \frac{E_0}{E(0)} = \frac{N(r)}{\tau^2 n(0)},$$

was taken as a characteristic of light field of DSM, where N is full photon flow.

The calculation of spatial illuminance F will be carried out under the following conditions: $\tau = 10^{-2}$ cm, $n = 1.5$, $\chi = 1$; $\Lambda = 0.999$, 0.99; $\rho_g = 0.795$; α (cm^{-1}) = 0.1, 1; β (cm^{-1}) = 99.9, 99. The relative radius of the beam will be selected equal to $r_0/\tau = 2$, 10, 20, 30 and 50 (r_0, cm) = $= 2 \cdot 10^{-2}$, 10^{-1}, $2 \cdot 10^{-1}$, $3 \cdot 10^{-1}$, $5 \cdot 10^{-1}$). Since we use laser beams bounded by a diaphragm to 0.8 intensity level, for the given values r_0/τ the Gauss parameter will be: σ (cm^{-1}) = $2.99 \cdot 10^{-2}$, $1.49 \cdot 10^{-1}$, $2.98 \cdot 10^{-1}$, $4.49 \cdot 10^{-1}$, $7.78 \cdot 10^{-1}$.

Fig. 1 shows distribution of spatial illuminance in depth of scattering layer for various sizes of a laser beam (in r_0/τ units).

The above distribution graphs (Fig. 1) show that the maximum illuminance grows with increasing the laser beam diameter and shifts into the depth of DSM. However, the growth stops when a certain value is reached (in this case $r_0/\tau \sim 50$), i.e. when an explosive is initiated with wide beams the tip effects disappear. All this is a consequence of multiple scattering of radiation in DSM which is observed for media with a high scattering factor and a low absorption factor. In depth conditions, the distribution of illuminance is close to the Burger distribution.

The dependence of maximum $F = E/E_0$ on r_0/τ agrees with experimentally observed dimensional effect (dependence of sensitivity of an explosive on a laser beam diameter).

In this experimentation explosive compositions (EC) were a mixture of explosive and binding material. As a binder we used a material characterized by a very low absorption index $\alpha_c \sim 10^{-3}$–10^{-4} cm, that is why absorption of laser radiation in such material may be neglected. Therefore, with increased concentration of the binder both absorption index of EC and scattering factor decrease owing to lower content of scattering centers (explosive crystals and microinhomogeneities) per volume unit.

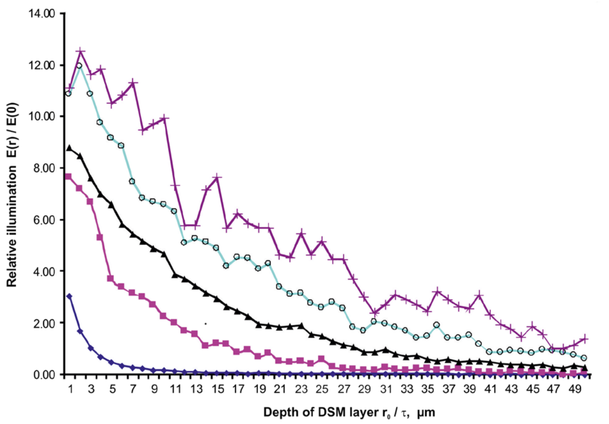

Fig. 1. Distribution of illuminance in depth of semi-infinite slab of DSM:
♦ – r = 2 τ; ■ – r = 10 τ; Δ – r = 20 τ; ○ – r = 30 τ; + – r = 50 τ

Fig. 2 shows illuminance distribution in a volume of DSM for these two cases at $r = 0.1$ and 0.3 cm.

Since for the analyzed primary explosives $\alpha << \beta$, the increase of binding material concentration has practically no influence on photon survival index, but it substantially increases its free path length. All this leads to considerable redistribution of volumetric illuminance of DSM.

The results of calculations are given under the following characteristics of DSM: $\alpha = 0.1$ cm^{-1}, $\beta = 90$ cm^{-1} and $\alpha = 0.01$ cm^{-1}, $\beta = 30$ cm^{-1}.

