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Kudryavy Volcano Crater Thick Rocks Electrical Breakdown Study in 50 Hz Electromagnetic Field

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ABSTRACT

Kudryavy volcano is the world's only deposit of rare elements in the form of pure rhenium mineralization. The development of the field is hampered by numerous factors: high temperatures of geothermal fields, strong winds, fumarolic activity, where the use of a drilling and blasting method to destroy rocks in a crater can lead to the closure of all fumarole channels, which will lead to the accumulation of enormous energy and further eruption. The article describes the existing electrical methods for the rock destruction, it was found that the current-voltage characteristic of volcanogenic breccia with an increase in the distance between the electrodes more than 50 cm turns into a *C*-shaped dependence, reducing the current strength from 0.85 A to 0.2 A, forming a full breakdown channel. In this case, the minimum breakdown strength of the electric field is 0.3±0.1 kV/cm, with an increase in this indicator to 3.7 kV/cm, the efficiency of channeling increases to 2%. Around the breakdown channel, a new substance is formed with new conductive properties, different from volcanic breccia, which prevents the formation of the channel along the old trajectory.

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1. INTRODUCTION

When evaluating various ways of rocks destruction, it can be stated that the development of a volcanogenic rhenium deposit in the crater of Kudryavy volcano showed the impossibility of using the traditional method of drilling and blasting to destroy rocks. This is caused by a number of factors, such as high temperature of the geothermal fields 300˚C, as well as non-interrupting fumarolic emissions.

The use of the electric method allows to destroy rocks safely without the risk of overlapping fumarole channels in the volcano depth.

The advantage of electrical approachs is a simple working medium supplying electrical energy to the rock. The development of these methods began in the 60s by number of scientists. In this research, the development trend analysis of this method was carried out, as well as the theories of dielectric breakdown of solids, in particular, the theory of thermal breakdown, were worked out, but the behavior of rocks with initial thermal stresses was not studied [1-6].

Many techniques of crushing rocks electrically developed up today [5-10] have not gone beyond laboratories; others have successfully passed industrial tests and can be recommended for commercial use.

Destroying rocks by electrical method was developed in various directions such as an electrothermal approach, an electrodynamic way, and a combined technology [1-4].

The electrothermal approach was used in the Iron Age, as oversized pieces of iron ore were splitted using the energy of fire. Currently, the source of such a way can be microwave radiation, high frequency current, industrial frequency current, or infrared radiation.

The electrothermal method of rock destruction is based on creation of an uneven distribution of temperature in the volume of the rock, as a result of which a solid working medium is formed that destroys the rock. The force generated by the working medium

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must exceed the force of the disruptive strength of the rock.

$$F_{rt} \geq P, \tag{1}$$

where F_{rt} is the force generated by the working medium measured in N, and P is the force needed to destroy the rock measured in N

$$F_{rt} = \overline{\sigma_t} S_0, \tag{2}$$

where $\overline{\sigma_t} = \frac{\alpha E \overline{T}}{1-\nu}$ is the thermal stress created by the working medium at the average temperature of $\overline{T}$ measured in N/m^2; S_0 is the area, to which the force from the working medium is applied (the area of the loaded surface of the working medium) measured in m^2; α is the coefficient of volumetric expansion of the rock measured in 1/*deg*, and E is Young's modulus of the rock, N/m^2; and ν is Poisson's ratio of the rock. $\overline{T}$ is the average temperature of the working medium measured in ^0C, and k is the coefficient that takes into account α decrease at working medium expansion in response to reaction from the rock surrounding the working medium ($k < 1$).

Since the working medium is located inside a piece of rock, it destroys the rock with tensile stresses. In this regard, using the theory of maximum stresses, we obtain:

$$P = \overline{[\sigma_r]} S_r, \tag{3}$$

where $\overline{[\sigma_r]}$ is the breakdown point of the tensile strength of the rock measured in N/m^2, and S_r is the area of the newly formed surface measured in m^2.

The temperature of the working medium is determined by the amount of energy supplied to it

$$\overline{T} = \frac{\omega\eta}{C_\nu V_0}, \tag{4}$$

where ω is the energy supplied from the source to the working medium, *J*; η is the efficiency of the input into the working medium; C_ν is the volumetric heat capacity of the rock, $J/m,^3 \cdot \deg$; and V_0 is the working medium volume, m^3.

Consequently, we get:

$$S_0 \frac{\alpha E k \omega \eta}{(1-\nu) C_\nu V_0} \geq \overline{[\sigma_r]} S_r, \tag{5}$$

That is the efficiency of electrothermal destruction is determined by the properties of the rock, the size of the destroyed piece, and the power of the current source [3, 7-10].

Energy ω can be imparted to the working medium by either electric current or electromagnetic radiation.

In contrast to the electrothermal method with a solid substance as a working medium and a low intensity of the energy input process, the electrodynamic method is a way with a gaseous working medium, and it is characterized by a high intensity of energy release, which gives a complete separation of the destroyed rock into several single pieces. The essence of this method is the use of an electrical impulse from a capacitor bank to destroy the rock [7-11].

Depending on the nature of preparing a piece for the supply of an energy pulse, there are two main versions of this method: with the preliminary formation of a breakdown path in the rock (high-frequency voltage or power-frequency voltage), and with the use of the electrohydraulic effect (with or without an exploding wire) [10, 11]. This method has not been widely applied in the mining industry. Installations for crushing oversized rocks have been manufactured and tested only based on the electrohydraulic effect [11-13].

In order to destroy a rock electrohydraulically, it is necessary to drill a hole, fill it with water, put into it a wire connected by a spark gap to the capacitor bank, or place in the water electrodes applying a high voltage to them to form a breakdown path and the subsequent discharge of the capacitor bank [10, 12, 13, 14].

