



## BENEFICIATION AND PROCESSING OF NATURAL AND TECHNOGENIC RAW MATERIALS

Research article

<https://doi.org/10.17073/2500-0632-2021-3-170-180>**Selection of recycled water electrochemical conditioning parameters for preparation of diamond-bearing kimberlite for froth separation**G. P. Dvoichenkova<sup>1,2</sup>  , V. V. Morozov<sup>3</sup>   , E. L. Chanturia<sup>3</sup>  , E. G. Kovalenko<sup>2,4</sup> <sup>1</sup> Institute of Comprehensive Exploitation of Mineral Resources Russian Academy of Sciences, Moscow, Russian Federation<sup>2</sup> Mirny Polytechnic Institute (Branch) of the North-Eastern Federal University named after M. K. Ammosov, Mirny, Russian Federation<sup>3</sup> National University of Science and Technology “MISiS” (NUST “MISiS”), Moscow, Russian Federation<sup>4</sup> “Yakutnioproalmaz Institute, ALROSA JSC, Mirny, Russian Federation [dchmggu@mail.ru](mailto:dchmggu@mail.ru)**Abstract**

The main reason of decreasing diamond recovery through froth separation is their surface hydrophilization by hypergene minerals and technogenic films, crystallized from the supersaturated aqueous phase, fixed on the surface structurally or by adhesion. Various types of physical actions, including thermal and ultrasonic treatment of the initial feed of froth separation, are recommended to increase the diamond-bearing kimberlite beneficiation process performance, providing cleaning of the surface of diamonds due to destruction of their accretions with rock minerals and removal of film hydrophilizing coatings from the surface of diamond crystals. A sample of kimberlite material with a given content of diamonds of 1.5–2 mm in size was used as a subject of research in the process of froth separation. The results of thermodynamic calculations and experimental research have substantiated the necessity of using electrochemical conditioning of recycled water for increasing the efficiency of diamond surface cleaning in froth separation operation when using the process of thermal treatment of initial ore feed. The use of diaphragmless electrochemical conditioning of recycled water increases the efficiency of thermochemical dissolution of hydrophilizing compounds on the surface of diamonds through reducing the concentration of calcium and carbonate ions as well as through shifting the medium pH to 6.1–6.5. The measurements of the limiting wetting angle showed that the maximum effect of increasing the diamond surface hydrophobicity was achieved when heat and electrochemical treatment were used together. Laboratory studies showed the possibility of increasing flotation diamond extraction from 65.7 to 91.4 % through application of electrochemical conditioning of recycled water. The optimum parameters of diaphragmless electrochemical treatment of recycled water of the froth separation cycle in conditions of application of pulp heat treatment: current density of 175–200 A/m<sup>2</sup> and power consumption of 1.2–1.5 kWh/m<sup>3</sup>. Tests carried out at processing plant No. 3 of the Mirny GOK (Mining and Processing Complex) (Mirny, Yakutiya) showed that the application of the developed froth separation process intensification method with the use of thermal treatment of pulp and electrochemical diaphragmless treatment of recycled water allowed increasing the recovery of diamonds of +0.5–2 mm size by 4.9–5.1 %.

**Keywords**

diamond, extraction, mining, kimberlite, hydrophilizing compounds, purification, froth separation, recycled water, electrochemical conditioning, heat treatment, Mirny GOK, Yakutiya

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## ОБОГАЩЕНИЕ, ПЕРЕРАБОТКА МИНЕРАЛЬНОГО И ТЕХНОГЕННОГО СЫРЬЯ

Научная статья

**Выбор параметров электрохимического кондиционирования оборотной воды при подготовке алмазосодержащих кимберлитов к пенной сепарации**Г. П. Двойченкова<sup>1,2</sup>  , В. В. Морозов<sup>3</sup>   , Е. Л. Чантурия<sup>3</sup>  , Е. Г. Коваленко<sup>2,4</sup> <sup>1</sup> *Институт проблем комплексного освоения недр РАН (ИПКОН РАН), г. Москва, Российская Федерация*<sup>2</sup> *Мирнинский Политехнический институт – филиал Северо-Восточного федерального университета им. М. К. Аммосова (МПТИ (ф) СВФУ), г. Мирный, Российская Федерация*<sup>3</sup> *Национальный исследовательский технологический университет «Московский институт стали и сплавов» (НИТУ МИСИС), г. Москва, Российская Федерация*<sup>4</sup> *Институт «Якутнипроалмаз», АК «АЛРОСА» (ПАО), г. Мирный, Российская Федерация* [dchmggu@mail.ru](mailto:dchmggu@mail.ru)**Аннотация**

