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Research into electro-hydraulic blasting impact on ore masses to intensify the heap leaching process

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Abstract

Purpose. Substantiating the main explosive impulse parameters and determining the dependences of metal recovery during forced loosening and shaking of the ore mass by an electro-hydraulic blasting to intensify the heap leaching process.

Methods. The experimental laboratory studies have revealed the dependences of the discharge energy influence on the blasting pressure at various parameters of the discharge capacity and inductance, as well as the change in the metal content in the productive solution when the ore mass is exposed to an electro-hydraulic blasting.

Findings. A research methodology using the models of the electro-hydraulic blasting impact on the ore mass is proposed. In addition, the similarity criteria have been substantiated, which make it possible to study the nature of shaking and loosening under various loading parameters. It has been determined that using the method of influencing the ore mass with an electric discharge in a liquid increases the degree of metal recovery from the ore during heap leaching and increases the rate of the solution penetration into the depth of the ore mass. When using the method of loosening the ore mass by artificial shaking, the recovery of copper increases by 10-15% and the leaching time decreases by 1.5 times.

Originality. It has been determined that due to the possibility of regulating the electric discharge capacity in the required range during blasting operations, loosening and additional crushing of the ore mass occurs; fractures are formed in lumpy ores, which contribute to an increase in the rate of leaching solution infiltration.

Practical implications. The proposed technology makes it possible, without dismantling the equipment and irrigation communications, to perform additional loosening of the ore mass and increase the rate of the leaching process, as well as significantly reduce the time of the technological process.

Keywords: *ore, heap leaching, electro-hydraulic blasting, ore mass, loosening*

1. Introduction

Nowadays, many mining-and-metallurgical enterprises in Kazakhstan have significant reserves of low-grade, off-balance, oxidized and refractory ores that could be put into operation by the heap leaching method, which, in turn, would increase the resource base of the republic [1]-[4].

However, the special conditions for leaching the cupriferous sandstones due to the lack of analogues in world practice require additional research on both chemical and bacterial leaching technologies. In recent years, in Kazakhstan, substandard ores, including refractory oxidized ores, have been processed in small quantities, as a result of which they are stockpiled in dumps that pollute the environment and occupy significant agricultural lands [5]. If to involve these dump substandard ores into operation, it would be possible not only to reduce the level of environmental pollution, but also produce additional amounts of such scarce metals as copper, silver, gold, etc.

Current practice and the results of pilot research on leaching show that the main obstacle to the development of the heap leaching method is the relatively low recovery of target metals caused by the low rate of their dissolution. This is conditioned by the presence of metals in poorly soluble compounds, a decrease in the oxygen content in the solution and the occurrence of various colmatation processes [6], [7].

In addition, a peculiar heap leaching of clay ores should be noted, which is characterized by low water permeability. World practice confirms that with an increase in the content of clay minerals in ore from 15-20 to 35-40%, the duration of heap leaching increases by 2 times, with an increase in the clay content to 60%, the duration of leaching increases by 8-10 times [8].

Heap leaching of ores is characterized by a relatively long duration of the technological process, caused by the slow penetration of the solution into the ore lump and into the rock mass as a whole due to the gradual colmatage. In other words, in the process of continuous irrigation, the ore mass in the pile is compacted, and the flow of leaching solutions finds the most favorable filtration paths. In this case, many compacted local areas are not affected by reagents, that is, they are not leached [9], [10].

In production, various methods of intensifying the heap leaching process are used: physical, chemical, bacterial, microbiological etc. [9]-[15]. It is well known that the effi-

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ciency of heap leaching of metals from raw ore depends on the climatic factors [16]-[18].