To maximize the destruction effect, it is proposed to use the phenomenon of mechanical resonance, for which such parameters of the discharge circuit or such a medium are selected, in which the maximum energy of vibrations excited by each electrohydraulic shock falls on the spectrum that coincides with the natural vibration frequency of the rock particles.

The combined technique is a combination of the electrothermal way with either the mechanical or the electrodynamic one [6, 14-33].

The destruction of rocks with the lowest energy was carried out better in heated rocks [13-24]. Taking into account this fact, the use of the combined (electrical and mechanical) method for destroying a rock having an initial thermal stress is promising for use on a volcanogenic deposit of rare elements [14, 15].

In this regard, the Kudryavy volcano crater thick rocks electrical breakdown study in 50 Hz electromagnetic field remains relevant, since the development of the volcanogenic deposit of rare elements with high temperatures of geothermal fields is associated with the solution of this issue.

Thus, the aim of the study is to explore the current-voltage characteristic of the rock subjected to an initial thermo-stressed state under the temperature 300°C and to study the thick rocks electrical breakdown in order to increase the efficiency of its destruction by an electrical way.

The innovation of this research are studied the dependences of rock current-voltage characteristics on the electrode spacing and the electric field breakdown intensity as well as the dispersion of the resistance depending on the spacing.

Electric field breakdown intensity as a function of the rock resistance was examined as well as the path forming efficiency depending on the spacing and on the electric field intensity.

Interrelationship between temporal variation of current and that of voltage at breakdown path crystallization at *t* moment was traced.

The practical significance of this study lies in the fact that the object under study will make it possible to destroy the rocks of the geothermal fields of Kudryavy volcano safely without closing the fumarolic emission paths in the depth of the crater, which can provoke an eruption.

2. MATERIALS AND METHODS

The object of present study is to investigate the rock selected at the geothermal field of the volcanogenic deposit in the crater of Kudryavy volcano on the Kuril Islands (Russia).

The rocks have the following strength properties, determined by the method of coaxial counter-directed spherical indeters: the ultimate strength in uniaxial tension is 32 MPa, the ultimate strength of uniaxial compression is 133 MPa, and shear without normal stresses is 43 MPa [34-36].

Volcanic breccia are the complex multicomponent media, for which it is possible to determine the nature of the interaction with the electric field and reveal the type of the required dependencies in the laboratory conditions only [15-22]. For this purpose, an experimental plant was created, on which the whole complex of studies on rock breakdown in an electric field of industrial frequency was performed (Figure 1).

The electrodes were made of aluminum and in the experiments they were placed on the surface of the piece of rock ($l_{electrode\,gap}$ =length of the breakdown path $L_{surface}$) (Figure 1b).

Two types of the single-phased oil-cooled (IOM) transformers were used to supply power: IOM 100/25 with the rated power of 25 kVA and the other, more powerful, IOM 100/100, with the rated power of 100 kVA.

The studies were carried out on the volcanic breccia heated up to 300°C. The rocks of the geothermal fields represented by porous slag and tuff that could be destroyed mechanically did not study for the thick rock breakdown.

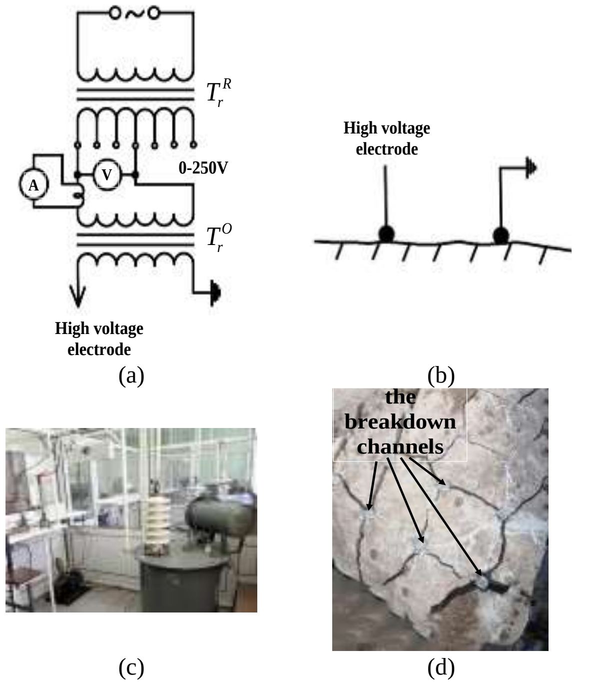

Figure 1. The diagram of the experimental plant for studying the breakdown of rocks in geothermal fields of Kudryavy volcano, heated to 300°C

T_r^R is the regulating transformer; T_r^O is the main transformer; a – is the power supply schematic drawing (split-winding transformer) is shown; b – is the arrangement schema of electrodes ($l_{electrode\ gap} = L_{surface}$); c – presents the I-V characteristics of the studying plant appearance; d – is the breakdown channels

The phenomenon of the thermal breakdown is described by the following differential equation system [1-4, 22]:

$$\left.\begin{aligned} &div(\lambda \cdot gradT) + \sigma \cdot (grad\varphi)^2 = 0 \\ &div(\sigma \cdot grad\varphi) = 0 \end{aligned}\right\} \qquad (6)$$

where φ is the potential; T is the temperature; σ is the specific electrical conductivity; and λ is the coefficient of the thermal conductivity of the dielectric.

The first equation shows that the amount of Joule heat released per unit time in the unit volume of the dielectric is equal to the of heat released amount by this volume per unit of time into its environment.