Основной причиной снижения извлечения алмазов методом пенной сепарации является гидрофилизация их поверхности вследствие структурно или адгезионно закрепившихся на ней гипергенных минералов и выкристаллизованных из пересыщенной водной фазы техногенных пленок. Существенное повышение извлечения алмазов в концентрат пенной сепарации может быть достигнуто на основе комбинирования физических и физико-химических методов воздействия на твердую и жидкую фазу рудной пульпы, что определяет актуальность исследований. В качестве предмета исследований в процессе пенной сепарации использована проба кимберлитового материала с заданным содержанием алмазов крупностью 1,5–2 мм. Результатами термодинамических расчетов и экспериментальных исследований обоснована необходимость применения электрохимического кондиционирования оборотной воды для повышения эффективности очистки поверхности алмазов в операции пенной сепарации при применении технологии тепловой обработки исходного рудного питания. Использование бездиафрагменного электрохимического кондиционирования оборотной воды повышает эффективность термодинамического растворения гидрофилизирующих образований на поверхности алмазов за счет снижения концентрации ионов кальция и карбоната, а также смещения pH среды до 6,1–6,5. Проведенными измерениями краевого угла смачивания показано, что максимальный эффект увеличения гидрофобности поверхности алмазов достигается при совместном применении тепловой и электрохимической обработки. Лабораторными исследованиями показана возможность повышения извлечения алмазов при флотации с применением электрохимического кондиционирования оборотной воды с 65,7 до 91,4 %. Выбраны оптимальные параметры бездиафрагменной электрохимической обработки оборотной воды цикла пенной сепарации в условиях применения технологии тепловой обработки пульпы: плотность тока 175–200 А/м<sup>2</sup> и расход электроэнергии 1,2–1,5 кВтч/м<sup>3</sup>. Проведенными на обогатительной фабрике № 3 Мирнинского ГОКа (г. Мирный, Якутия) испытаниями показано, что применение разработанного режима интенсификации процесса пенной сепарации с применением тепловой обработки пульпы и электрохимической бездиафрагменной обработки оборотной воды позволяет повысить извлечение алмазов из класса +0,5–2 мм на 4,9–5,1 %.

**Ключевые слова**

алмазы, извлечение, кимберлиты, гидрофилизирующие образования, очистка, пенная сепарация, оборотная вода, электрохимическое кондиционирование, тепловая обработка, обогатительная фабрика, Мирнинский ГОК, Якутия

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## Introduction

The main reason of decreasing diamond recovery through froth separation is their surface hydrophilization by hypergene minerals and technogenic films, crystallized from the supersaturated aqueous phase, fixed on the surface structurally or by adhesion [1, 2]. Hydrophilic compounds on diamonds converge the degree of hydrophobicity of their surface and the surface of kimberlite minerals that reduces selectivity of diamond-containing product froth separation process in beneficiation flow sheets [3, 4]. Various types of physical actions, including thermal and ultrasonic treatment of the initial feed of froth separation, are recommended to increase the diamond-bearing kimberlite beneficiation process performance, providing cleaning of the surface of diamonds due to destruction of their accretions with rock minerals and removal of film hydrophilizing coatings from the surface of diamond crystals [2, 5, 6]. Significant increase of diamond recovery into froth separation concentrate can be achieved through applying a combination of physical and physical-chemical action methods to solid and liquid phases of diamond-bearing material pulp [7, 8]. The combination of diaphragmless electrochemical treatment of the froth separation cycle recycled water with thermal treatment of the initial material entering the froth separator was proposed as an effective physical-and-chemical method for modifying the properties of mineral components and the liquid phase of the diamond-containing pulp [9], which provided the change in the ionic-molecular composition of the aqueous phase and encourages solving the problem of cleaning the diamond surface from the surface hydrophilizing compounds.

In order to improve the efficiency of the proposed combined process, it is necessary to reveal the regularities of dissolution processes of surface compounds on the diamond crystals when using electrochemical conditioning of recycled water of the froth separation cycle, which allow selecting the method of the most intensive and complete removal of hydrophilizing impurities from the diamond surface and restoration of their natural floatability.

## Research methods

The chemical analysis of the surface compounds on diamonds was performed by electron-probe X-ray spectral analysis (EPXSA) with the use of an electron microscope Jeol-5610 and an energy dispersive attachment (EDA) [10]. The thickness and character of spreading of the selected salient, point and film mineral compounds were determined during scanning of the crystal surface. Assessment of changes in the composition of the surface compounds on diamonds was performed by infrared spectroscopy using a Bruker FTIR spectrophotometer with standard tech-

niques and databases for deciphering infrared spectra [11, 12]. Modeling the processes formation – dissolution of hydrophilizing compounds on the surface of minerals was carried out by plotting and analysis of thermodynamic stability diagrams for calcium and magnesium compounds in coordinates  $\lg[\text{CO}_3] - \text{pH}$  based on thermodynamic analysis of chemical reactions [13]. To estimate the diamond surface hydrophobicity, the method of measuring three-phase limiting wetting angles was applied. The studies were carried out at an OCA 15EC device using standard techniques [14]. A drop of the aqueous phase (1 mm in diameter) was applied with a syringe to flat area of the diamond surface, which was pretreated with the initial recycled water of the froth separation cycle to achieve the effect of technogenic hydrophilization, and then with its electrochemical conditioning product obtained in the established treatment conditions.