For these pairs of α and β, Λ and τ are respectively equal: $\Lambda = 0.9989$, $\tau = 1.1 \cdot 10^{-2}$ cm, $\Lambda = 0.9996$, $\tau = 3.33 \cdot 10^{-2}$ cm. The survival indices differ by 0.07 %, and the free path length – by 3 times.

When comparing the results shown in Figs. 1 and 2, it can be said that the nature of dependencies essentially depends on the relation of the beam radius r and the mean free path length τ, i.e. on the value r/τ.

The calculations also give values of the quantity $F \approx 2 \div 12$, which agrees with the results of works by E. I. Aleksandrov. Such increase in spatial illuminance inside the explosive layer can explain the results of low-threshold ignition, that, as pointed out above, was done dy E. I. Aleksandrov et alias. However, it should be remembered that semi-infinite slab of DSM was investigated.

While investigating a limited layer, boundary effects appear which can reduce the value F. Surface roughness has a strong effect on light penetration into DSM. The structure of scattering radiation inside the layer is defined by absorption and scattering indices and scattering indicatrix. These parameters depend on radiation spectrum, as well as polarization. Therefore, $\Lambda < 0.999$, resulting in reduction of maximum F. Apart from the mentioned factors, the decrease in F can be influenced by interference effects associated with passing through the given space point of photons having phase shifts and damping each other partially or completely. Consequently, correct physical interpretation of the phenomenon of low-threshold ignition of explosives and VS is impossible without due regard to processes of photon scattering in these materials.

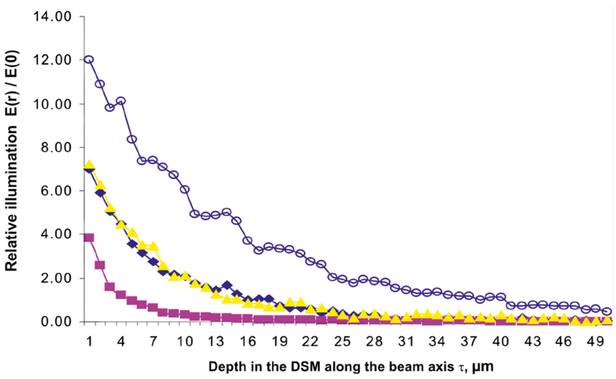

Fig. 2. Illuminance in a volume of DSM along the laser beam axis:

♦ – $r = 0.1$ cm (9τ); $\tau = 1.1 \cdot 10^{-2}$ cm; $\Lambda = 0.9989$; $\rho_\infty = 0.780$; ■ – $r = 0.1$ cm (3τ); $\tau = 3.33 \cdot 10^{-2}$ cm, $\Lambda = 0.9996$, $\rho_\infty = 0.871$; Δ – $r = 0.3$ cm (9τ), $\tau = 3.33 \cdot 10^{-2}$ cm, $\Lambda = 0.9996$, $\rho_\infty = 0.875$; ○ – $r = 0.3$ cm (30τ), $\tau = 1.1 \cdot 10^{-2}$ cm, $\Lambda = 0.9989$, $\rho_\infty = 0.786$

Conclusions.

1. Initiation of highly sensitive explosives and photosensitive explosives (VS) cannot be explained in terms of multiple increase in volumetric illuminance inside DSM relative to surface illuminance, while such increase is unfeasible. However, light conditions in DSM make one of the decisive factors of ignition of explosives with a pulse of an optical-quantum generator.

2. The diffuse-reflection factor of DSM mainly depends on photon survival index and refraction index.

3. For each DSM there exists a limit value of a laser ray radius beginning with which spatial illuminance does not change with increasing the laser ray radius r.

4. As polymer binder concentration in VS samples increases, the depth of material layer with high illuminance values grows. Along with this, the rate of growth is inversely proportional to the laser ray radius. This regularity correlates well with the observed experimental dependence of photosensitive explosive sensitivity on binder concentration.

The results of theoretical studies have been used for preparing laboratory samples of optical detonators and in investigations of optical detonator firing depending on laser ray energy and geometrical characteristics.

References.

1. Chernai, A. V., Sobolev, V. V., Ilyushin, M. A. and Zhitnik, N. E., 1994. Generating mechanical pulses by the laser blasting of explosive coatings [pdf]. *Combustion, Explosion, and Shock Waves*, 2, pp. 106–111. Available at: <http://sibran.ru/upload/iblock/789/789051705b1d5f2d37dbb20809f27ca8.pdf> [Accessed 25 January 2017].