The second equation expresses the continuity of the streamlines in the dielectric.

This equation system solution is rather difficult mathematically. In addition, it is known that this system does not fully reflect the processes occurring in the rock when exposed to a strong field. In particular, this concerns the anomalous conductivity preceding the breakdown, which significantly changes the nature of the process [2, 6].

Equation (6) establishes the nature of the various rock properties influence on the breakdown process. It is impossible to obtain the quantitative values of electric field breakdown intensity and breakdown time for the rocks at different electrode spacings from the dependences; therefore, they have to be determined experimentally.

In practice, it is very difficult to determine the exact value of the breakdown voltage due to the imperfection of their structures. Therefore, some average value is determined according to the appropriate methodologies. [1-4, 13, 23-33] For rocks, which are complex heterogeneous multicomponent media, breakdown voltages depend on composition, rock structure, the occurrence conditions, the shape of the piece being destroyed, and the thermal stresses, etc. [2-5].

The methodology for determining the dependence of the electric field breakdown intensity on the electrode spacing included:

1) the current-voltage characteristics of volcanic breccia heated to 300°C in the non-uniform field for different electrode spacings were obtained;

2) the electric field breakdown intensity based on the current-voltage characteristics are determined at the following condition

$$\frac{dt}{dE} = tg\alpha, \text{ at } \alpha \to \frac{\pi}{2} \tag{7}$$

3) the breakdown intensity dependence on the electrode spacing from the obtained data were determined.

The experimental method for studying thick rocks electrical breakdown provides for gradually raising the voltage applied to the breakdown path, as well as lowering it gradually by fixing the current-voltage characteristics of the breakdown path.

3. RESULTS AND DISCUSSION

3. 1. Rocks Current-Voltage Characteristics Study

The nature of the heated volcanic breccia electrical conductivity can be determined only by the detailed study of the current-voltage characteristics.

Figure 2 shows the volcanogenic breccia current-voltage characteristics for the various electrode spacing $l_{electrode\ gap}$.

The transition of the current-voltage characteristic to an *C*-shaped one corresponds to the rock breakdown with formatting the complete breakdown path closing the electrodes.

To achieve it, it is necessary to ensure the minimum pre-breakdown current density, since for large thicknesses this factor determines the breakdown. It was

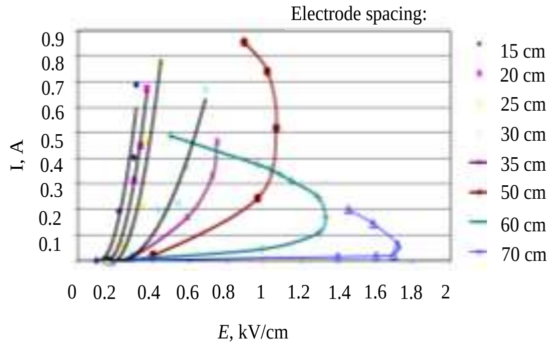

Figure 2. Current-voltage characteristic of the volcanic breccia heated up to 300˚C depending on the electrode spacing at $l_{electrodegap} = L_{surface}$

calculated from the experimental data that the current density in the rock required for the breakdown is constant and equal to $j \approx 0{,}3\times10^{-3}$ A/cm^2.

The decrease in j at $l_{electrode\ gap} > 50$ cm is associated with lack of power of the source, and not with the breakdown process.

If the power of the source is low, then there is a sharp drop in voltage at the output of the high-voltage transformer connected to the load, in comparison with its open circuit voltage

$$U_2 = \varepsilon - I_2 Z_2, \tag{8}$$

where U_2 is the voltage applied to the rock and ε is the transformer e.m.f., V; Z_2 is the transformer secondary winding resistance, Ω; I_2 is the secondary winding current (through the rock), *A*.
From expressions (8) and $I = jS_{T.C.}$ we get

$$U_2 = \varepsilon - jB_{T.C.}Z_2 \tag{9}$$

where $S_{T.C.}$ is the conducting section, m^2, i.e. the preservation of the required current density with an increase in the conducting section $S_{T.C.}$ is ensured only by the ε (e.m.f.) of the transformer.

It was found that, at a large electrode spacing, the current-voltage characteristics of the rock were stable. Therefore, there is a slight dispersion of the resistance.

The resistance dispersion studied as a function of the electrode spacing and that of the electric field intensity showed that the resistance dispersion decreases with increasing in both the spacing and intensity (Figure 3).

The small dispersion of the rock resistance for large distances between the electrodes and the uniformity of the current-voltage characteristics show that when the rock is destroyed, the operating parameters of the electrical installation will be quite stable.

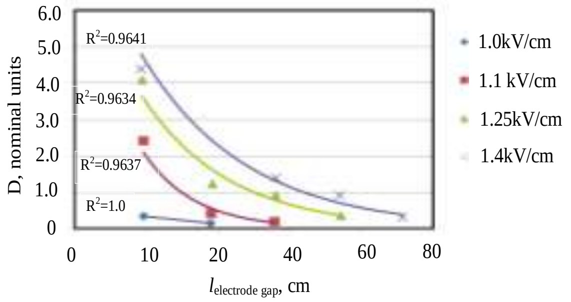

Figure 3. 300°C volcanic breccia resistance dispersion dependence on electric field intensity at $l_{electrodegap} = L_{surface}$

When placing the electrodes along the horizontal surface of the rock (half-space) (Figure 1b), the electric field intensity, E, which leads to anomalous conductivity and, as a consequence, to an electrical breakdown, decreases with increasing the spacing, tending to a certain constant at a larger spacing, $l_{electrode\ gap}$ (Figure 4).