A sample of kimberlite material with a given content of diamonds of 1.5–2 mm in size was used as a subject of research in the process of froth separation. Preparation of diamonds for the experimental studies included chemical cleaning of their surface, which was repeated for each individual experiment and consisted of the following operations: diamond crystals were dried, washed in carbon tetrachloride, alcohol, distilled water, and treated with concentrated solution of hydrochloric acid, which removes mineral films. To obtain reliable results, each experiment was repeated twice. The prepared diamonds were mixed with a selected kimberlite grain size of  $-1+0.5$  mm, and the resulting sample was fed to froth separation into a laboratory facility. After the experiment was completed, the diamonds were extracted from the concentrate and tailings, weighed and fed back into the purification cycle.

Process tests were carried out according to the accepted technique of semi-industrial tests using the current products of the diamond-containing kimberlite beneficiation process flow sheet with the plant reagent treatment scheme.

## 1. Analysis of composition and conditions of destruction of hydrophilizing compounds on the diamond surface

The elemental and phase composition of compounds on the diamond surface was determined by method of X-ray photoelectron spectroscopy. On the hydrophilic surface of the crystals, it was detected the presence of relief mineral compounds of carbonate-silicate composition (Fig. 1), film compounds of predominantly carbonate composition, and slurry coatings of predominantly aluminosilicate composition.

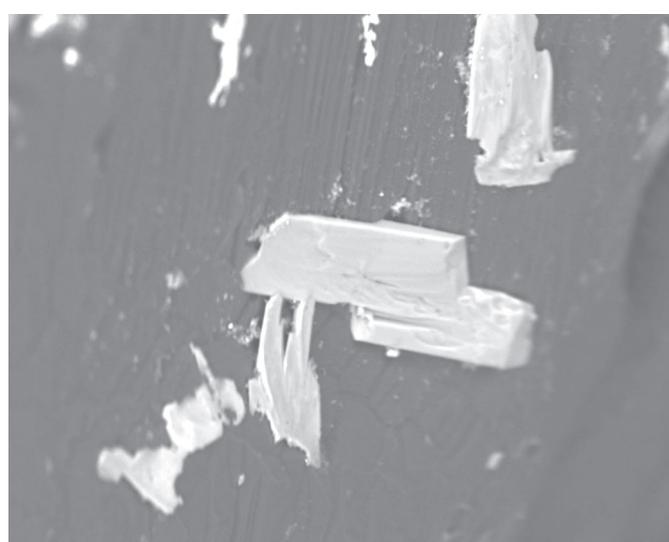
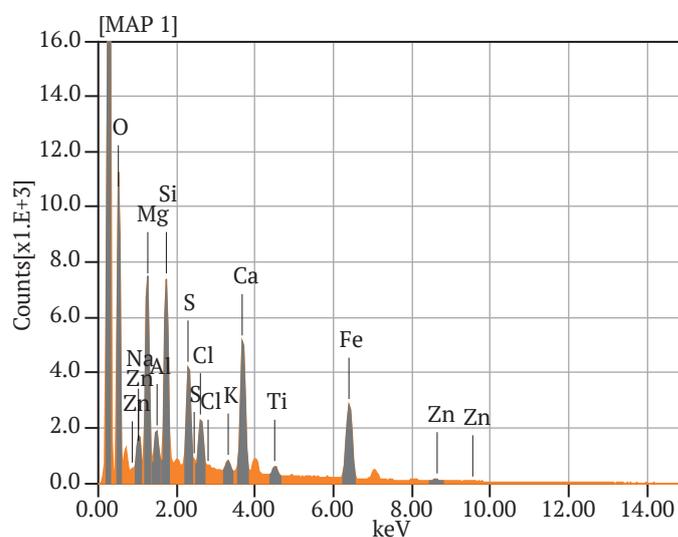
Analysis of the study results showed that the share of mineral compounds on hydrophobic diamonds does not exceed 25 % of the surface area, whereas on

hydrophilic diamonds the share of mineral compounds reaches 70 % and their thickness is 2–3 times greater than on hydrophobic diamonds.

