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THE X-RAY ABSORPTION IMMERSION TECHNOLOGY FOR ENRICHMENT OF DIAMOND ORES: PHYSICAL FOUNDATIONS AND PRACTICAL IMPLEMENTATION

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Abstract. The paper presents physical principles of X-ray absorption immersion technology (XRAIT) based on recording X-ray radiation passed through diamond-containing ore, pore spaces between the pieces of which are preliminarily filled with an immersion medium (IM). The energy range of X-ray photons where the diamond is more transparent than the ore components has been determined. Based on the proposed approximation of the mass attenuation coefficients of elements by the sum of two power functions, a justification for a conscious choice of the mass attenuation coefficient of the IM equal to the average value for all ore components was carried out taking into account their weight content. An optimal composition of the IM in the form of a bulk material, namely aluminum-zinc alloy powder, was proposed. Experiments conducted on a developed and manufactured prototype of the separator confirmed the possibility of using the XRAIT with significant advantages over analogues.

Keywords: X-ray absorption technology, immersion medium, mass attenuation coefficient, X-ray radiation, diamonds

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РЕНТГЕНО-АБСОРБЦИОННАЯ ИММЕРСИОННАЯ ТЕХНОЛОГИЯ ОБОГАЩЕНИЯ АЛМАЗОСОДЕРЖАЩИХ РУД: ФИЗИЧЕСКИЕ ОСНОВЫ И ПРАКТИЧЕСКАЯ РЕАЛИЗАЦИЯ

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Аннотация. В работе представлены физические основы рентгено-абсорбционной иммерсионной технологии (РАИТ), основанной на регистрации рентгеновского излучения, прошедшего через алмазосодержащую руду, пустоты между кусками которой предварительно заполняются иммерсионной средой (ИС). При этом определен диапазон энергий рентгеновских фотонов, в котором алмаз более прозрачен, чем компоненты руды. На основе предложенной аппроксимации массовых коэффициентов ослабления элементов суммой двух степенных функций проведено обоснование осознанного выбора массового коэффициента ослабления ИС, равного среднему значению по всем компонентам руды с учетом их весового содержания. По результатам тестирования предложен оптимальный состав ИС в виде сыпучего материала: порошок сплава алюминия с цинком. Эксперименты, проведенные на разработанном и изготовленном образце сепаратора, подтвердили возможность применения РАИТ, обладающей существенными преимуществами над аналогами.

Ключевые слова: рентгено-абсорбционная технология, иммерсионная среда, массовый коэффициент ослабления, рентгеновское излучение, алмазы

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Introduction

The physical basis of the X-ray absorption technology for enrichment of minerals is the attenuation (absorption and scattering) of electromagnetic radiation in the X-ray spectrum passing through diamond-bearing ore. A distinguishing feature in separation of minerals is the difference in radiation intensities transmitted through the ore in its cross-sections with and without diamonds.

The advances in the X-ray absorption technology made recently allow to replace the common methods for processing diamond-bearing ores with this technology, not only during recovery but also in the main stages of enrichment [1].

Currently, X-ray fluorescence (XRF), gravity-based separation and techniques using grease tables are widely used in mining.

The physical basis of the XRF technique is the fluorescence of the diamond exposed to X-ray pulses. To analyze this fluorescence, two separation criteria are used: the autocorrelation function and the ratio of the components of the fluorescence lifetime [1]. The diamond must be located on the surface of a piece of kimberlite for such analysis, otherwise it will not be detected. Consequently, ore should be disintegrated in wet ball mills or jaw crushers, which causes damage (chipping) to the stones, significantly reducing their cost. In addition to chipping, losses due to uncharacteristic fluorescence kinetics typical for diamonds occur during XRF separation [2].

To overcome this drawback, research is underway on treating raw materials with organic luminophores to modify the X-ray fluorescent properties of weakly fluorescent diamonds and selectively identify them in XRF separators [3].

The physical basis of gravity (heavy-media) separation technology is the difference in the density of diamonds and gangue. The density of a diamond is 3.40–3.55 g/cm^3, while that of gangue is about 2.5 g/cm^3. In the process of such separation in a liquid medium with a density of about 3.0 g/cm^3, diamond-bearing ore sinks to the bottom of the container and gangue floats to the surface. Rotating the liquid together with ore pieces in special hydrocyclones accelerates the separation process [4]. The advantage of gravity technology is that it allows to extract rough diamonds (located inside pieces of ore). Its disadvantages include the need for precision control of the density of heavy liquid, maintained at the level of 3.0 g/cm^3, and most importantly, environmental damages.

The physical basis of the grease-based technology is the difference in the adhesion of diamond and kimberlite pieces to the grease table. Grease separation is mainly used in at the recovery stage.

Great efforts are made to improve the technologies for processing diamond ore. Recent advances include a dual-energy X-ray separation method using nanosecond pulses of two energy levels of an explosive electron emission-based X-ray tube [5], as well as complementing the X-ray fluorescence method with X-ray absorption [6, 7].