Averaging the electric field breakdown intensity, $E_{el\ br}$, one can say that for a breakdown with the buried path, an electric field intensity not less than 0.3 ± 0.1 kV/cm is sufficient at an electrode spacing < 1 m.

The considered rock makes up the absolute majority among the rocky non-destructible rocks of the Kudryavy volcanic deposit, the rest of the rocks are the rocks that are amenable to mechanical destruction.

Having determined the average values, the electric field breakdown intensity of the rock under study, let us consider their relationship with the duration of staying of the sample under voltage before the breakdown. This is one of the most difficult questions, and it is possible to calculate an electrical breakdown time of a dielectric using a complex mathematical apparatus and for a one-dimensional case only [12-16, 25, 26]. Therefore, in each specific case, it is advisable to carry out experimental studies.

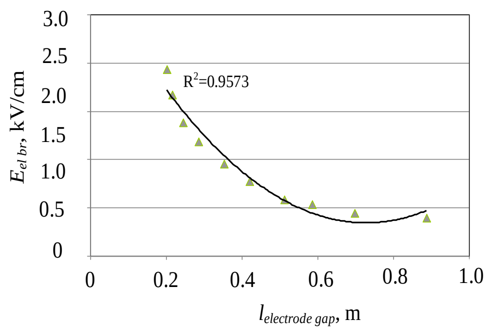

Figure 4. Electric field breakdown intensity dependence on the electrode spacing in volcanic breccia

The time to dielectric breakdown is determined by an intensity of the electric field in that it is located. The found values of the electric field breakdown intensity for the considered rock (Figures 4) are not limitation, that is, the values whose outreaching may lead to a surface breakdown.

As mentioned above, the more the exposure time, the less the electric field breakdown intensity. However, when a rock is destroyed, it is necessary, on the contrary, to minimize the exposure time before breakdown. This is achieved by increasing the electric field intensity to its limiting value, i.e., almost to the surface overlap intensity.

The more the field intensity, the less both the time to the dielectric breakdown and the dispersion of this time, which ultimately will make it possible to determine the performance of the plant or unit more accurately.

To estimate the breakdown time, we use the equation of the energy balance of the process.

The energy supplied to the rock is spent on heating the rock to the melting point, on the phase transition of matter in the volume of the path from the solid state to the liquid state, and on losses due to thermal conductivity.

The energy balance equation is as follows:

$$\int_0^t Pdt = \int_0^{T_{melt.}} cm_{Path}dT + q + \int_0^t \lambda S_{Path\_Surf.} gradTdt, \tag{10}$$

where P is the incoming power; $m_{Path} = \pi r_{Path}^2 l \gamma k_2$ is the breakdown path mass; $S_{Path\_Surf.} = 2\pi r_{Path} l k_2$ is the breakdown path lateral surface area; $T_{melt.}$ is the rock melting temperature; c, λ are rock thermal properties; k_2 is the heat transfer coefficient; and q is the elektrische ladung.

The Equation (10) integration is as follows:

$$\bar{t} = \frac{\pi C_v r_{Path}^2 l k_2 \gamma T_{melt.} + q}{P - 2\pi r_{Path} l k_2 \overline{gradT}} \tag{11}$$

The power incoming to a rock

$$P = UI \tag{12}$$

can be expressed through the transformer e.m.f. from Equation (9) as follows:

$$P = I_2(\varepsilon - I_2 Z_2) \tag{13}$$

By substituting Equation (13) into Equation (11), we have:

$$\bar{t} = \frac{\pi C_v r_{Path}^2 l k_2 \gamma T_{melt.} + q}{I_2(\varepsilon - I_2 Z_2) - 2\pi r_{Path} l k_2 \overline{gradT}} \tag{14}$$

Figure 5 shows the results of a study of the average number of breakdowns N dependence on the time t of volcanic breccia being under stress at various electric field intensities.

The functions presented in the form of graphs in Figure 5, they have the properties of a gamma distribution, the density of which has presented in the following form [9-10]:

$$f(x)=\frac{\lambda_r}{G(\eta)}x^{\eta-1}e^{-\lambda x}, \quad (15)$$

where $G(\eta)=\int_0^{\infty}e^{\eta-1}x^{-x}dx$ is the gamma function; $\lambda_r>0$ is a scale parameter; and η is a form parameter.

With an increase in λ_r parameter, which, in our case, is the increase in electric field intensity, the distribution shape remains constant, and the time to the breakdown decreases and is determined with a smaller scatters.

The $\bar{t}$ oscillations are associated with the dispersion of the resistance of the rock, which was indicated above, since the resistance of the dielectric determines the electric field breakdown intensity.

For volcanic breccia, this dependence is linear (Figure 6).

Due to the fact that when a rock is destroyed, breakdown path formation is a technological operation, it is necessary to determine the efficiency of energy use in this process. This is done by calculating the ratio of the energy required to form a breakdown path of a given diameter to the energy actually expended. When calculating the energy spent on the formation of the breakdown path itself, the diameter of the breakdown path was taken to be constant and equal to 3 mm, and the path length was 1.25 times larger than the electrode spacing. Thus, the energy during formation of the breakdown path 3 mm in diameter is spent on heating its volume to the melting temperature and on the phase transition from the solid to the liquid state. The actually expended energy was determined by device readings. The study results are shown in Figures 7 and 8.

As one can see, the breakdown path formation is an inefficient process. Its efficiency can be increased by using a high-intensive electric field.

However, it should be taken into account that while forming a breakdown path due to the high temperature gradient, a solid working medium is formed, which deforms the rock. Solid working medium formation in parallel with breakdown path formation significantly increases the efficiency of energy use.