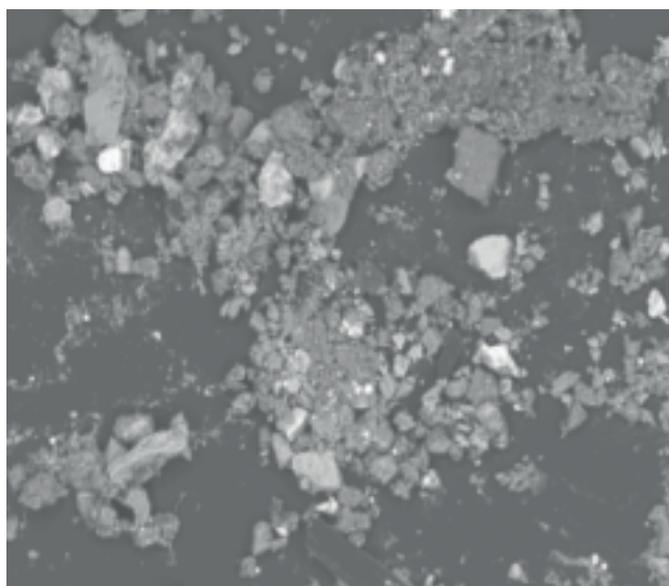
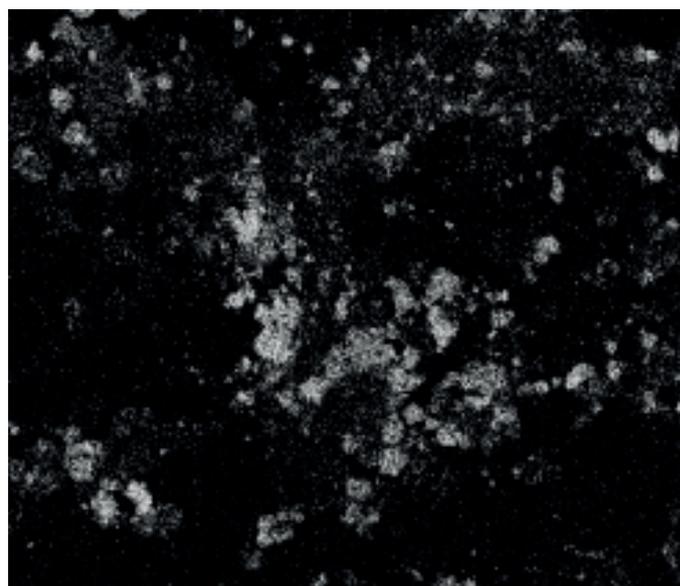
Mineral compounds containing carbonates and silicates, as well as, in limited amounts, sulfates, chlorides and other salt-like minerals were identified on the surface of the studied diamonds by the method of infrared spectroscopy based on the character of location of absorption peaks in the spectra. The presence of carbonate minerals was established through characteristic IR absorption bands in the 1400–1500  $\text{cm}^{-1}$  range. In most cases the band of valence vibrations (1400–1500  $\text{cm}^{-1}$ ) was asymmetrical and polymodal that was typical for calcite-dolomite series carbonates.

Semi-quantitative analysis of very thin (up to 1  $\mu\text{m}$ ) film compounds on the surface of diamonds revealed high surface concentration of calcium in them. The ratio of the sum of magnesium, silicon and aluminum to calcium did not exceed 20 %. This allowed concluding that the thin films on the diamond surface had predominantly calcium-carbonate composition.

Micro-X-ray spectral analysis of the mineral form distribution pattern showed that calcium minerals (mainly calcite) were dispersed together with silicates and occurred on the diamond surface both as individual compact forms and as uniformly distributed films and microspheres (Fig. 2).

*a**b*

**Fig. 1.** Image of the carbon replica (*a*) and X-ray spectrum (*b*) of the mineral formation on the hydrophilic diamond

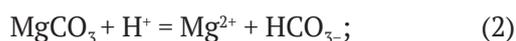
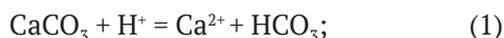
*a**b*

**Fig. 2.** Images of a combination of mineral compounds (*a*) and distribution of calcium (*b*) on the diamond surface (calcium is shown by white color)

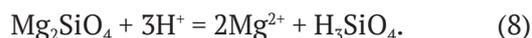
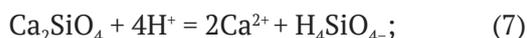
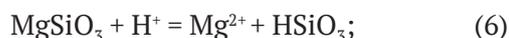
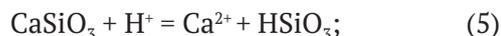
Historical studies established that the most effective method for destruction of such mineral forms of the given composition and, correspondingly, their removal from the surface of diamonds was thermal treatment of ore slurry of the diamond-bearing material froth separation cycle [2].

Purification of the diamond surface during heat treatment proceeds through the thermomechanical mechanism, which implies destruction of intergrown pieces of diamonds with other kimberlite minerals during heating due to different linear expansion [6]. The use of heat treatment is simultaneously a factor influencing the mechanism and rate of dissolution-crystallization processes of the mineral impurities in question. On the one hand, heating of the medium promotes dissolution of simple calcium carbonates and complex magnesium carbonates on the diamond surface due to decreasing carbonic acid solubility [15]. On the other hand, at elevated temperatures, solubility of carbonate minerals decreases, and their crystallization is observed [16]. Therefore the effect of the medium heating on stability of calcium and magnesium carbonate minerals manifests itself at certain conditions which can be determined by thermodynamic analysis of crystallization – dissolution processes.

Decomposition of calcium and magnesium carbonates is described by dissolution reactions, (reactions 1, 2), as well as reactions of transformation of magnesium carbonate and hydroxy carbonate into magnesium hydroxide (reactions 3, 4) [17, 18]:



Similar reactions occur involving minerals that are salts of silicic acid:

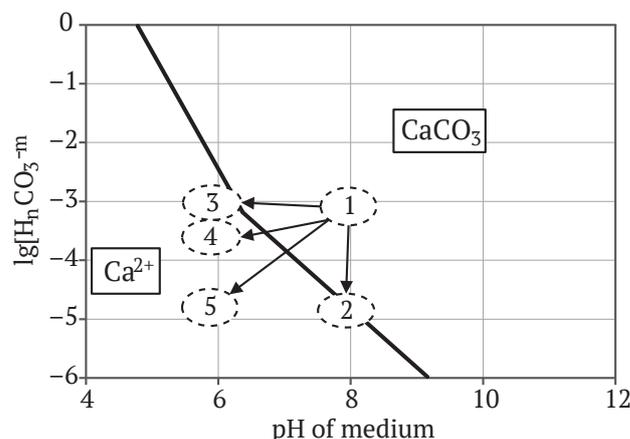


Proceeding of the considered reactions results in intensive dissolution or destruction of carbonate and silicate minerals, and their mechanical or thermomechanical removal from the surface of diamonds is also facilitated.