The above-mentioned drawbacks of diamond ore processing technologies can be significantly mitigated or even completely eliminated by introducing the X-ray absorption immersion technology (XRAIT) [8].

XRAIT is based on placing pieces of diamond ore into an immersion medium (IM) with a linear X-ray attenuation coefficient close to the linear attenuation coefficient of kimberlite. The IM is intended for filling all cavities between diamond ore pieces, ore with a constant thickness on the transporter [9].

IM allows to arrange pieces of diamond-bearing ore on a transporter as a parallelepiped made of kimberlite, inside which a diamond may be located. The schematic diagram for XRAIT is shown in Fig. 1.

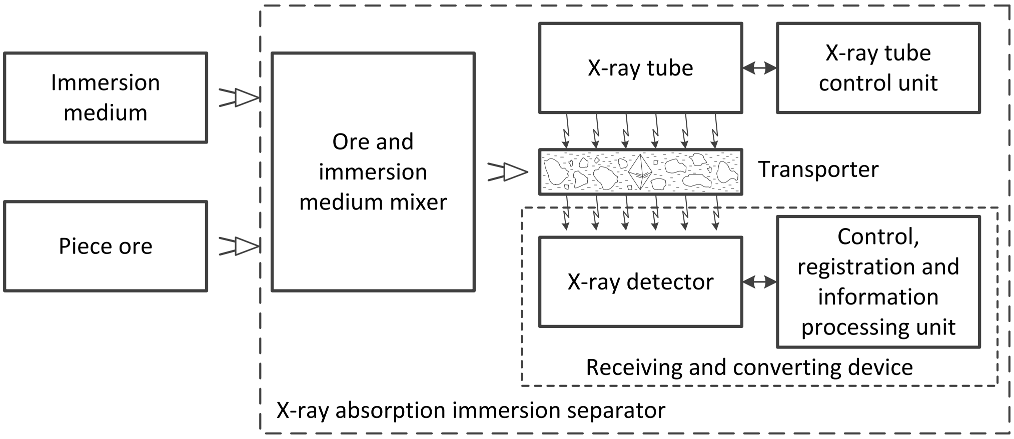

Fig. 1. Schematic diagram of X-ray absorption immersion technology:
immersion medium; piece ore; X-ray tube control unit; receiving and converting device

The goals of this study consisted in theoretical analysis of the physical foundations of X-ray absorption immersion technology, aimed at resolving its main technological drawbacks.

To achieve these goals, we analyzed the attenuation of X-ray radiation in diamond and related minerals, conducting experimental tests to validate the proposed technology

Attenuation of X-ray radiation by different media

The penetrating radiation generated in the X-ray tube passes through a mixture of ore and IM, is converted into optical radiation in the scintillator, which, in turn, is converted into electrical signal in the receiving and converting device. The braking radiation of the X-ray tube is generated during the curvilinear motion of electrons in the Coulomb field of atoms in the tube's anode. In addition to braking radiation, X-ray tubes emit rather narrow spectral lines of characteristic X-ray radiation associated with the transition of electrons from one orbit to another. However, significantly lower energy is concentrated in the characteristic radiation compared to the braking radiation, which makes it possible not to neglect the characteristic radiation in calculations of intensity and transmitted radiation.

The XRAIT is based on the detecting radiation transmitted through ore placed in IM with a linear attenuation coefficient close to the linear attenuation coefficient of gangue of diamond-bearing ore. As a result, the intensity level of X-ray radiation after passing through diamond-bearing ore in IM is determined by the attenuation of radiation in kimberlite, diamond, IM and scintillator. A photocurrent proportional to the intensity of the transmitted X-ray radiation is formed in the receiving and converting device.

The X-ray radiation intensity I_x at the medium depth x is determined by the Bouguer—Lambert law:

$$I_x = I_0 \exp\{-\mu_x x\} = I_0 \exp\{-\mu_m \rho x\}, \tag{1}$$

where μ_x is the linear attenuation coefficient of X-ray radiation, μ_m is the mass attenuation coefficient, ρ is the density of absorbing substance, I_0 is the intensity of incident radiation.

The mass attenuation coefficient, unlike the linear one, does not depend on the aggregate state of the substance. The mass attenuation coefficients of the elements obtained experimentally can be found in reference tables in [10].

Approximations of the energy dependence of mass attenuation coefficients are used for analytical calculations of penetrating radiation. In contrast to the discrete range of energies given in the tables with experimental data [10], the approximated dependences allow to calculate X-ray attenuation continuously for all photon energies.

The smallest error of the approximations of mass attenuation coefficient considered is provided by the approximation in the form of a sum of two power functions:

$$\begin{cases} \mu_1 = a_{11}E^{-b_{11}} + a_{12}E^{-b_{12}} + c_1, \; E < E_k, \\ \mu_2 = a_{21}E^{-b_{21}} + a_{22}E^{-b_{22}} + c_2, \; E \geq E_k, \end{cases} \tag{2}$$

where E_k is the energy of the k-absorption edge.