3. 2. Thick Rocks Electrical Breakdown Study Results When the stationary mode of electrical conductivity is violated, thermal destruction of the dielectric occurs, which entails breakdown path

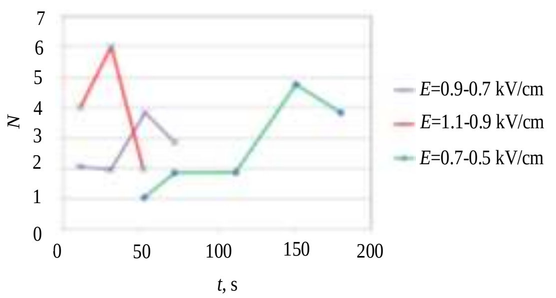

Figure 5. Specimen time to dielectric breakdown distribution at various electric field intensities (for volcanic breccia) at $l_{electrode\ gap}$=0.5m

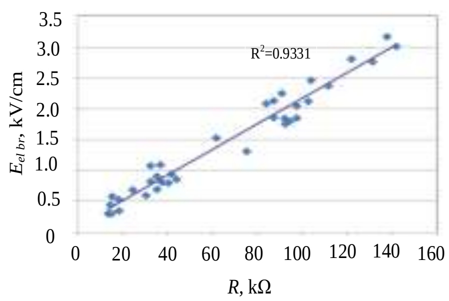

Figure 6. Electric field breakdown intensity dependence on rock resistance

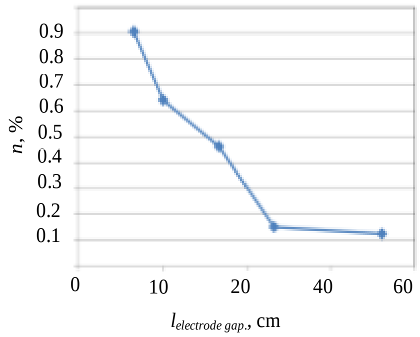

Figure 7. Path forming efficiency dependence on electrode spacing (IOM 100/100 single-phased oil-cooled transformer)

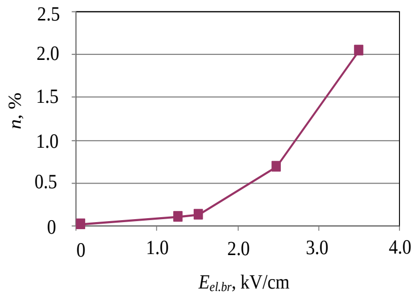

Figure 8. Path forming efficiency dependence on electric field intensity (IOM 100/100 single-phased oil-cooled transformer, $l_{electrode\ gap}$=50 cm, specific electrical resistance $R_{specific}$=1kΩ/cm (volcanic breccia)

formation. Such a path passes through the volume of the dielectric from one electrode to another. While the breakdown path is forming, the object destruction preparation is coming to its end, since the breakdown path is a circuit element in which the electrical energy is converted into mechanical work, accompanied by the destruction of the rock.

The supply of energy to the breakdown path, as is known, can be produced from a power transformer or a capacitor bank. In both cases, the efficiency of energy input is determined by resistance of the breakdown path formation, which depends on its length, electric field intensity, and mineral composition of the rock. The breakdown path resistance and its change in time determine the design parameters of the rock-cutting installation: the response time of the switching devices, the power, and operating voltage of the power current sources.

The thermal breakdown path in the rock consists of two phases: liquid (melt of mineral matter) and gaseous (vapor of mineral matter and air), which are in the condition of intense turbulent motion. The process of rock heating, formation, and growth of the path is accompanied by the ejection of the components that make up the path through its mouth. The intensity of their release is determined by the electric field intensity and the energy source power.

When the molten substance is released from the path, the resistance of the path increases, the energy is lost, and the efficiency of the process decreases.

Breakdown path resistance as a function of the effective voltage and the released power was studied with the experimental setup shown in Figure 1.

The voltage was reduced until the moment of regeneration of the dielectric properties of the sample caused by the melting crystallization. The change in current in the path with time at a constant voltage value was studied, as well as intensity of regeneration of dielectric properties in the sample. It was found that, for each voltage step, the value of the current passing by the path is stationary with respect to time (Figure 9).

The volcanic breccia breakdown path resistance established experimentally is 5.0 kΩ/cm. In the experiments, a high-voltage transformer of IOM 100/25 type with a rated power of 25 kVA was used. When operating the more powerful source, the transformer of IOM 100/100 type, the breakdown path resistance was 1 kΩ/cm.

The subsequent action of the current on the rock does not cause any breakdown path formation along the same trajectory, and its formation occurs in a new region of the dielectric. This is due to the fact that as a result of melting and subsequent crystallization, a new substance is formed, which has more ordered structure and, consequently, lower conductivity.

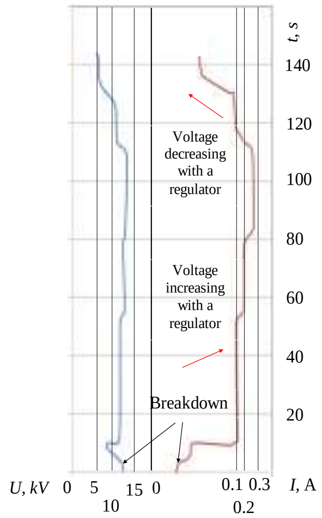

Figure 9. Current and voltage use in breakdown path diagram

The regenerating is a very intensive process determined by the amount of power released in the path. It was found that when it decreases to 0.4-0.6 kW, a phase transition occurs (Figure 10, point 1) and regeneration of the dielectric properties of the rock, and it can be seen that the resistance of the former path increases by 50% (which was obtained by comparing R_{Path} path resistance at points 1 and 2). Such an increase in the resistance of the circuit leads to a sharp decrease in the current in the rock and to an even greater cooling of the path. (Figure 10, from point 2 to point 3).