Modeling of the processes of hydrophilizing compounds dissolution on the surface of minerals was carried out by construction and analysis of thermodynamically stable calcium and magnesium compounds diagrams in coordinates  $\lg[\text{CO}_3] - \text{pH}$  based on thermodynamic analysis of chemical reactions involving

calcium minerals. These minerals form a basis of the film hydrophilizing coatings on diamonds, crystallizing (coatings) from the liquid phase in technological processes of beneficiation, and cement matrix of the relief polymineral accretions, formed as a result of hypergenic processes in kimberlite [6].

Formation of calcium carbonate is possible both at the stage of grinding of diamond-bearing material and in the subsequent process of its froth separation. This was proved by location of area 1 at a noticeable distance from the phase boundary (Fig. 3). The thermodynamic calculations showed that heat treatment leads to dissolution of surface films of calcium-carbonate composition on the diamond surface at the expense of significant removal of carbon dioxide from the aqueous phase (less than  $10^{-5}$  mol/l, Fig. 3, area 2). Lower intensity of heat treatment did not provide dissolution of calcium carbonate due to lower decrease in concentration of carbonic acid ions.



**Fig. 3.** Diagram of thermodynamic stability of  $\text{CaCO}_3$  (calcite) in the liquid phase of froth separation, where 1 – without using preparation techniques; 2 – when using heat treatment; 3 – at chemical regulation of the medium pH; 4 – when using electrochemically treated recycled water; 5 – at combined application of electrochemical and thermal treatment

Under the conditions considered, intensification of dissolution of carbonate compounds on the surface of diamonds can be also achieved through acidification of the aqueous phase (Fig. 3, area 3).

Electrochemical conditioning of recycled water of the froth separation cycle leads to changes in both pH values of the ore slurry aqueous phase and concentrations of ion-molecular components in it. For example, the application of diaphragmless electrochemical conditioning of recycled water led to 30–40 % decrease in concentrations of calcium and magnesium ions and bicarbonate ions in it, and the aqueous phase thus became less supersaturated in relation to the process of formation of calcium carbonates [4]. However, as can be seen from Fig. 3 (area 3), the magnitude of acidification (decreasing pH) achieved through electrochemi-



cal treatment of recycled water and the corresponding decrease in the concentration of calcium ions may be insufficient to dissolve calcium carbonate precipitates.

The most effective way to solve the problem of dissolution of carbonate compounds on the surface of diamond crystals is a combination of thermal and electrochemical treatment of diamond-containing ore pulp and recycled water of froth separation respectively, at which maximum possible dissolution of calcium carbonate is achieved (Fig. 3, area 4).

Similarly, application of the combined technology of the pulp thermal treatment and electrochemical conditioning of recycled water provides destruction of the main magnesium carbonates ( $MgCO_3 \cdot Mg(OH)_2 \cdot nH_2O$ ).

Thus, the obtained results of thermodynamic calculations explained the efficiency of the combined application of thermal treatment of ore slurry and the electrochemical method of the aqueous phase ionic-molecular composition regulation in the diamond-containing material froth separation cycle through creating optimal conditions for dissolution of hydrophilizing compounds on the surface of diamonds.

## 2. Determination of optimal parameters of electrochemical treatment of the froth separation cycle recycled water

Taking into account the above-mentioned recommendations for using the electrochemical conditioning of recycled water of the froth separation cycle as an additional method, activating the process of dissolution of carbonate hydrophilizing compounds on the surface of diamond crystals, a set of experimental studies to determine the optimal parameters of the liquid phase, providing maximum efficiency of the method application was implemented.

At the first stage of the experimental researches, stability of hydrophilizing compounds on diamond surface was estimated by method of determination of limiting pH values of calcium carbonate precipitation in liquid phase of aqueous systems at different mineralization and temperatures.

To determine dissolution conditions of carbonate compounds under the given conditions, two series of experiments with use of low-mineralized and highly mineralized aqueous systems were carried out. In the experiments, control measurements of pH of aqueous phase in the conditions of the sediment crystallization were executed (Table 1).

The boundary values of pH of sedimentation were calculated from equations for the reaction 1 constants taking into account the actual concentrations of calcium ions and carbonates. Formation of calcium carbonate precipitates occurs in more alkaline region (pH = 6.4–7.2) than their dissolution (pH = 6.0–6.57). The results obtained agree with the data of other researchers, explaining such effect by the necessity of conditions of "supersaturation" in the ions forming crystallizing compounds for their precipitation [16]. Comparison of the calculated data with the actual pH values of formation and dissolution of the precipitates showed that the calculated boundary pH values of the calcium carbonate stability area are close to the experimental data.