In order to increase the efficiency of the leaching process, Kazakh scientists [19] have tested a method for pretreating the ore of the Zhezkazgan field: irrigation with concentrated sulphuric acid and holding it in a heap for 1-3 days. Then the ore is leached with H_2SO_4 solution with pH = 1.0; 2.0; 3.0 at S:L = 1:1. As a result of these experiments, the authors have determined that the best solvent is sulphuric acid with a concentration of 0.5 g/l (pH = 2.0). Besides, the authors propose an optimal way to stockpile the heap: place large fractions (+5 mm) at the bottom and small fractions (–5 mm) above. In such a way, it has been revealed that leaching in this way makes it possible to recover 88% of copper with a minimum specific acid consumption (1.9 tons per ton of recovered copper).

For the first time in Kazakhstan, the commercial development of oxidized gold ores by the heap leaching method was conducted at Vasilkovsky GOK (Altyntau Kokshetau JSC) [20]. The raw material for leaching is oxidized gold-bearing ore with an average gold grade of 1.75 g/t. The bulk density of the ore is 1.6 t/m^3, the mass fraction of water in the original ore is 10%, and the mass fraction of water in the maximum saturated ore is 18%. The field belongs to the gold-sulphide-quartz and moderately sulphide types. The main technological parameters of the heap leaching process at Vasilkovsky GOK can be formulated as follows. Before leaching, the ore is carefully prepared by crushing to a particle size of 200 mm. Sodium cyanide and caustic soda with pH = 10-11 are used as leaching solutions, and the volume of the supplied solution is 120 m^3/h. Productive solutions are fed to sorption columns for settling the gold onto sorbents. Resin grade AM-2B is used as a sorbent. The average content of gold in a saturated resin is in the range of 2-8 mg/g. The saturated resin is treated with a sulphuric acid solution at t = 55-60°C for 1-1.5 hours, after which it passes through the stage of thiourea solution sorption. Desorption of gold is performed by reverse gold-free acidic thiourea solutions, after which it is sent for filtration. From the filter the commercial reagent is supplied to electrolysis. The dried sludge is mixed with the addition of soda and other additives, and then melted in an electric furnace to obtain a gold alloy of 95-98%.

This GOK is located in the northern area of Kazakhstan, where the climate of the region is sharply continental. In winter, at low temperatures down to – 45°C, the upper part of the heap freezes and the penetration of the solution decreases, thereby increasing the leaching time. The height of the frozen part reaches 2.0-2.5 m. In this regard, some scientists have conducted special experimental work to loosen the frozen layer of the ore pile by blasting the borehole charges in the heap using the simplest explosives.

In Kazakhstan, at the Zherek deposit, heap leaching of gold-bearing ores is performed with solutions of ammonium thiosulphate [21], [22]. At this deposit, the ore is characterized by high clay content, and the average clay fraction content is 0.2 mm to 30%. Heap leaching is applied to ore, washed from clay. The average content of gold in the washed ore is 2.44 g/t. Initially, the pile is irrigated with a leaching solution without the presence of copper ions. The solution flowing out from under the pile is constantly monitored for gold, copper and pH value. The alkalinity of the reverse solution is maintained within the range of 8.5-9.5. At a value of pH < 8, an additional dosage of aqueous ammonia is made to a stable value of pH > 8 in the solution flowing out from under the pile. When the gold content in the solution is low (less than 1 mg/l) and there are no copper ions in it, the copper ammonia solution is dosed to a content of 0.3 g/l in the leaching solution of $CuSO_4$. If more than 1 mg/l of gold appears in the productive solution, a cementator is introduced into the work, where gold is extracted from the solution. The gold-free solution from the cementator is additionally strengthened with reagents and again fed to the pile for irrigation. The flow of the solution, supplied to the cementator, is maintained within the range of 25-30 m^3/h, while the rest portion continues to circulate through the pile. In this paper, the authors propose a method for increasing the efficiency of heap leaching by regular shaking of ore dumps using low-density explosive charges. From the industrial research results, it has been determined that when applying a new method for influencing an ore dump by blasting the low-density explosives, the permeability of the ore mass increases almost 2 times, the recovery time of the useful component decreases by 25-30%.