2. Chernai, A. V., Sobolev, V. V., Chernai, V. A., Ilyushin, M. A. and Dlugashek, A., 2003. Laser initiation of charges on the basis of di-(3-hydrazino-4-amino-1,2,3-triazol)-copper (II) perchlorate [pdf]. *Fizika Goreniya i Vzryva*, 3, pp. 105–110. Available at: < http://www.sibran.ru/upload/iblock/c21/c21aeefbffd79e0c9dbcdd538dc9d9fd.pdf> [Accessed 25 January 2017].

3. Ilyushin, M. A., Kotomin, A. A. and Dushenok, S. A., 2017. Laser initiation of photosensitive energy materials, promising for spacecraft pyroautomatics systems [pdf]. *Vestnik "NPO im. S. A. Lavochkina"*, 1, pp. 43–52. Available at: <http://www.laspace.ru/upload/ iblock/c1d/c1d4330a58a437cdce27cd471b97975c.pdf> [Accessed 25 January 2017].

4. Ilyushin, M. A., Sudarikov, A. M. and Tselinsky, I. V., 2010. *Metal complexes in high-energy compositions*. St. Petersburg: Leningrad State University named after Pushkin.

5. Privalov, V. E., Seteikin, A. Yu. and Fotiadi, A. E., 2013. Simulation of laser radiation propagation in inhomogeneous media with complex geometry, *St. Petersburg SPU Journal of Engineering Science and Technology. Physics and Mathematics*, 1(165), pp. 45–54.

6. Wang, L.-H., Jacques, S. L. and Zheng, L.-Q., 1995. Monte Carlo modeling of photon transport in multi-layered tissues [pdf]. *Computer Methods and Programs in Biomedicine*, 47, pp. 131–146. Available at: <http://oilab.

seas.wustl.edu/epub/1995LWCMPBMcml. pdf> [Accessed 25 January 2017].

7. Pavlov, M. S. and Krasnikov, I. V., 2010. Monte Carlo modelling of optical-radiation propagation in biological media with closed internal inhomogeneities [pdf]. *Journal of Optical Technology*, 10, pp. 15–19. Available at: <http://opticjourn.ifmo.ru/file/article/10049.pdf> [Accessed 25 January 2017].

8. Starukhin, P. Y. and Klinaev Y. V., 2011. Application of the Monte Carlo method for modeling passage of ultrashort laser pulses through an inhomogeneous medium with moving scatterers, *Journal of Applied Spectroscopy*, 2, pp. 277–281 [online]. Available at: <https://elibrary.ru/item.asp?id=15591148> [Accessed 25 January 2017].

9. Akhmetshin, R., Razin, A. and Ovchinnikov, V., 2014. Effect of laser radiation wavelength on explosives initiation thresholds. *Journal of Physics*: *Conference Series* [e-journal], 552, pp. 1–4. http://dx.doi.org/10.1088/1742-6596/552/1/ 012015.

10. Kriger, V. G., Tsipilev, V. P. and Kalenskii, A. V., 2009. Explosive decomposition of silver azide single crystals for various diameters of the irradiated area [pdf], *Combustion, Explosion and Shock Waves*, 6, pp. 105–107. Available at: <http://www.sibran.ru/upload/iblock/ 08d/08dfe86ac938 9cce7322d8e162b89e9b.pdf> [Accessed 25 January 2017].

Мета. Теоретичний опис поширення лазерного випромінювання в енергонасичених світлочутливих композитах як у дифузно-розсіюючих середовищах зі щільною упаковкою розсіювачів.

Методика. Аналіз і узагальнення теоретичних досліджень. Застосовано метод прямого статистичного моделювання Монте-Карло. Проведено чисельний експеримент процесу розсіювання фотонів у світлочутливих енергонасичених композитах, проаналізовані результати чисельного експерименту.