It should be noted here that when the closed breakdown path is formed, the reverse process with the same transition between phases occurs. This explains the fact that today it has not been possible to obtain a smooth current-voltage characteristic of the dielectric from its pre-breakdown state to its breakdown. The

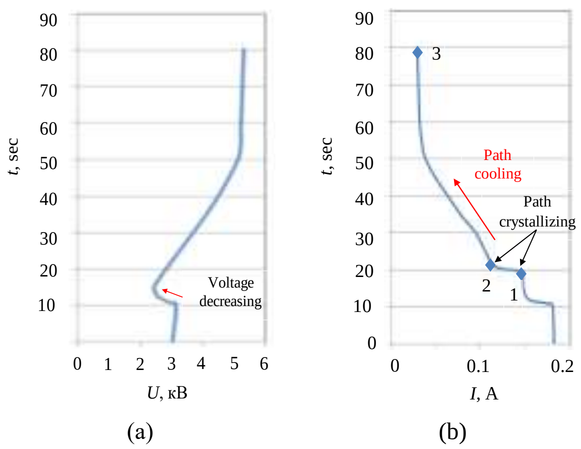

Figure 10. Temporal variation of voltage (a) and current (b) in crystalizing the breakdown path

transition from solid phase into liquid one reduces the resistance, which leads to a sharp increase in the current, the rate of which is determined by the dynamics of the phase transition, which gives a special point on the current-voltage characteristic of the dielectric, which undergoes breakdown (Figure 10).

Breakdown path temporal behavior study makes it possible to determine very important design parameter of the plant for an electrical destruction of rocks — the response time of switching devices, which switch power sources of current that load the path.

Crystallization of the breakdown path, the current-voltage characteristics of which are given in Figure 10, lasted for 1 second. With a higher released power, before removing the voltage, the crystallization process takes more time (Figure 11).

The trend of time of the path being in the melt state until the moment of its crystallization depending on the power released before removing the voltage is shown in Figure 12.

Thus, when using the high-voltage transformer of the greater power, the switches can operate in a relatively unstressed time mode, which allows the use of electromechanical drive.

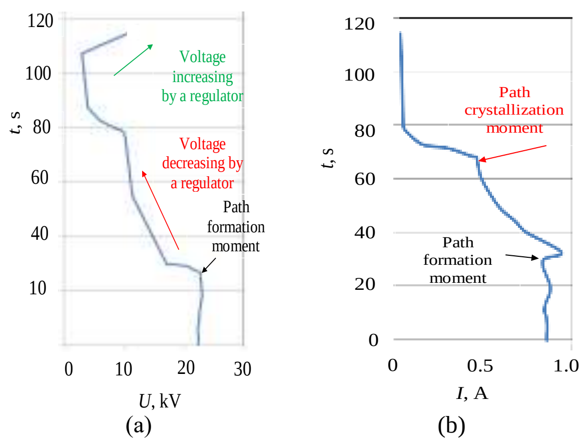

Figure 11. Temporal variation of voltage (a) and current (b) in crystalizing the breakdown path

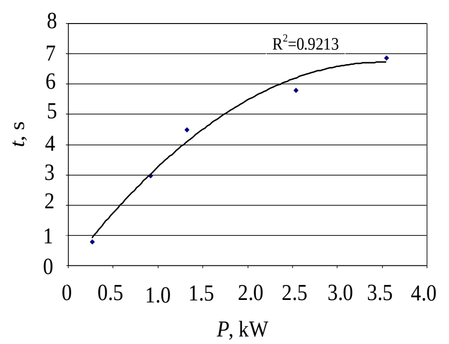

Figure 12. Time of the path being in the melt state until the moment of its crystallization, depending on the power released in the path at the moment of removing the voltage

4. CONCLUSIONS

Summing up, we can conclude that the study of thick rocks electrical breakdown in a 50 Hz electromagnetic field makes it possible to establish that the current-voltage characteristics of volcanogenic breccia, with an increase in the distance between the electrodes from $l_{эл}$ = 50 cm, transforms into a *C*-shaped curve, which corresponds to the breakdown of the rock with the formation of a complete breakdown channel closing the electrodes.

It was calculated that the current density required for breakdown in the rock is constant and equal to $j \approx 0{,}3\times10^{-3}$ A/cm^2. The decrease j at $l_{эл} > 50$ cm is associated with a lack of source power and not with the breakdown process. Given this feature, the studies were carried out with the distance between the electrodes up to 50 cm.

The study of the dispersion of resistance as a function of the distance between the electrodes and the electric field strength showed that it decreases with an increase in the distance between the electrodes and an increase in the electric field strength. A decrease in the dispersion of resistance in large gaps between the electrodes is associated with averaging the composition, and hence the properties of the rock.

Averaging the values of the breakdown strength $E_{el\,br}$ for volcanogenic breccias, one can conclude that the field strength of 0.3 ± 0.1 kV/cm is sufficient for the breakdown with the deepening of the channel at the distance between the electrodes <1 m.

The resistivity of the breakdown channel in volcanogenic breccia is 5.0 kOhm/cm when using the high-voltage transformer of the IOM 100/25 type with a rated power of 25 kVA, increasing the power of the transformer to 100 kVa (transformer of the IOM 100/100 type), the resistivity of the breakdown channel is 1 kΩ/cm.

In this case, the process of complete registration of the dielectric properties of the rock occurs after the stress is removed. The repeated action of the electric current on the rock forms the breakdown channel along the new trajectory. This is due to the formation of the new substance around the breakdown channel, which has new conductive properties.