The relative error of this approximation for elements with the atomic number Z lower than 26 in the energy range of 1–150 keV does not exceed 1% compared with experimental data [10]. The relative error does not exceed 2% for elements with the atomic number higher than 26 (^{26}Fe) in the range of 1–400 keV. Table 1 gives the approximations obtained for the mass attenuation coefficients of the elements of diamond-bearing ore, the materials of anodes of X-ray tubes, filters and scintillators. Characteristic radiation was not taken into account.

The mass attenuation coefficient of a complex molecule is

$$(\mu_m)_{mol} = \sum_i C_i \mu_{mi}, \tag{3}$$

where μ_{mi} is the mass attenuation coefficient of the ith element in the molecule, C_i is the mass fraction of the ith element in the molecule; summation is carried out for all elements in the molecule. The mass attenuation coefficients of mixtures of suspensions, alloys and solutions are determined similarly. In this case, C_i is the mass fraction of the ith substance in such medium [11].

The intensity of transmitted radiation is reduced by half in the so-called half-value layer (HVL) [11]:

$$d(E) = \frac{\ln 2}{\mu_m(E) \cdot \rho} = \frac{\ln 2}{\mu_x(E)}. \tag{4}$$

The chemical compositions of the main components of the diamond-bearing ore are given in Table 2. Based on the energy dependences obtained for the mass attenuation coefficients of the elements, in accordance with expressions (3) and (4), we calculated the HVL of the components of diamond-bearing ore depending on the energy of X-ray photons for the ranges of 10–100 and 100–1000 keV (Fig. 2).

The HVL of diamond significantly exceeds those of any components of the diamond-bearing ore in the photon energy range of 10–50 keV (see Fig. 2, *a*). At an energy of 30 keV, the HVL of diamond exceeds the HVL of the nearest component of the diamond-bearing ore, serpentine, by two times.

XRAIT is based on X-ray attenuation by the diamond in the photon energy range of 10–50 keV, where the half-value layer exceedsthose for all other minerals in the ore. An additional factor is that the cavities between the ore pieces are filled with the immersion medium with a linear attenuation coefficient close to the average for all ore components taking into account their mass fraction.

Diamond is significantly more transparent than any of the other components of the diamond-bearing ore in the photon energy range of 10–50 keV. The IM is used to fill cavities between pieces of diamond-bearing ore. Then there is a significant increase in the intensity of transmitted X-ray radiation in the diamond cross-section. If the cavities are left unfilled, the intensity of the transmitted X-ray radiation in the cross-sections of the cavities increases as if this cross-section contained a large diamond. There are a lot of cavities between pieces of ore on the multilayer transporter, therefore XRAIT without the IM cannot be used to isolate pieces of ore containing diamonds.

Table 1

Formulas of approximations obtained for mass attenuation coefficients of elements by summation of two power functions (see Eq. (2))