The obtained results allow estimating the interval of pH at which the stability of carbonate films decreases, and their dissolution becomes possible both at normal and at elevated temperatures. However, the calculated pH values of the aqueous phase cannot be used as the only criterion for its ability to dissolve the mineral impurities due to the significant influence on the processes of crystallization – dissolution of such additional factors as temperature, concentrations of ionic-molecular components, ionic strength of the solution [17, 18].

The ability of aqueous phase to dissolve or precipitate salts, particularly calcium carbonates, in related areas of industry (oil production and heat power engineering) is evaluated using specialized complex criteria. As such a complex criterion for the ability of recycled water of diamond-containing material froth separation to dissolve hydrophilizing films on the surface of diamond crystals, a pH-based criterion, the Ryznar Stability Index ( $JS_t$ ) is used [19]:

$$JS_t = 2 \cdot pH_s - pH. \tag{9}$$

Table 1

Calculated and experimentally measured pH of calcium carbonate dissolution

Experimental conditions	[Ca <sup>2+</sup> ], mg/L	T °C of aqueous phase	[CO <sub>3</sub> ] concentration, mg/L	pH of precipitate formation		pH of precipitate dissolution
				Calculated value	Revised value	Revised value
Low mineralized aqueous system	2150	20	30	6.48	6.6	6.2
		70	4	6.92	7.2	6.57
Highly mineralized aqueous system	7000	20	30	6.23	6.4	6.0
		70	4	6.62	6.88	6.34

The Ryznar Index compares the actual pH value of the medium with the required value ( $pH_s$ ) for the formation of calcium carbonate, which is calculated using the following equation:

$$pH_s = pK_2 - p\text{PPCaCO}_3 - \lg[\text{Ca}^{2+}] - \lg\text{Alk}_0 + 2,5\sqrt{I} \quad (10)$$

where  $pK_2$  is the negative logarithm of the  $\text{H}_2\text{CO}_3$  2<sup>nd</sup> stage dissociation constant;  $p\text{PPCaCO}_3$  is the negative logarithm of the solubility product of  $\text{CaCO}_3$  (calcite);  $[\text{Ca}^{2+}]$  is the concentration of  $\text{Ca}^{2+}$  ions in the aqueous phase, mg/l;  $\text{Alk}_0$  is the total alkalinity of the aqueous phase, mg-eq/l;  $I$  is the ionic strength of the aqueous phase.

At values of  $JS_t > 8.7$  the aqueous phase tends to dissolve carbonates, and  $\text{CaCO}_3$  precipitate is not formed or dissolves easily. At  $8.7 > JS_t > 6.9$  the aqueous phase is characterized as “moderately aggressive” in which  $\text{CaCO}_3$  precipitate is not formed and dissolves slowly. At  $6.9 > JS_t > 6.4$ , the aqueous phase is “stable”; at  $6.4 > JS_t > 3.7$ ,  $\text{CaCO}_3$  precipitates from the aqueous phase; at  $JS_t = 3.7$ , the aqueous phase is supersaturated with the precipitate-forming ions that stipulates intensive formation of  $\text{CaCO}_3$  precipitate [16].

The technology of diaphragmless electrochemical treatment of recycled water of diamond-containing ore material froth separation, which provides simultaneous saturation of the aqueous phase with fine bubbles of electrolytic gases and decreasing concentration of hardness salts in it, was proposed to regulate pH of aqueous phase [7]. Analysis of the influence of diaphragmless treatment of water system on its properties showed the following: at diaphragmless electrochemical conditioning of recycled water of the

froth separation cycle at processing plant No. 3 of Mirny Mining and Processing Complex, a shift of pH to more acidic area ( $pH = 6.2-6.7$ ) takes place. At the same time, an equally important decrease in the concentration of calcium ions and the sum of concentrations of carbonic acid derivatives takes place, which provides intensification of calcium carbonate dissolution. According to the calculated values of stability index  $JS_t$  (Table 2), recycled water that has undergone electrochemical conditioning at power consumption of more than  $0.5 \text{ kWh/m}^3$ , changes its properties and passes from the category “prone to calcium carbonate precipitation” to the category “stable”, i. e. not prone to precipitate formation ( $JS_t = 6.9$ ). At further increasing consumption of electricity to more than  $1.0 \text{ kWh/m}^3$  the recycled water passes into the category “moderately aggressive”, i.e. capable of dissolving calcium carbonate precipitate ( $JS_t \geq 7.05$ ).

Similar results were obtained at electrochemical conditioning of recycled water of processing plant No. 12 of Udachninsky GOK (Mining and Processing Complex), which was characterized by higher mineralization, in particular, increased concentration of calcium ions (Table 2).