In another work [23], in order to improve the efficiency and control of sulphide ore dumps, the peculiarities of bacterial leaching and leaching modes of low-grade copper-nickel ore with the use of a bioreagent-oxidizer have been studied. The authors propose the optimal ore size and a rational bioreagent concentration for heap leaching. The use of this method makes it possible to increase the extraction of nickel into solution up to 19.5% and copper up to 24.2% with a relatively low consumption of sulphuric acid 14.6% compared to traditional leaching bacteria.

In order to increase the heap permeability and the ore leaching rate, Chinese researchers [24] have conducted an experimental work with the impact on the ore pile with a shock tube during heap leaching. The results have revealed that the shock wave has a shaking effect, influencing on the pile permeability, increasing it by 5.72%. At the same time, according to the authors, the pile permeability increases by 3.8-10 times and, accordingly, the ore leaching rate due to the impact of the shock wave increases by almost 10%.

In the work [25] the authors study the influence of the heap structure and work organization on the efficiency of heap leaching of ores. As a result of the research performed by the authors, it has been determined that the parameters and structure of the heap, as well as the scheduling of the operation (time of operation) are interactive factors. The results indicate that heap height and leaching time are the variables that have the greatest influence when determining the most optimal schemes. Although this is limited by the structural constraints of the setup, that is, the permissible flow rate and solution concentration.

Analysis of various methods for leaching intensification shows that they all accelerate the process and increase the degree of the useful component recovery. However, they are not universal, labor-intensive and can only be used in specific field conditions.

In order to increase filtration, it is necessary to conduct research on the method for additional loosening and shaking of the ore mass by acting on the heap with an electro-hydraulic blasting with controlled power characteristics. For this, the following tasks have been set and solved:

– development of a methodology for studying the electro-hydraulic blasting impact on ore mass using the models made of an equivalent material with the substantiation of the similarity criterion, which makes it possible to study the nature of shaking and loosening at various loading parameters;

– laboratory study of the method for loosening and shaking the ore mass by an electro-hydraulic blasting and substantiation of the optimal parameters of the voltage power for the studied model and the pressure pulse in the liquid at different discharge parameters;

– determining the dependence of the pressure on the length of the charging gap and the electrical parameters of the discharge, the influence of the discharge energy on the pressure at various parameters of the discharge capacity and inductance, as well as the influence of the discharge energy on the diameter of the loosened rock funnel.

2. Materials and methods

The analysis of the research results of the process of directed impact on the loosened rock mass by an electro-hydraulic blasting indicates its insufficient knowledge [26]. The mathematical description of the process is quite complex, does not take into account all factors and is not reliable enough. It is expedient to experimentally study the nature of loosening and shaking of the ore mass during an electric discharge in a liquid in production conditions. However, such a research requires a large amount of work. Therefore, as a method for studying additional loosening and shaking of the heap, the process has been modeled, but with smaller fractions of ore mass. For this purpose, a chamber is specially modeled (Fig. 1) with external dimensions of 500×400×300 mm, made of a plastic frame and plexiglass sheets.

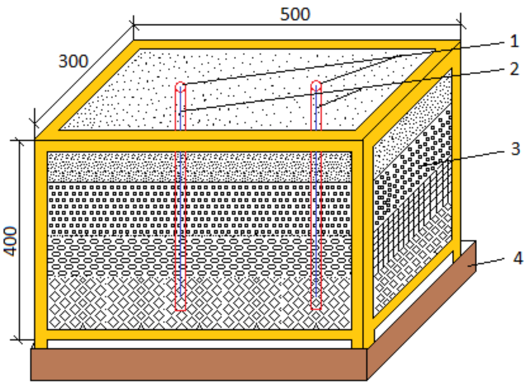


Figure 1. General view of the model chamber: 1 – glass tubes for placement of electrodes; 2 – EGS electrodes; 3 – model chamber with ore mass; 4 – protecting bath

Oxidized ores of the Zhezkazgan field in the following fractions are used for modeling: the main ore fractions are up to 15 mm, sandstones are 0.6-0.4 mm, and clay dust of 0.01-0.005 mm is used to create artificial colmatation. The useful main component is copper, associated silver and rhenium. The main type of ore is disseminated ore in sandstone. The sizes of ore inclusions vary from thousandths of a millimeter to 0.2-0.3 mm. The most widespread are ore grains with a diameter of 0.01-0.1 mm.