Element	Approximation formula for μ (*E*, keV), cm²/g	Energy range *E*, keV
^{6}C	$2.781\cdot10^{3}\cdot E^{-3.100} - 8.477\cdot10^{-4}\cdot E^{0.840} + 0.1930$	$1.0000 \le E < 200.00$
^{8}O	$6.284\cdot10^{3}\cdot E^{-3.032} - 3.403\cdot10^{-4}\cdot E^{0.977} + 0.1820$	$1.0000 \le E < 200.00$
^{11}Na	$1.575\cdot10^{4}\cdot E^{-3.010} - 7.884\cdot10^{-7}\cdot E^{2.044} + 0.1557$	$1.0000 \le E < 200.00$
^{12}Mg	$2.130\cdot10^{4}\cdot E^{-3.007} - 6.825\cdot10^{-6}\cdot E^{1.655} + 0.1640$	$1.0000 \le E < 200.00$
^{13}Al	$1.955\cdot10^{3}\cdot E^{-2.623} - 10.5560$ $2.390\cdot10^{4}\cdot E^{-2.961} - 1.880\cdot10^{4}\cdot E^{-4.541} + 0.1430$	$1.0000 \le E < 1.5596$ $1.5596 \le E < 105.00$
^{14}Si	$1.582\cdot10^{3}\cdot E^{-2.616} - 12.2000$ $3.190\cdot10^{4}\cdot E^{-2.967} - 3.020\cdot10^{4}\cdot E^{-4.403} + 0.1480$	$1.0000 \le E < 1.8389$ $1.8389 \le E < 110.00$
^{19}K	$4.272\cdot10^{3}\cdot E^{-2.684} - 2.100\cdot10^{2}\cdot E^{-6.354} - 3.7300$ $7.720\cdot10^{4}\cdot E^{-2.949} - 1.080\cdot10^{5}\cdot E^{-4.094} + 0.1350$	$1.0000 \le E< 3.6074$ $3.6074 \le E < 125.00$
^{20}Ca	$5.163\cdot10^{3}\cdot E^{-2.677} - 2.900\cdot10^{2}\cdot E^{-6.183} - 4.3500$ $8.565\cdot10^{4}\cdot E^{-2.930} - 1.855\cdot10^{5}\cdot E^{-4.367} + 0.1365$	$1.0000 \le E < 4.0381$ $4.0381 \le E < 125.00$
^{25}Mn	$9.770\cdot10^{3}\cdot E^{-2.716} - 1.680\cdot10^{3}\cdot E^{-4.701} - 1.3000$ $1.380\cdot10^{5}\cdot E^{-2.902} - 7.830\cdot10^{5}\cdot E^{-4.580} + 0.1185$	$1.0000 \le E < 6.5390$ $6.5390 \le E < 150.00$
^{26}Fe	$1.113\cdot10^{4}\cdot E^{-2.709} - 2.050\cdot10^{3}\cdot E^{-4.758} - 1.4000$ $1.555\cdot10^{5}\cdot E^{-2.897} - 10.45\cdot10^{5}\cdot E^{-4.609} + 0.1204$	$1.0000 \le E < 7.1120$ $7.1120 \le E < 150.00$
^{29}Cu	$1.505\cdot10^{4}\cdot E^{-2.709} - 3.700\cdot10^{3}\cdot E^{-4.741} - 1.0000$ $1.840\cdot10^{5}\cdot E^{-2.864} - 8.300\cdot10^{6}\cdot E^{-5.350} + 0.1120$	$1.0961 \le E < 8.9789$ $8.9789 \le E < 175.00$
^{30}Zn	$1.685\cdot10^{4}\cdot E^{-2.710} - 4.600\cdot10^{3}\cdot E^{-4.617} - 0.9000$ $2.029\cdot10^{5}\cdot E^{-2.859} - 3.600\cdot10^{6}\cdot E^{-4.872} + 0.1100$	$1.1936 \le E < 9.6586$ $9.6586 \le E < 195.00$
^{39}Y	$3.210\cdot10^{4}\cdot E^{-2.660} - 2.777\cdot10^{4}\cdot E^{-5.381} - 0.9100$ $3.131\cdot10^{5}\cdot E^{-2.791} - 8.232\cdot10^{7}\cdot E^{-5.558} + 0.0950$	$2.3725 \le E < 17.0384$ $17.0384 \le E < 220.00$
^{42}Mo	$4.007\cdot10^{4}\cdot E^{-2.665} - 9.713\cdot10^{4}\cdot E^{-5.978} - 0.6500$ $3.852\cdot10^{5}\cdot E^{-2.792} - 1.489\cdot10^{8}\cdot E^{-5.533} + 0.0970$	$2.8655 \le E < 19.9995$ $19.9995 \le E < 220.00$
^{47}Ag	$5.557\cdot10^{4}\cdot E^{-2.667} - 5.017\cdot10^{5}\cdot E^{-6.354} - 0.3500$ $4.413\cdot10^{5}\cdot E^{-2.751} - 1.476\cdot10^{9}\cdot E^{-6.066} + 0.0895$	$3.8058 \le E < 25.5140$ $25.5140 \le E < 280.00$
^{48}Cd	$5.733\cdot10^{4}\cdot E^{-2.663} - 8.930\cdot10^{5}\cdot E^{-6.629} - 0.3200$ $4.439\cdot10^{4}\cdot E^{-2.743} - 4.511\cdot10^{8}\cdot E^{-5.663} + 0.0850$	$4.0180 \le E < 26.7112$ $26.7112 \le E < 320.00$
^{53}I	$8.091\cdot10^{4}\cdot E^{-2.693} - 1.333\cdot10^{6}\cdot E^{-5.932} + 0.0600$ $5.245\cdot10^{5}\cdot E^{-2.724} - 1.200\cdot10^{9}\cdot E^{-5.790} + 0.0824$	$5.1881 \le E < 33.1694$ $33.1694 \le E < 320.00$
^{55}Cs	$8.757\cdot10^{4}\cdot E^{-2.684} - 2.230\cdot10^{6}\cdot E^{-6.050} + 0.0260$ $5.920\cdot10^{5}\cdot E^{-2.732} - 2.150\cdot10^{10}\cdot E^{-6.447} + 0.0860$	$5.7143 \le E < 35.9846$ $35.9846 \le E < 320.00$
^{56}Ba	$8.986\cdot10^{4}\cdot E^{-2.679} - 2.253\cdot10^{6}\cdot E^{-5.983} + 0.0210$ $5.943\cdot10^{5}\cdot E^{-2.725} - 1.631\cdot10^{10}\cdot E^{-6.368} + 0.0839$	$5.9888 \le E < 37.4406$ $37.4406 \le E < 320.00$
^{64}Gd	$1.294\cdot10^{5}\cdot E^{-2.669} - 3.501\cdot10^{5}\cdot \mathrm{E}^{-6.639} + 0.0800$ $7.300\cdot \text{١٠}^{5}\cdot E^{-2.689} - 1.330\cdot10^{8}\cdot E^{-4.800} + 0.0818$	$8.3756 \le E < 50.2391$ $50.2391 \le E < 320.00$
^{65}Tb	$1.341\cdot10^{5}\cdot E^{-2.664} - 4.335\cdot10^{7}\cdot E^{-6.673} + 0.0740$ $7.520\cdot10^{5}\cdot E^{-2.684} - 2.260\cdot10^{7}\cdot E^{-4.300} + 0.0804$	$8.7080 \le E < 51.9957$ $51.9957 \le E < 320.00$
^{74}W	$1.959\cdot10^{5}\cdot E^{-2.665} - 2.036\cdot10^{7}\cdot E^{-5.619} + 0.1390$ $7.715\cdot10^{5}\cdot E^{-2.623} - 3.140\cdot10^{8}\cdot E^{-4.981} + 0.0775$	$12.0998 \le E < 69.5250$ $69.5250 \le E < 400.00$
^{79}Au	$2.194\cdot10^{5}\cdot E^{-2.642} - 3.200\cdot10^{7}\cdot E^{-5.631} + 0.1290$ $8.118\cdot10^{5}\cdot E^{-2.600} - 2.784\cdot10^{7}\cdot E^{-4.400} + 0.0795$	$14.3528 \le E < 80.7249$ $80.7249 \le E < 400.00$
^{82}Pb	$2.385\cdot10^{5}\cdot E^{-2.636} - 3.226\cdot10^{7}\cdot E^{-5.471} + 0.1250$ $7.526\cdot10^{5}\cdot E^{-2.569} + 0.0770$	$15.8608 \le E < 88.0045$ $88.0045 \le E < 400.00$