As a result of the electrochemical treatment at power consumption of  $1.0 \text{ kWh/m}^3$  the recycled water of the Udachninsky processing plant passes into the category of “stable” ( $JS_t = 6.87$ , see Table 2), and at electricity consumption of  $1.5-2 \text{ kWh/m}^3$ , into the “medium aggressive” category ( $JS_t = 6.94-7.43$ , see Table 2). It should be noted that for the more saturated with calcium ions recycled water of processing plant No. 12 (Udachninsky GOK) the transition to the state, in which dissolution of calcium carbonates takes place,

Table 2

**Ionic composition and characteristics of carbonate equilibrium indices at varying intensity of diaphragmless treatment of recycled water**

Power consumption, kWh/m <sup>3</sup>	pH of aqueous phase	Concentration of ions, mg/l			Values of carbonate equilibrium indices		
		Ca <sup>2+</sup>	HCO <sub>3</sub> <sup>-</sup>	CO <sub>3</sub> <sup>2-*</sup>	S <sub>1</sub>	pH <sub>s</sub>	JS <sub>t</sub>
<i>Recycled water of the Mirny Processing Plant No. 3</i>							
No treatment	7.6	2389	61.2	0.11	17.00	7.12	6.52
0.3	7.5	2302	62.4	0.091	13.35	7.15	6.82
0.5	7.2	2120	46.5	0.034	4.61	7.10	6.90
1.0	7.1	1833	44.2	0.026	3.04	7.05	7.00
1.5	6.9	1545	41.5	0.015	1.59	7.11	7.33
2.0	6.7	1455	31.5	0.0073	0.73	7.04	7.80
<i>Recycled water of Udachninsky GOK Processing Plant No. 12</i>							
No treatment	8	2900	32	0.33	27.11	7.41	6.13
0.3	7.9	2880	28	0.25	18.82	7.47	6.28
0.5	7.7	2650	26	0.16	10.18	7.31	6.47
1.0	7.5	2500	21	0.074	3.93	7.31	6.87
1.5	7.3	2355	14	0.031	1.64	7.50	6.94
2.0	6.9	2189	10	0.011	0.56	7.46	7.43

is achieved at greater consumption of electricity for its electrochemical conditioning.

To evaluate the effectiveness of the selected boundary values of the  $JS_t$  criterion and the electrochemical treatment modes, the method of measuring the three-phase limiting wetting angles of the surface of diamond crystals was applied. The studies were carried out at an OCA 15EC device using standard techniques [14]. A drop of the aqueous phase was placed with a microsyringe on a certain area of a diamond surface, which was pretreated with recycled water that underwent the electrochemical conditioning. The measurements results showed that the hydrophobicity of naturally-hydrophilic diamonds increases in the process of interaction with electrochemically treated recycled water (the hydrophobicity was determined by the value of the three-phase limiting wetting angle). The best result – the maximum increase in the limiting wetting angle of the hydrophilized diamonds was achieved when combining thermal conditioning of the diamonds and diaphragm-free electrochemical treatment of recycled water (Fig. 4, curve 2). The increment of the three-phase limiting wetting angle (33 %) achieved by the combined treatment is significantly higher than the sum of the limiting wetting angle increments of the separate application of the heat treatment technology (17 %, Fig. 4, curve 1).

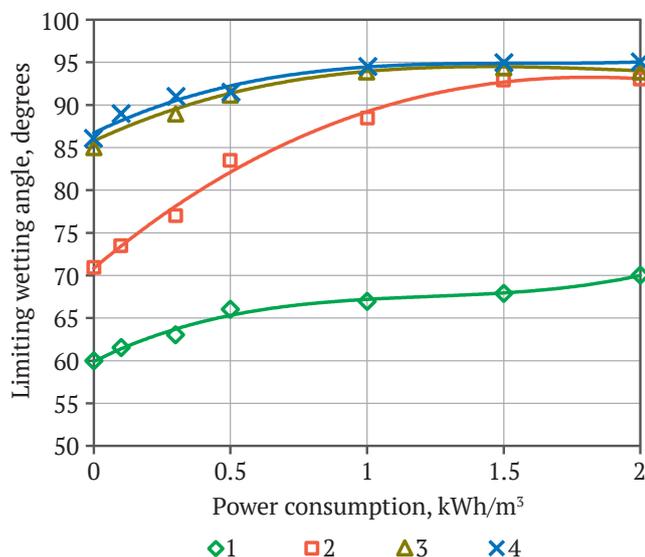


Fig. 4. Curves of the three-phase limiting wetting angle when using thermal treatment of diamonds and diaphragmless electrochemical treatment of recycled water, where 1, 2 – naturally-hydrophilic diamond; 3, 4 – naturally-hydrophobic diamond; 1, 3 – without thermal treatment; 2, 4 – with thermal treatment

When naturally-hydrophobic diamonds come in contact with recycled water, electrochemically treated in diaphragmless electrolyzer, an increase in the three-phase limiting wetting angle is also observed. A similar result, the maximum degree of surface

hydrophobicity, was also achieved with the combined treatment of naturally-hydrophobic diamonds (Fig. 2, curve 4). Analysis of the obtained results showed that the maximum degree of diamond hydrophobicity restoration was achieved at the consumption of electric power (during processing of recycled water in the diaphragmless electrolyser) of more than 1.5 kWh/m<sup>3</sup>.