Результати. Викладені результати розрахунку освітленості в дифузно-розсіюючому середовищі (ДРС) за методом Монте-Карло. Зокрема, встановлено, що ініціювання високочутливих вибухових речовин (ВР) і світлочутливих композитів не може бути пояснено на основі уявлень про багаторазове збільшення об'ємної освітленості всередині дифузно-розсіюючого середовища щодо поверхневої, оскільки таке збільшення нездійсненне. Однак світловий режим у дифузно-розсіюючому середовищі є одним із визначальних чинників запалювання ВР лазерним випромінюванням.

Наукова новизна. Коефіцієнт дифузного віддзеркалення дифузно-розсіюючого середовища головним чином залежить від коефіцієнта виживання фотона й показника заломлення. Для кожного дифузно-розсіюючого середовища існує граничне значення радіуса лазерного променя, починаючи з якого просторова освітленість не змінюється при збільшенні радіуса лазерного променя *r*. Показано, що при збільшенні у зразках світлочутливих вибухових речовин (ВС) концентрації зв'язки глибина шару матеріалу з високими значеннями освітленості зростає. Причому, швидкість росту обернено пропорційна радіусу променя. Ця закономірність добре корелює зі спостережуваною експериментальною залежністю чутливості ВС від концентрації зв'язки. Так, у разі ініціювання речовини марки ВС2 лазерним променем діаметром 1,5 мм чутливість збільшилася приблизно у 2 рази при збільшенні концентрації зв'язки з 10 до 20–30 %, у той час як для променя діаметром 4,5 мм зростання чутливості склало ~ 13 %.

Практична значимість. Результати теоретичних досліджень використані при створенні лабораторних зразків оптичного детонатора та у дослідженнях спрацьовування оптичних детонаторів у залежності від енергетичних і геометричних характеристик лазерного променю.

Ключові слова: *метод Монте-Карло, чисельний розрахунок, дифузно-розсіююче середовище, лазер, випромінювання, розсіювання, фотони, вибухові речовини*

Цель. Теоретическое описание распространения лазерного излучения в энергонасыщенных светочувствительных композитах как в диффузно-рассеивающих средах с плотной упаковкой рассеивателей.

Методика. Анализ и обобщение теоретических исследований. Применен метод прямого статистического моделирования Монте-Карло. Проведен численный эксперимент процесса рассеяния фотонов в светочувствительных энергонасыщенных композитах, проанализированы результатов численного эксперимента.

Результаты. Изложены результаты расчета освещенности в диффузно-рассеивающей среде (ДРС) по методу Монте–Карло. В частности, установлено, что инициирование высокочувствительных взрывчатых веществ (ВВ) и светочувствительных композитов не может быть объяснено на основе представлений о многократном увеличении объёмной освещенности внутри диффузно-рассеивающей среды относительно поверхностной, поскольку такое увеличение неосуществимо. Однако световой режим в диффузно-рассеивающей среде является одним из определяющих факторов зажигания ВВ лазерным излучением.

Научная новизна. Коэффициент диффузного отражения ДРС главным образом зависит от коэффициента выживаемости фотона и показателя преломления. Для каждой диффузно-рассеивающей среды существует предельное значение радиуса лазерного луча, начиная с которого пространственная освещенность не изменяется при увеличении радиуса лазерного луча *r*. Показано, что при увеличении в образцах светочувствительных взрывчатых веществ (ВС) концентрации связки глубина слоя материала с высокими значениями освещенности растет. Причем, скорость роста обратно пропорциональна радиусу луча. Эта закономерность хорошо коррелирует с наблюдаемой экспериментальной зависимостью чувствительности ВС от концентрации связки. Так, в случае инициирования вещества марки ВС2 лазерным лучом диаметром 1,5 мм чувствительность увеличилась приблизительно в 2 раза при увеличении концентрации связки с 10 до 20–30 %, в то время как для луча диаметром 4,5 мм рост чувствительности составил ~13 %.

Практическая значимость. Результаты теоретических исследований использованы при создании лабораторных образцов оптического детонатора и в исследованиях срабатывания оптических детонаторов в зависимости от энергетических и геометрических характеристик лазерного луча.

Ключевые слова: *метод Монте-Карло, численный расчет, диффузно-рассеивающая среда, лазер, излучение, рассеяние, фотоны, взрывчатые вещества*

Рекомендовано до публікації докт. техн. наук О. О. Сдвижковою. Дата надходження рукопису 15.11.16.