Table 2

Key characteristics of natural minerals of diamond-bearing ore

Number	Mineral	Chemical formula	Density, kg/m^3
1	Serpentine	$Mg_6Si_4O_{18}H_8$	2.52
2	Quartz	SiO_2	2.60
3	Diamond	**C**	**3.51**
4	Calcite	$CaCO_3$	2.65
5	Pyrope	$Mg_3Al_2Si_3O_{12}$	3.55
6	Kyanite	Al_2O_8Si	3.58
7	Diopside	$CaMgSiO_2$	3.28
8	Biotite	$KMg_3Fe_3AlO_{12}H_2F_2$	3.00
9	Ilmenite	$FeTiO_3$	4.73
10	Pyrite	FeS_2	4.95
11	Magnetite	Fe_3O_4	5.00
12	Zircon	$SrSiO_4$	4.66
13	Scheelite	$CaWO_4$	5.90

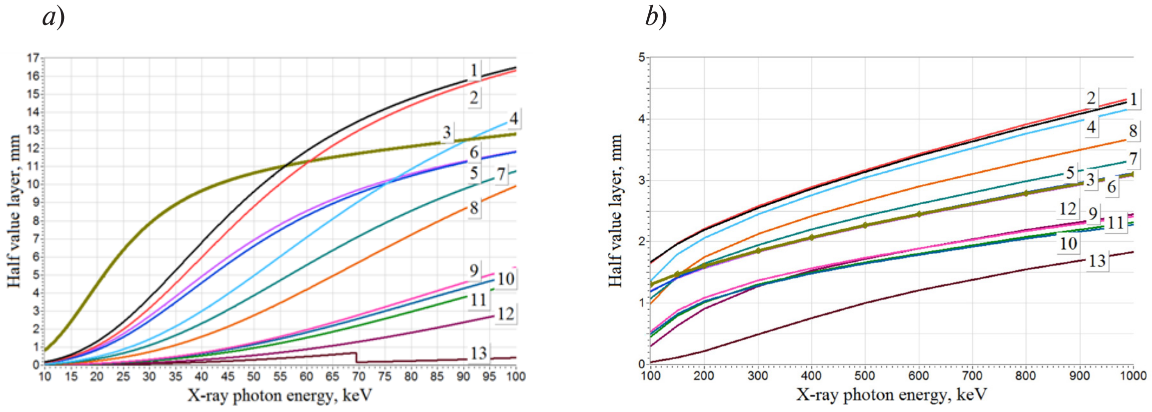

Fig. 2. Dependences of half-value layer for components of diamond-bearing ore on X-ray photon energies in range of 10–100 keV (*a*) and 100–1000 keV (*b*)
Curve numbers correspond to those in Table 2

In the case when the IM evenly fills all cavities between the ore pieces, X-ray radiation is guaranteed to pass through the same thickness of the component mixture: ore, diamond and IM. The characteristic differentiating the diamond from gangue is the transmitted X-ray radiation exceeding the threshold determined by fluctuations in the X-ray background associated with inhomogeneous composition of the ore.

The patent [5] proposes a method for dual-energy X-ray projection separation of mineral raw materials based on reducing the attenuation coefficient compared to the host rock at low X-ray radiation energy (values of 20–230 keV are given) and (conversely) increasing this coefficient at a high energy level (250–700 keV).