### 3. Selection of modes of combined conditioning technology of initial feed and recycled water of froth separation cycle

Selection of rational parameters of electrochemical conditioning of recycled water for the preparation of diamond-bearing material – feed of the froth separation cycle – was justified by the results of the laboratory research, carried out in conditions close to the plant conditions. The reagent scheme included feeding bunker fuel F5 (1.3 kg/t) as a collector and sodium hexametaphosphate (0.3 kg/t) as a depressor of rock minerals.

In the research, the diamond-containing material entering the froth separation process was treated with open steam at 60–90 °C. Electrochemical conditioning of the froth separation recycled water was carried out in a diaphragmless electrolyzer EKVB-0.5. The treated recycled water was fed to the attrition and desliming process. The flow rate of water through the electrolyzer was kept constant due to requirements of the production process. Electricity consumption for conditioning of the recycled water was regulated by changing the electrolyzer electrode current density.

The results of the experiments showed that thermal treatment of froth separation feed (diamond-bearing material pulp) allows to increase diamond recovery from 65.7 to 84.1 % (Table 3) at heating the pulp to 80–85 °C with duration of steam treatment from 1 to 2 minutes. Simultaneous applying thermal treatment of the froth separation feed (diamond-bearing material pulp) and electrochemical conditioning of the recycled water increased the diamond recovery to 91.4 % (see Table 3).

Table 3

#### Diamond recovery into froth separation concentrate when using heat treatment of initial feed and electrochemical conditioning of recycled water

Temperature of initial froth separation feed, °C	At five values of electricity consumption for recycled water conditioning, kWh/m <sup>3</sup>				
	0	0.5	1.0	1.5	2.0
14	65.7	69.1	72.5	72.8	73.4
60	72.3	77.8	81.7	81.9	82.3
80	75.1	84.0	88.3	88.5	88.7
85	84.1	89.4	91.4	91.4	91.3
90	83.9	89.9	90.9	90.8	90.9



Table 4

**Parameters of the froth separation semi-industrial tests with the use of electrochemical conditioning of recycled water and thermal treatment of the initial feed**

Test condition	Froth separation feed temperature, °C	Electricity consumption for water conditioning, kWh/m <sup>3</sup>	Current density on the electrodes, A/m <sup>2</sup>	Diamond recovery, %
Check sampling	11–14	–	–	76.5
With heat treatment of froth separation feed	80–85	–	–	77.5
With thermal treatment of froth separation feed and electrochemical conditioning of recycled water	81–86	1.2	175	81.4
		1.5	200	81.6

The increase of electric power consumption for electrochemical conditioning of recycled water above 1.5 kWh/m<sup>3</sup> (when the electrode current density is more than 200 A/m<sup>2</sup>) is ineffective, because it doesn't lead to an increase in diamond recovery. Heating of the froth separation feed to 90 °C also turned out to be inexpedient because of the identified decrease in diamond recovery. The conducted studies showed a positive synergetic effect of using the combined technology of processing diamond-containing material in the froth separation cycle, which consisted in a significant increase in diamond recovery, significantly exceeding this indicator when heat treatment of the initial diamond-bearing material feed and electrochemical treatment of the recycled water of the froth separation cycle were used separately.

The developed technology of diamond hydrophobic properties restoration in the froth separation cycle of diamond-bearing material was tested during pilot tests in the froth separation cycle of processing plant No. 3 at Mirny GOK. Electrochemical conditioning modes were selected based on the laboratory test data. Recycled water that passed electrochemical conditioning in the diaphragmless electrolyzer was fed to the initial feed desliming unit (removal of grain size class –0.5 mm).

Parameters of thermal treatment of diamond-bearing material feed (the feed temperature of 80–86 °C) also corresponded to the results of the historical studies. Reagent treatment scheme of the froth separation corresponded to the industrial one used in the laboratory researches as well. The analysis of the aqueous phase in the froth separation process

confirmed the shift of the medium pH to acidic area (6.1–6.5).

The conducted tests showed that application of the developed method of intensification of the froth separation process with application of the selected modes of thermal treatment of the initial feed (temperature 80–86 °C) and electrochemical diaphragmless treatment of recycled water ( $Q = 1.2–1.5$  kWh/m<sup>3</sup>) provided increasing diamond recovery by 4.9–5.1 % (Table 4).

### Conclusions

The efficiency of application of recycled water electrochemical conditioning, which provided increasing probability of removal of hydrophilizing compounds from the surface of diamonds during thermal treatment of diamond-bearing feed of froth separation, was shown using the findings of thermodynamic calculations. Rational parameters of diaphragmless electrochemical conditioning of recycled water in the froth separation cycle of diamond-bearing kimberlite with the use of the combined technology for restoration of hydrophobic properties of diamond crystal surface were determined. It was experimentally shown that the maximum increase of hydrophobicity and floatability of diamonds was achieved at the electrolyzer electrode current density of 175–200 A/m<sup>2</sup> and power consumption of 1.2–1.5 kWh/m<sup>3</sup>. Pilot tests showed that application of the combined technology, including thermal treatment of diamond-bearing feed and electrochemical conditioning of recycled water of diamond-bearing material froth separation cycle with the selected parameters provided 4.9–5.1 % increase in 2 + 0.5 mm size diamond recovery.

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