I. Rouaiguia,
M. Bounouala, Dr. Sc. (Tech.),
C. Abdelmalek, Dr. Sc. (Tech.),
A. Idres, Dr. Sc. (Tech.)

Badji Mokhtar University, Annaba, Algeria, e-mail: rouaiguia.issam@gmail.com

VALORIZATION OF WASTE ROCKS FROM BOUKHADRA IRON ORE MINE FOR BETTER ENVIRONMENTAL MANAGEMENT

І. Руаігіа,
М. Бунуала, д-р техн. наук,
С. Абделмалек, д-р техн. наук,
А. Ідрес, д-р техн. наук

Університет Аннаба імені Баджи Мухтара, м. Аннаба, Алжир, e-mail: rouaiguia.issam@gmail.com

ВАЛОРИЗАЦІЯ ВІДХОДІВ ГІРСЬКИХ ПОРІД ПРИ РОЗРОБЦІ РОДОВИЩА ЗАЛІЗНОЇ РУДИ БУХАДРА ДЛЯ ВДОСКОНАЛЕННЯ ЗАХОДІВ ІЗ ЗАХИСТУ НАВКОЛИШНЬОГО СЕРЕДОВИЩА

Purpose. Characterization of mining wastes for the valorization of waste rocks from the Boukhadra iron ore mine which is located near the Algerian-Tunisian border in the city of Tebessa (Algeria).

Methodology. Analyses by X-Ray Diffraction, petrographic studies on thin sections and polished sections, particle size analysis, analysis by X-ray Fluorescence of the raw sample including those for the different particle size of waste rocks of the Boukhadra mine were carried out to identify their mineralogical and chemical composition. Based on the physical properties of these mining wastes, magnetic susceptibility was taken into account for possible enrichment of the weakly magnetic iron minerals by high intensity magnetic separation on dry way (DHIMS). During the separation of wastes, we took into account the particle size distribution and the intensity of the electrical current.

Findings. The studies realized have enabled us to deduce that the Boukhadra waste rocks, which are generally extracted from the open-pit mine, mainly consist of limestone, hematite, gray and yellow marls, with an average grade in Fe_2O_3 of 19.97 %. The particle size analysis carried out on a representative sample of the waste rocks from the Boukhadra mine weights 500 g and crushed to 4 mm reveals that the iron-rich class (27.67 % Fe_2O_3) is located between -0.5 + 0.25 mm. Tests by dry high-intensity magnetic separation on different classes: (-1 + 0.5 mm), (-0.5 + 0.25 mm), (-0.25 + 0.125 mm) and (-1 + 0.125 mm) with alternatives amperages (3–12 A) show that the experiment carried out in the class (-0.5 + 0.25 mm) at 12 A offers a concentrate of iron (40 % Fe_2O_3) against a reject of limestone and marls (43 % CaO, 15 % SiO_2, 8 % Al_2O_3, 2 % Fe_2O_3).

Originality. This is a topical issue in the Algerian mining industry, which causes serious problems for the mining environment and local residents following the increase in volumes of mining wastes and their pollution in the Boukhadra region. So, the management of waste rocks represents a major preoccupation for protecting the environment and contributes to the sustainable development. It represents a model for the valorization and the management of waste rocks from this mine or any other iron mine.

Practical value. The installation of mining wastes enrichment equipment allows, on the one hand, the recovery of a marketable product and, on the other hand, the rejects resulting from magnetic separation (DHIMS) can be used in various fields, namely: cement plants, ceramic, construction materials (economic interest), it will also contribute to the rehabilitation of the mining site and the protection of the environment.

Keywords: *Boukhadra, magnetic separation, mining wastes, sustainable development, valorization*

Introduction. Compared to all the activities of the national economy, the mining sector is the driving force for the sustainable development; technological fields are consumers of metal pieces (construction, automotive industry, various tools, agriculture, etc.) which are in turn based on iron ore. On the other hand, our environment, for a long time, has been affected by dangerous and very complicated problems, which results in the fallouts of volumes of mining wastes on the ecosystem. These wastes are deposited or stockpiled within the mine site and con-