Notably, such ore components as serpentine, quartz, calcite, and biotite attenuate primary radiation to a smaller extent than diamond in the energy range of 250–700 keV (see Fig. 2,*b*). Therefore, these minerals fit the differentiation criterion proposed in the patent [5]. However, minerals such as diopside, pyrope, and kyanite are practically indistinguishable from diamonds in terms of attenuation of penetrating radiation. As for minerals such as ilmenite, pyrite, magnetite, zircon and scheelite, they have significantly lower transparency compared to diamond the same as in range of 10–50 keV. This means that these minerals do not fit the differentiation criterion proposed in the patent [5]. As a result, the method proposed by in the patent [5] is not always applicable for separating diamond from its ore.

Experimental results obtained with X-ray absorption immersion separator

The proposed technology is based on X-ray absorption immersion separators. We fabricated a prototype separator, using to detect rough diamonds in pieces of kimberlite. The separator consists of the following parts:

X-ray tube with control unit and cooling system for tungsten anode with running water;
vibratory feeder supplying ore;
feeder supplying immersion medium;
separation device;
receiving and converting device.

The X-ray radiation transmitted through the ore in IM is converted into electrical signal in the receiving and converting device, which includes a position-sensitive scintillation detector based on gadolinium oxysulfide $Gd_2O_2S(Tb)$ (0.3 mm thick), 256 photodiode-based integrated photodetectors and operational amplifiers with capacitive feedback and control unit for detection of penetrating X-ray radiation, information processing and control of separator actuators. The $Gd_2O_2S(Tb)$ scintillator converts transmitted X-rays into green light (visible range), which is then transmitted to photodiodes. The electric charge from the photodiodes, proportional to the transmitted X-ray radiation, is supplied to the operational amplifier integrators. The control unit allows to visualize the intensity of the transmitted X-ray radiation in the cross-section of the transporter as graphs on a computer screen.

The IM can be liquid: both in the form of suspensions and aqueous solutions of salts. The experimental studies conducted confirmed the possibility of using suspensions of barium sulfate ($BaSO_4$) and ferrosilicon (FeSi). Testing of many aqueous solutions made it possible to isolate potassium iodide (KI), lead acetic acid ($Pb(CH_3COO)_2 \cdot 3H_2O$) and sodium tungstate ($Na_2WO_4 \cdot 2H_2O$) for practical use. To achieve the required linear attenuation coefficient of the IM, it is necessary to select the appropriate concentration. Importantly, the required mass density of immersion suspensions and solutions turned out to be lower than the density of liquid media in gravity technology.

However, the following problem arose: when ore pieces and liquid IM were mixed, air bubbles were formed that were even more transparent to X-rays than diamonds; as a result, the bubbles were mistakenly detected as large diamonds. Despite attempts to remove the bubbles by flushing, it was not possible to obtain an effective solution to this problem.

The immersion medium in the form of bulk powder yielded much better results. In this case, uniform thickness of the bulk material layer had to be achieved, but this task was easily solved using a scraper mounted above the transporter. Experiments were conducted for milled ferrosilicon, iron oxide, separately for iron and aluminum powders, aluminum alloy powders with tin and copper, with zinc, with nickel and quartz sand.

Metal alloy powders are used in powder metallurgy, so they are more affordable, as they are produced industrially. In terms of X-ray absorption and consumer properties, aluminum alloy powder with zinc (94% Al + 6% Zn) with a fraction of 100–200 μm has proved to be the best option. This material has a number of advantages: it is completely non-hazardous, it has good flowability, it is dust-free, it separates perfectly from pieces of diamond-bearing ore, dries and does not clump. Due to these properties, it is comparatively easy to return the material to the circulation cycle of the immersion medium at mining facilities. The powder made it possible to completely solve the problem of air bubbles on the transporter.

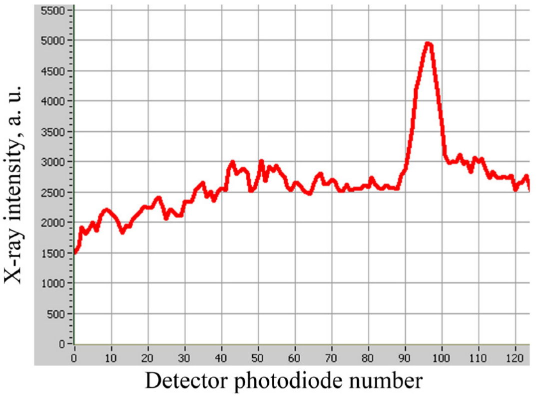

Fig. 3. Distribution of X-ray radiation intensity transmitted through ore with 4 mm diamond placed in immersion medium (Al +Zn alloy powder) along transporter cross-section

Photodiode numbers of the position-sensitive scintillation detector are plotted along the ordinate

Detection of rough diamonds using the proposed XRAIT was carried out on with an experimental prototype separator. The obtained results are presented in Fig. 3, showing the intensity distribution of the transmitted X-ray radiation through ore pieces in the cross section of the transporter at a 30 kV anode voltage of the X-ray tube and a layer thickness of 26 mm. The IM was an aluminum alloy powder with zinc (94% Al + 6% Zn), fraction of 100–200 μm, bulk density of 1.46 g/cm^3.