The results obtained are of great importance in rocks electrothermal destruction theory development; namely, they show the behavior of current-voltage characteristics of the rock when electrode spacing is being increased. Besides, they can prove that rocks with initial thermal stress can be destroyed more easily and with minimal energy costs if the electrothermal method is used. The practical significance of the study is due to the way of destruction being applicable at the volcanogenic rhenium deposit of the Kudryavy active volcano crater.

5. REFERENCES

1. Sarapuu Erich, "Electro-energetic rock breaking systems", Mining Congress Institut, Vol. 59, (1973), 44-54.
2. Li Changping, Duan Longchen, Wu Laijie, Tan Songcheng, Zheng Jun, Chikhotkin Victor, "Experimental and numerical analyses of electro-pulse rock-breaking drilling", ***Journal of Natural Gas Science and Engineering***, Vol. 77, (2020), 103-263. doi: 10.1016/j.jngse.2020.103263
3. Rzhevskii V., Protasov Yu, Dobretsov V., "On the intensification of superhigh-frequency rock breaking", ***Journal of Mining Science - J MIN SCI-ENGL TR***, Vol. 5, (1969), 509-511. Doi: 10.1007/BF02501266
4. Yudin A. S., Kuznetsova N. S., Bakeev R. A. Zhgun D.V., Stefanov Yu. P. "Destruction of reinforced concrete by electric impulse discharges: Experiment and simulation", AIP Conference Proceedings 1909, Vol. 1, (2017), 15-39. doi:10.1063/1.5013915
5. O'Dwyer, J., "The Theory of Dielectric Breakdown of Solids", ***Journal of the Electrochemical Society***, Vol. 116, (1969), 239-242. Doi: 10.1149/1.2411805
6. Hassani, F., Nekoovaght, P. M., Radziszewski, P., & Waters, K. E., "Microwave assisted mechanical rock breaking", Harmonising Rock Engineering and the Environment - Proceedings of the 12th ISRM International Congress on Rock Mechanics, (2012), 2075-2080. doi: 10.1201/b11646-395
7. Zhou Huisheng, Xie Xinghua, Feng, Yuqing, "Rock breaking methods to replace blasting", IOP Conference Series: Materials Science and Engineering, Vol. 322, No. 2, (2018), 1-6. Doi: 10.1088/1757-899X/322/2/022014.
8. Ren F., Fang T., Cheng X., Chang Y., "Rock-breaking stress analysis and rock-breaking region under particle-waterjet impact", ***Shiyou Xuebao/Acta Petrolei Sinica***, Vol. 39, (2018). 1070-1080. doi: 10.7623/syxb201809011
9. Segsworth R., Kuhn K., "Electrical Rock Breaking", ***IEEE Transactions on Industry Applications,*** Vol. IA-13, (1977), 53-57. doi: 10.1109/TIA.1977.4503362
10. Moiseyenko Undina, Sokolova Liudmila, Istomin Vladimir, "Electrical and Thermal Properties of Rocks", (1970).
11. Segsworth R., Kuhn K., "Electrical Rock Breaking", ***IEEE Transactions on Industry Applications,*** Vol. IA-13, (1977), 53-57. doi: 10.1109/TIA.1977.4503362
12. Zhu Xiaohua, Dan Zhaowang, "Numerical simulation of rock breaking by PDC bit in hot dry rocks", ***Natural Gas Industry B,*** Vol. 6, No. 6, (2019), 619-628. doi 10.1016/j.ngib.2019.04.007
13. Mashchenko Volodymyr, Khomenko Oleh, Kvasnikov V., "Thermodynamic aspect of rock destruction", Naukovyi Visnyk Natsionalnoho Hirnychoho Universytetu, Vol. 6, (2020) 25-30. doi: 10.33271/nvngu/2020-1/025
14. Tretyak A. Ya, Popov V. V., Grossu A. N., Borisov K. A., "Innovative approaches to designing highly efficient rock-breaking tool", ***Mining Informational and Analytical Bulletin***, Vol. 8, (2017), 225-230. doi: 10.25018/0236-1493-2017-8-0-225-230
15. Wang M.S, Li Z.K., Geng Y.C., Tang H. L., "Laboratory study on rock breaking mechanism and its application", Vol. 29. (2008). 711-716.
16. Holman B.W., "Heat treatment as an agent in rock breaking". Vol. 36, (2020), 219-234.
17. Korostovenko, V. V., Sukhanova, A. V., "System analysis for estimating the opportunity of applying discharge-pulse methods in development of mineral resources", ***Successes of Modern Science,*** Vol. 11, (2017), 73-77
18. Rostovtsev, V. I., Kondrat'ev, S. A. and Baksheeva, I. I., "Improvement of Copper–Nickel Ore Concentration under Energy", ***Deposition Journal of Mining Science,*** Vol. 53, (2017), 907-914
19. Korzhenevsky S. R., Bessonova V. A., Komarsky A. A., Motovilov V. A. and Chepusov A. S., "Selection of electrohydraulic grinding parameters for quartz ore", ***Journal of Mining Science***, Vol. 52, (2016), 40-56
20. Korostovenko V. V., Korostovenko L. P., Stepanov A. G. and Sukhanova A. V., "Discharge-impulse methods application in technologies of mineral resources mastering", ***Journal of Physics: Conference Series***, Vol. 1399, No. 5, (2019), 493-496. doi: 10.1088/1742-6596/1399/5/055039 5 493-496
21. Lifshitz A. L., Otto M. S., "Pulse Electrical Engineering". Electroatomizdat, Moscow, (1983), 352
22. Yang, W., Li L. Zhao Y., "Preliminary inquiry of theory of resonance rock breaking", ***Energy Technology and Management***, Vol. 4, (2007), 7-9.
23. Belin V. A., Paramonov G. P., Jamiyan J., "Peculiarities of manufacturing and application of mixedexplosives of anfo type at mining enterprises of mongolia", ***Journal of Mining Institute,*** Vol. 232, (2018), 364-367 doi: 10.31897/PMI.2018.4.364
24. Salmi, A., Bousshine, L., Lahlou, K. A., "New Model of Equivalent Modulus Derived from Repeated Load CBR Test", ***International Journal of Engineering, Transactions A: Basics***, Vol. 33, No. 7, (2020), 1321-1330. doi: 10.5829/ije.2020.33.07a.19
25. AkbarpourShirazi, M., Adibee, N., Osanloo, M., Rahmanpour, M. An, "Approach to Locate an in Pit Crusher in Open Pit Mines», ***International Journal of Engineering, Transactions C: Aspects***, Vol. 27, No. 9, (2014), 1475-1484. doi: 10.5829/idosi.ije.2014.27.09c.18
26. Kovalevskyi V. N., Moldovan D. V., Chernobai V. I., "Determination of focal length for cumulative charges with various concavity shapes", ***International Journal of Mechanical Engineering and Technology***, Vol. 8, No. 11, (2017), 1119-1125
27. Mysin A. V., Kovalevskiy V. N., "Creation and Verification of Numerical Model of Explosive Charge Blast in the Ansys Software System, for the Purpose of Substantiating the Optimal Parameters of Drilling and Blasting Operations", E3S Web of Conferences, No. 174, (2020). 1046-1052. doi: 10.1051/e3sconf/202017401046
28. Marinin, M. A., Dolzhikov, V. V., "Blasting preparation for selective mining of complex structured ore deposition", IOP Conference Series: Earth and Environmental Science, Vol. 87, No. 5, (2017), 6-10. doi: 10.1088/1755-1315/87/5/052016
29. Dolzhikov, V. V., Marinin, M. A., "Quality preparation improvement of mined rock for mining extraction considering spatial temporary formation of field strain", IOP Conference Series: Earth and Environmental Science, Vol. 87, No. 5, (2017), 1-5. doi: 10.1088/1755-1315/87/5/052003
30. Afanasev, P. I., Sergey, K., Valentin, I., "The equation of state for explosive detonation products", International Journal of Mechanical Engineering and Technology, Vol. 9, No. 13, (2018), 865-868
31. Sidorov D. V., Ponomarenko T. V., "Estimation methodology for geodynamic behavior of nature-and-technology systems in implementation of mineral mining projects", Gornyi Zhurnal, No. 1, (2020), 40-53. doi: 10.17580/gzh.2020.01.09
32. Yastrebova K., Moldovan D., Chernobay V., "Influence of the nature of the outflow of explosion products from blast holes and boreholes on the efficiency of rock destruction", E3S Web of Conferences, Vol. 174, (2020), 1-6. doi: 10.1051/e3sconf/202017401017