The ore mass (82 kg) inside the chamber is placed depending on the fraction (Fig. 1). Thus, ore with coarse fractions is placed in the lower part, gradually decreasing towards the top. And also to create artificial colmatation, a layer of clay dust with a thickness of 50 mm is placed between the layers. In the modeled ore mass during the stacking process, glass tubes with a diameter of 10 mm and a height of 3 mm are set inside it to accommodate EGS electrodes.

An electric discharge in a liquid makes it possible to vary the transmitted energy, the values of the excess pressure inside the chamber and the voltage value, as well as the time of energy release (shattering properties and blasting capacity) within a wide range. All this is provided by changing the electric voltage, capacity of the capacitor bank and inductance.

An electric discharge in a liquid is a process with a high energy concentration. The essence of such a discharge is nothing more than blasting – a very rapid release of a large amount of energy in the initial small volume of the discharge channel, which occurs under the action of a high electric potential between opposite electrodes.

Until the moment of an electrical blasting, energy is contained in a latent potential form in an electric capacitor. The rapid energy release causes a strong mechanical action, that is, the emergence of mechanical forces applied to the medium and individual bodies placed in the discharge zone.

From the moment the interelectrode gap is closed by a highly conductive channel, electrical energy is rapidly introduced into it and the current increases sharply [27], [28]. In this case, the substance in the electric discharge channel heats up strongly, and plasma of water vapor is formed with some admixture of ionized particles of the electrode substance. The main particles enter the electric discharge channel as a result of overheating of a thin layer of liquid surrounding the channel. Strong heating of the plasma leads to an increase in pressure and an electrical blasting occurs.

The value of the shock wave impulse is of great importance for the effective loosening and shaking of the ore mass. Energy absorption depends on the disturbance frequency [29]. The shock wave has an infinitely high rate of pressure rise. Small particles of material, accelerated to high speeds together with the flow, are crushed when they hit each other. The liquid, compressed by high pressure behind the shock wave front, rushes towards the weakly resisting compressible gas, intensively opening microfractures along the way.

An electric discharge in water inside a chamber placed in an ore mass, as well as blasting of chemical explosives, is characterized by a variety of ongoing processes and phenomena. The propagation of a stress wave through the rock is accompanied by a change in stress at its various points [30], [31]. The Equation 1 describing the parameters of stress waves can be written in the form:

$$\frac{\partial^2 \cdot U}{\partial \cdot r^2} + k\frac{\partial}{\partial \cdot r}\left(\frac{U}{r^2}\right) = \frac{1}{c^2}\cdot\frac{\partial^2 \cdot U}{\partial \cdot r}, \tag{1}$$

where:

U – radial displacement of medium particles depending on distance and time, m/ms;

r – radial coordinate;

c – longitudinal stress wave velocity, m/ms;

k – coefficient that depends on the type of waves (for plane waves $k = 0$, for cylindrical waves $k = 1$, for spherical waves $k = 2$).

Given the set initial and boundary conditions, it is possible to determine similarity criteria for modeling the dynamic stress fields arising from an electro-hydraulic blasting. At the initial moment of time ($t = 0$), the medium is not loaded, the displacement velocity of the medium and stress value are equal to zero. The displacement velocity is determined by the nature of the applied load and the properties of the medium.

The rational discharge gap for the studied parameters can be expressed by the following correlation Dependence:

$$l_p = 5 \cdot 10^{-6} \cdot U \sqrt{\lg C + 6}, \text{m}. \tag{2}$$

The pressure pulse in an open water volume, depending on the electric voltage, capacity, inductance and distance of the discharge gap, can be determined by the following Formula:

$$P = \frac{3 \cdot U \left(\lg C + 7.6 \right)}{r \cdot l^{0.2}} - A, \text{ Pa}, \tag{3}$$

where:

A – capacitance-dependent correction factor, Pa, ($A = 7 \cdot 10^5 \div 0.2 \cdot 10^5$; at $C = 3 \div 100$ μF).