The response amplitude of the 4 mm diamond was twice as high as the average level of the transmitted X-ray radiation. The ratio of useful signal depending on the presence of diamond to the fluctuation level associated with the inhomogeneity of fractions in kimberlite pieces exceeded a fivefold value. As a result, the probability of detecting diamond in a piece of diamond-bearing ore was 99%.

Conclusion

Studies of the physical foundations of X-ray absorption immersion technology provided insights into the propagation of X-rays in diamond-bearing ore containing many different minerals: serpentine, quartz, calcite, pyrope, kyanite, diopside, biotite, ilmenite, zircon and scheelite. We found and justified a convenient range of X–ray photon energies, 10–50 keV, where diamond is more transparent to penetrating X-rays compared with other natural minerals of diamond-bearing ore. It was established that serpentine is the closest in transparency to diamond in this range.

To mathematically describe the physical phenomenon of attenuation of penetrating X-ray radiation through objects, we constructed a model with an approximation of the mass attenuation coefficients by the sum of two power functions containing a set of key parameters. The proposed approximations give a relative error of 1–2% in the energy range of 1–400 keV and are suitable for calculating the energy dependences of penetrating X-ray radiation.

Based on the detected patterns of X-ray attenuation, we proposed an X-ray absorption immersion technology for extracting natural diamonds, which involves filling cavities between pieces of kimberlite with an immersion medium with a linear attenuation coefficient equal to the average for all ore components, taking into account their mass fractions. We established the advantages of using an immersion medium in the form of a bulk material (aluminum alloy powder with zinc) over liquid immersion media where the influence of air bubbles has to be eliminated.

The proposed X-ray absorption immersion method was validated with a prototype separator we developed and fabricated, used for experiments to detect rough diamonds in pieces of kimberlite. The experiments revealed that the response amplitude of a 4 mm diamond is twice as high as the average level of the transmitted X-ray radiation. Such an important indicator as the ratio of useful signal corresponding to the presence of diamond to the level of fluctuations associated with the inhomogeneity of fractions in the composition of kimberlite pieces was found to exceed a fivefold value. As a result, the presence of diamond in a piece of diamond-bearing ore is determined with a high probability of 99%.

The proposed X-ray absorption immersion technology for extracting natural diamonds offers significant advantages:

possibility of extracting rough diamonds,
reduced amount of chipping during ore disintegration,
possibility of extracting weakly fluorescent diamonds,
low environmental damage.

Naturally, such advantageous technology will require additional equipment at mining facilities to mix the immersion medium (dry powder) with disintegrated diamond-bearing ore and ensure a closed cycle reusing the immersion medium. The workflow of the facilities will also require restructuring.

However, such costs are undoubtedly justified and will pay off quickly: even saving only one 100-carat diamond from chipping generates revenue of up to tens of millions of dollars.

Adjusting the technical parameters of X-ray absorption immersion separators will make it possible to achieve diamond extraction in poor and remote deposits, and even mining of tailings in existing deposits with high economic efficiency.