33. Isheyskiy V. A., Yakubovskiy M. M., "Determination of strength reduction factor in blasted rocks versus the distance from the blast center", ***Gornyi Zhurnal***, Vol. 12, (2016), 55-59. doi: 10.17580/gzh.2016.12.12

34. Korshunov V. A., Kartashov Yu. M., Kozlov V. A., "Determination of indices of strength certificate of rocks using the method of specimens failire with spherical indentors", ***Journal of Mining Institute***, Vol. 185, (2010), 41-45

35. Beron A. I., Koifman M. I., Chirkov S. E., Solomina I. A., "The method for determination of strength of rocks using the specimens of irregular form", ***The Institute of mining named after A.A. Skochinski***, Moscow, 1976, 40

36. Korshunov V. A., "Determination of indices of volumetric strength of rocks under their loading with spherical indentors", ***Rock Geomechanics and Mining Surveying, Proc. VNIMI***, (1999), 70-75

Persian Abstract

چکیده

آتشفشان کودریاوی تنها رسوب عناصر کمیاب در جهان به صورت کانی سازی خالص رنیوم است. عوامل مختلفی مانع توسعه این میدان می شوند: دمای بالا در زمینه های زمین گرمایی ، وزش باد شدید ، فعالیت فومارولیک ، جایی که استفاده از روش حفاری و انفجار برای از بین بردن سنگ ها در یک دهانه می تواند منجر به بسته شدن تمام کانال های fumarole شود ، که منجر به تجمع انرژی عظیم و فوران بیشتر می شود. این مقاله روش های الکتریکی موجود برای تخریب سنگ را توصیف می کند ، مشخص شد که ولتاژ جریان مشخصه برش های آتشفشانی با افزایش فاصله بین الکترودها بیش از ۵۰ سانتی متر به یک وابستگی C شکل تبدیل می شود ، باعث کاهش قدرت جریان از ۰.۸۵ A تا ۰.۲ A ، تشکیل یک کانال شکست کامل. در این حالت ، حداقل مقاومت در برابر شکست میدان الکتریکی ۰.۳ ± ۰.۱ کیلو ولت بر سانتی متر است ، با افزایش این شاخص به ۳.۷ کیلو ولت بر سانتی متر ، بازده کانال سازی تا ۲٪ افزایش می یابد. در اطراف کانال تجزیه ، ماده جدیدی با خصوصیات رسانایی جدید ، متفاوت از برش آتشفشانی ، ایجاد می شود که از تشکیل کانال در امتداد مسیر قدیمی جلوگیری می کند.