By processing the above data, Formula 3 can be expressed as follows:

$$P = 40 \cdot C^{0.16} \cdot U^{1.33} \cdot l^{-0.2} \cdot r^{-0.75}, \text{ Pa}, \tag{4}$$

where:

U – electric voltage, kV;

l – inductance, μH;

C – battery capacity, μF;

r – blasting cavity radius, mm.

The peak value of the discharge current is equal to:

$$I = \frac{U_0}{\omega \cdot l} = \frac{U_0 T}{2 \pi l}, \text{ A}, \tag{5}$$

where:

U_0 – initial voltage, V;

ω – frequency, c^{-1};

T – period of the discharge current, s.

The inductance of the discharge circuit is composed of inductances: busbar of a capacitor bank, a conducting circuit, discharge devices and a discharge channel. The inductance value cannot be determined by direct measurement, since it is measured during the discharge process. Therefore, the average value is calculated through the value of the discharge current and the discharge time.

To shake the ore mass on the models with an electro-hydraulic blasting, the EGS laboratory setup is used, which allows smoothly changing the electric voltage from 0 to 50 kV and gradually changing the capacity from 1 to 1500 μF. The experimental setup is schematically shown in Figure 2.

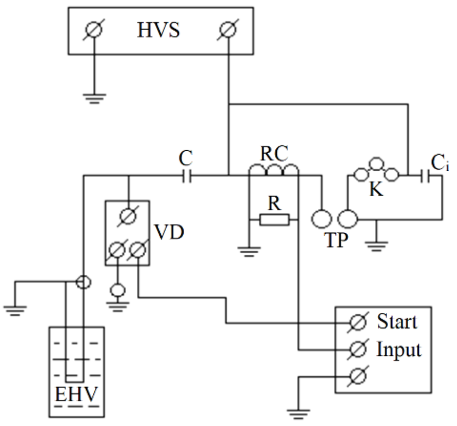


Figure 2. EGS experimental setup scheme: HVS – is a high voltage source; C – capacitor bank; C_i – ignition capacitor; K – capacitor; RC – Rogowski coil; R – resistance; TP – trigatron-type protector; VD – volt/ratio divider; EHB – electro-hydraulic blaster

The research involves studying several important processes: liquid filtration rate when shaking rocks with an electro-hydraulic blasting, production of blasting and its parameters, metal extraction from ore.

The beginning of the experiment includes fixing the time when the leaching solution is supplied for irrigation of the rock mass from a 5-liter tank at a velocity of 40 mm/h to a modeled heap. The ore is irrigated with sulphuric acid (10 g/l) with the addition of oxide sulphate (5 g/l). The irrigation intensity is on average 3.1 l/m^2 hour.

The maximum rate of uniform solution penetration is observed up to a depth of 100 mm (thickness of the upper layer), then it sharply decreases. The average rate of the solution penetration along the height of the ore mass is 0.4 mm/h. Further, there is a nonuniform penetration of the leaching solution over the volume of the ore mass, that is, the solution finds voids in the ore mass and then penetrates precisely through these channels.

After a day of leaching, a productive solution is drained from the chamber to analyze for copper content. The amount of copper recovered after the first day is 7%, after the second day – 19%. Nonuniform irrigation of the ore mass is also observed on the second day of the process.