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REFERENCES

1. **Zyryanov I. V., Yakovlev V. N., Ivanov A. V., Makalin I. A.,** Istoriya i perspektivy razvitiya otechestvennoy tekhnologii radiometricheskogo obogashcheniya almazosoderzhashchikh rud [History and prospects for the development of domestic technology for radiometric enrichment of diamond ores], Gornyi Zhurnal [Mining Magazine]. (2) (2024) 37–41 (in Russian).
2. **Mironov V. P., Emelyanova A. S., Shabalin S. A., et al.,** X-ray luminescence in diamonds and its application in industry, AIP Conf. Proc. 2392 (1) (2021) 020010.
3. **Morozov V. V., Chanturia V. A., Dvoichenkova G. P., et al.,** Selecting organic collectors for luminophore-bearing modifying agents to extract weakly fluorescent diamonds, J. Min. Sci. 59 (2) (2023) 292–301.
4. **Karlina A.,** Mineral gravity separation hydrodynamics study, Proc. Irkutsk State Techn. Univers. (3(98)) (2015) 194–199 (in Russian).
5. **Dvortsov M. A., Komarskii A. A., Korzhenevskii S. R., Korzhenevskii N. S.,** Method and device for X-ray projection separation of mineral raw materials, Pat. No. 2785068 Russian Federation, MPK B 07 C 5/34, G 01 N 23/083; OOO “IMPULS-U” is a declarant and patentee. No. 2022105162; declar.26.02.2022; publ. 02.12.2022, Bull. No. 34.
6. **Modise E. G., Zungeru A. M., Mtengi B., Ude A.,** A fast and noise rejecting Kolmogorov – Smirnov sorting algorithm in X-ray diamond sorting, Proc. 2022 Int. Conf. Smart Appl., Commun. Networking (SmartNets). Nov.29th–Dec. 1st, 2022. Palapye, Botswana (Southern Africa) (2022) 1–5.
7. **Modise E. G., Zungeru A. M., Chuma J. M., et al.,** The new paradox of dual modality X-ray diamond sorting, IEEE Photonics J. 13 (3) (2021) 3400124.
8. **Kuptsov V. D., Valjukhov V. P. Novikov V. V., Olkhovoy V. A.,** The new natural diamonds extraction out of fragmented kimberlite technology, Trudy SPbGTU [Transactions of St. Petersburg State Technical University]. (507) (2008) 98–100 (in Russian).
9. **Novikov V. V., Rudakov V. V., Zlobin M. N., et al.,** The method of separation of minerals, Pat. No. 2472595 Russian Federation, MPK B07C 5/346, Novikov Vladlen Vasilyevich is a declarant and patentee. No. 2011150666/12; declar. 14.12.2011; publ. 20.01.2013, Bull. No. 2.
10. Physical reference data. Tables of X-ray mass attenuation coefficients and mass energy-absorption coefficients. Access Mode: http://physics.nist.gov/PhysRef Data/ XrayMassCoef /cover.html (Date of Access is 15.06.2024).
11. **Pavlinsky G. V.,** Fundamentals of X-ray physics, Cambridge International Science Publishing, Cambridge, UK, 2008.

СПИСОК ЛИТЕРАТУРЫ

1. **Зырянов И. В., Яковлев В. Н., Иванов А. В., Макалин И. А.** История и перспективы развития отечественной технологии радиометрического обогащения алмазосодержащих руд // Горный журнал. 2024. № 2. С. 37–41.

2. **Mironov V. P., Emelyanova A. S., Shabalin S. A., Bubyr E. V., Kazakov L. V., Martynovich E. F.** X-ray luminescence in diamonds and its application in industry // AIP Conference Proceedings. 2021. Vol. 2392. No. 1. P. 020010.

3. **Морозов В. В., Чантурия В. А., Двойченкова Г. П., Чантурия В. А., Подкаменный Ю. А.** Выбор органических коллекторов в составе люминофорсодержащих модификаторов для извлечения слабосветящихся алмазов // Физико-технические проблемы разработки полезных ископаемых. 2023. № 2. С. 122–133.

4. **Карлина А. И.** Изучение гидродинамики гравитационного обогащения полезных ископаемых // Вестник Иркутского государственного технического университета. 2015. № 3 (98). С. 194–199.

5. **Дворцов М. А., Комарский А. А., Корженевский С. Р., Корженевский Н. С.** Способ и устройство для рентгенопроекционной сепарации минерального сырья. Пат. 2785068 Российская Федерация, МПК B 07 C 5/34, G 01 N 23/083., заявитель и патентообладатель ООО «ИМПУЛЬС-У». № 2022105162; заявл.26.02.2022; опубл. 02.12.2022, Бюл. № 34. 22 с.

6. **Modise E. G., Zungeru A. M., Mtengi B., Ude A.** A fast and noise rejecting Kolmogorov – Smirnov sorting algorithm in X-ray diamond sorting // Proceedings of the 2022 International Conference on Smart Applications, Communications and Networking (SmartNets). Nov.29th–Dec 1st, 2022. Palapye, Botswana (Southern Africa), 2022. Pp. 1–5.

7. **Modise E. G., Zungeru A. M., Chuma J. M., Prabaharan S. R. S., Mtengi B., Ude A., Nedev Z.** The new paradox of dual modality X-ray diamond sorting // IEEE Photonics Journal. 2021. Vol. 13. No. 3. P. 3400124.

8. **Купцов В. Д., Валюхов В. П. Новиков В. В., Ольховой В. А.** Новая технология извлечения природных алмазов в кусках кимберлита // Труды СПбГТУ. 2008. № 507. С. 98–100.

9. **Новиков В. В., Рудаков В. В., Злобин М. Н., Малаховский В. И., Купцов В. Д., Валюхов В. П., Купцов М. В., Ольховой В. А.** Способ сепарации минералов. Пат. 2472595 Российская Федерация, МПК B07C 5/346, заявитель и патентообладатель Новиков Владлен Васильевич. № 2011150666/12; заявл.14.12.2011; опубл. 20.01.2013, Бюл. № 2. 11 с.

10. Physical reference data. Tables of X-ray mass attenuation coefficients and mass energy-absorption coefficients. Режим доступа: http://physics.nist.gov/PhysRefData/XrayMassCoef/cover.html (дата обращения: 15.06.2024).

11. **Павлинский Г. В.** Основы физики рентгеновского излучения: Физматлит, 2007. 240 с.

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