After that, for uniform irrigation of the modeled heap, as well as increasing the rate of solution penetration into the preliminary set glass tubes, electrodes of the EGS laboratory setup are placed and an electro-hydraulic blasting with a current of 20 mA and a voltage power of 2.0-3.0 kV is performed (Fig. 3). In this case, the shaking effect of blasting is observed in the ore mass, and this, in turn, leads to an increase in the rate of the solution infiltration and the area of the modeled heap irrigation. In addition, traces of loosened rock in the form of round funnels with a diameter of 100 mm are observed on the surface of the ore mass around the glass tubes. It follows from this that at a voltage power of 2.0-3.0 kV, a current of 20 mA and a depth of electrode placement of 250 mm, no outbursts of ore lumps from the model are observed.

Figure 3. Model for studying the electro-hydraulic impact on ore mass during leaching

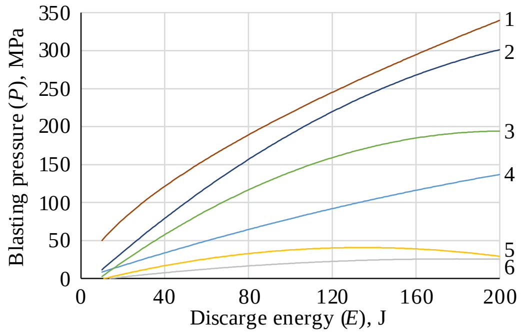
For a detailed study of the processes of impact on the ore mass by an electro-hydraulic blasting, a series of experiments with various blasting parameters have been conducted.

3. Results and discussion

The averaged experimental parameters of the electro-hydraulic explosive impulse are given in Table 1. The dependences of the discharge energy influence on the blasting pressure at different parameters and on the diameter of the loosening funnel are shown in Figures 4 and 5.

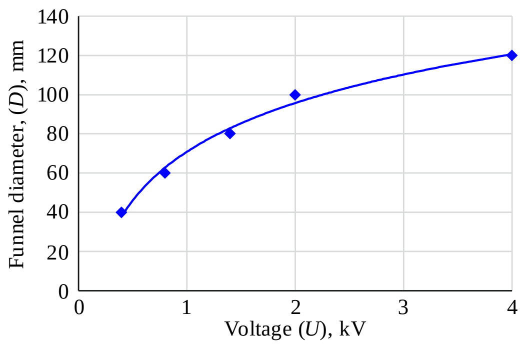
***Table 1.** Averaged experimental parameters of the electro-hydraulic explosive impulse*

Discharge parameters				Explosive impulse parameters	
C, μF	*U*, kV	*l*, μH	*r*, mm	Pressure, MPa	Time, ms
10	2.5	8	5	33.3	125
10	3.5	38	10	19.6	
10	1.5	26	20	5.2	
20	3.5	38	10	21.3	150
20	1.5	26	20	8.8	
20	2.5	8	5	24.7	
100	3.5	18	5	71.28	240
100	2.5	8	10	50.47	
100	1.5	26	15	11.8	
400	1.5	38	5	23.7	480
400	2.5	8	15	55.4	
400	3.5	18	20	49.3	



Parameters	1	2	3	4	5	6
C, μF	10	10	20	100	400	100
r, mm	5	5	5	5	5	15
l, μH	8	38	8	8	8	38

***Figure 4.** Discharge energy influence on the blasting pressure at different discharge capacity and inductance parameters*



Parameters	1	2	3	4	5	6
U, kV	0.3	1.0	2.0	2.5	3.5	4.0
L_p, mm	5	5	5	5	5	5
C, μF	100	100	100	100	100	100
D, mm	46	70	100	106	115	120

***Figure 5.** Discharge energy influence on the funnel diameter of the loosened ore mass: L_p – charging gap length, mm*

Analysis of the research results indicate that when using an electro-hydraulic blasting for loosening, it is possible to regulate the blasting pressure from 20 to 180 MPa and the size of the loosened rock funnel from 20 to 120 mm, which makes it possible to loosen the clay ore mass on dumps without scattering and outburst.

In addition, after the shock blasting, the copper content in the productive solution has been analyzed. Moreover, after blasting operations, on the third day of leaching, the copper content in the productive solution increases to 32%.

After blasting operations, the modeled heap has been leached with several volumes of fresh solution for a week. The total volume of supplied solutions for the experiment is 238 liters, and the L:S ratio is 3:1.

The initial copper content in the sample is calculated from the residual content, taking into account copper that passes into solution during the leaching process. The summarized research results of leaching the copper using sulphuric acid solutions in laboratory conditions with artificial shaking of ore samples are presented in Figure 6.

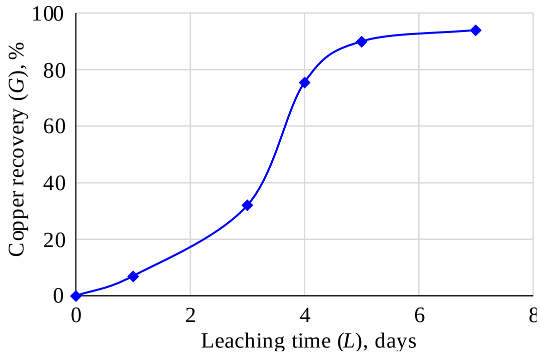


***Figure 6.** Copper recovery from oxidized ore at the Zhezkazgan field*

From the data obtained, it can be seen that when using the method of loosening the ore mass by artificial shaking, the recovery of copper increases by 10-15%, and the leaching time decreases by 1.5 times. This proves that the shaking method of the ore mass increases the metal recovery and significantly reduces the leaching time.

4. Conclusions

With a controlled electro-hydraulic blasting, the ore mass is loosened and additionally crushed around each charge, which leads to the formation of fractures in lumpy ores. These fractures contribute to an increase in the rate of leaching solution infiltration and improve of the heap leaching process.

At the same time, in industrial conditions, the parameters of the electro-hydraulic blasting for shaking and additional loosening of the leached heap can be adjusted within the following limits: discharge voltage from 25 to 40 kV; discharge energy from 150 to 250 kJ; specific energy 200-250 kJ/m^3.

The proposed technology makes it possible, without dismantling the equipment and irrigation communications, to perform additional loosening of the ore mass and increase the rate of the leaching process, as well as significantly reduce the time of the technological process.

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Дослідження впливу на рудні маси електрогідравлічним вибухом для інтенсифікації процесу кучного вилуговування

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Мета. Обґрунтування основних параметрів вибухового імпульсу та встановлення залежностей вилучення металу при примусовому розрихленні та струшуванні рудної маси електрогідравлічним вибухом для інтенсифікації процесу кучного вилуговування.

Методика. Лабораторно-експериментальними дослідженнями встановлювалися залежності впливу енергії розряду на тиск вибуху при різних параметрах ємності та індуктивності розряду, зміна вмісту металу на продуктивному розчині при впливі на рудну масу електрогідравлічним вибухом.

Результати. Запропоновано методику дослідження на моделях впливу на рудний масив електрогідравлічним вибухом, обґрунтовано критерії подібності, що дозволяють вивчати характер струшування та розрихлення при різних параметрах навантаження. Встановлено, що використання способу впливу на рудну масу електричного розряду в рідині підвищує ступінь вилучення металу з руди при кучному вилуговуванні, збільшує швидкість проникнення розчину в глиб рудного масиву. При застосуванні способу розрихлення рудної маси штучним струшуванням вилучення міді підвищилося на 10-15%, а час вилуговування зменшилася в 1.5 рази.

Наукова новизна. Встановлено, що за рахунок керованості потужністю електричного розряду в необхідному діапазоні при вибуху відбувається розрихлення і додаткове дроблення рудної маси, у великокускових рудах утворюються тріщини, які сприяють збільшенню швидкості просочування вулуговуючого розчину.

Практична значимість. Запропонована технологія дозволяє без демонтажу обладнання та зрошувальної комунікації здійснювати додаткове розрихлення рудної маси, підвищити швидкість процесу вилуговування і значно зменшити час технологічного процесу.

Ключові слова: *руда, купне вилуговування, електрогідравлічний вибух, рудна маса, розрихленя*