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Mining

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IMPROVING THE RETENTION OF MINERALS IN THE COURSE OF SEPARATING MONOLITH FROM BEDROCK WITH THE USE OF GAS GENERATOR CARTRIDGES

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Results are presented on the effect of firing rate on pressure pulse in charge camera and fracture stress during spalling. Results are presented of comparative calculations using the equations of autocatalytic reactions of firing rates and escape of reaction products for the system of sodium chlorate - polythene (propylene) in pipe shape. Dependences are obtained of firing rate on concentration of gas generating mixture, its density, components size distribution and cartridge case size. Experimental and computational data were used to consider the conditions of firing turning into explosion for compositions based on sodium chlorate and hydrocarbons in layered and powdered systems. The relation is retrieved between the technological parameters of mining activities (blast hole to blast hole distance, blast hole diameter, depth of cartridge placement) and specific cartridge consumption along the spalling line with gas generators going off.

Key words: quarry, block rock, gas generator, sodium chlorate, Hydrocarbons, firing rate, blast hole, pressure, polythene.

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Introduction. The basic prerequisites for effective spalling of block rock from rock massif is retaining its monolith nature and forming its even surface with small side roughness. One should provide for the minimal perturbation of the developed massif, preventing it from forming spall zones *which* could affect the quality of spalling other blocks [7].

There is quite a number of techniques available for spalling blocks from rock massifs, e.g. using low brisant explosives, non-explosive spalling mixtures, gas generating compositions, etc. Choosing a particular technique depends on rock nature, and spall zones and blocks present in the massif. Lately, when mining block rock in construction material quarries gas generating cartridges find wider and wider use.

The current study is an extension of the whole complex of studies dedicated to developing gas generators (GG) that operate using sodium chlorate and hydrocarbons [3, 5, 6]. The operating principle of gas cartridges is based on firing gas generating mixture in deflagration (detonation-free) mode to produce large volume of gases that generate the stress needed to spall the monolith along the lines of concentrated tension (the line of blast holes). The components for gas generators (sodium chlorate as oxidizer and hydrocarbons as fuel are used for various technical purposes themselves and are of non-explosive nature. In the open they would not blast off even when initiated by high explosives, and closed spaced is needed for their proper functioning. By their design gas generators may present two different systems: powdered (a powdered mix of oxidizer and fuel) or stratified (powdered oxidizer and fuel in the form of polythene pipes).

Study [1] presented the results of studying the effect of developing spall areas in granite while spalling its blocks from rock massif by blast hole gas pressure generator (HPG). HPG is a powder system. In the course of our tests induced spall areas were analyzed in the vicinity of HPG charges in plate samples obtained in the result of spalling. The analysis of these results demonstrated that the longest fissures reach 14 blast hole radii. It results in deterioration of quality of ready products and undermines conservation of mineral raw materials.

Study results and discussion. To stabilize the properties and improve the level of conservation of mineral raw materials when spalling the monolith from the massif of rock with the use of gas generators(of various system design) one needs to investigate the effect of firing rate, the properties and components of gas generating mixture on the dynamic characteristics of these GGs.

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In our study [4] we have demonstrated good agreement between the results of computations of bomb pressure according to the equations of autocatalytic reactions with experimental data for the tested compositions (the correlation coefficient not lower than 0.98). Assuming that the final pressure in a bomb is defined by the mass of gaseous firing products of the charge (for their initial concentration [A], and the concentration of "prime" [B]), we write the modified equation of reaction in the form

$$\frac{d\alpha}{dt} = k(1-\alpha)(\alpha+\beta), \tag{1}$$

where α is the completeness of firing process (the ratio of pressure at complete firing of the mixture to the current pressure); k is the constant of reaction rate; β is the share of autocatalyzer in the total mass, $\beta = [B]/[A]$.

The solution of that equation has the form

$$\alpha(t) = \frac{\beta e^{(\beta+1)kt} - 1}{1+\beta e^{(\beta+1)kt}}. \tag{2}$$

Applying equation (2) to describe the process of combustion of polythene powder or diesel fuel demonstrates that the correlation factor stays not lower than 0.98. To apply that equation to thee composition of sodium chlorate and polythene pipes (a stratified system) one has to account for the non-diabatic nature of the firing process (firing time for the stratified system exceeds that of compositions based on powdered hydrocarbons or diesel fuel by more than an order of magnitude). For a stratified system we use the equation that accounts for thermal losses:

$$\alpha(t) = \frac{\beta e^{(\beta+1)k_1 t} - 1}{1+\beta e^{(\beta+1)k_1 t}}, \tag{3}$$

where t is time.

Meanwhile

$$k_1 = \left(\frac{a}{T_0} + bt\right)^{-1}, \tag{4}$$

where T_0 is the initial firing temperature; a and b are the factors retrieved experimentally.

Applying such a scheme to account for the losses enables one to describe the process at a correlation level not worse than 0.98. Using equations (2), (3) with charge (diameter and height) and bomb (bomb volume and its reduced height) parameters known has made it possible to define such parameters of the process as the change of linear firing rate in the bomb, the rate of drain of combustion products from the firing surface and compare it with the speed of sound in combustion products. The rate of drain characterizes the stability of the firing process of the mixture, and it may be considered as one of the criteria of deflagration proceeding to detonation: the higher the drain rate, the lower is the probability of deflagration proceeding to explosion and vice versa. Studying the process of deflagration developing into a detonation is of great importance in chosing the GG design, hence working to provide the safety of mineral resources. The principal characteristics of the studied process and comparative parameters of respective compositions are presented in Table 1. Mixture tests were conducted using a manometric bomb of 300 cm^3 capacity, the mass of fired mixture in the GG being 1.5 g. All the tests were run in textolite caps of 38 mm internal diameter and ~100 mm height.

Calculational data were analyzed on the maximum values of linear (u) and mass (g) firing rates, the drain rate of combustion products (W) from the burning surface, the time of reaching the maximum values of linear (τ_u) and mass drain rate of combustion products (τ_W), the maximum values of pressure growth rate in the bomb ($dp/d\tau$) and the moment of time corresponding to it (τ_p), plus the specific productivity of combustion products (RT).

The data presented in Table 1 indicate that bringing the mass of igniting mixture to 3 g results in higher drain rate of combustion products so that it reaches the critical values of: 940 and 1,960 m/s for

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the powder system. These results may be interpreted as transformation of the firing process into low rate detonation, as proved by disintegration of the charge body. Analyzing the results for mixtures of sodium chlorate liquid hydrocarbons (diesel fuel) one sees that their firing rates exceed those for stratified system but remain lower than those for the powdered system, especially when an igniter of large mass is used. For comparison purposes Table 1 quotes the data from the experiment with gunpowder. As seen from Table 1, all the considered dynamic parameters for gunpowder lag behind those for the system based on diesel fuel and sodium chlorate and the composition of powdered polythene and sodium chlorate.

Table 1

Comparison of mixture parameters

u, m/s	g, kg/s	τ_u, s	W, m/s	τ_W, s	$dp/d\tau$, Pa/s	τ_p, s	RT, kJ/kg
Stratified system							
2.79	1.74	–	12.9	0.055	$7.4\cdot10^{8}$	0.016	599.5
0.32	0.55	0.09	15.2	0.05	$8.45\cdot10^{8}$	0.022	573.5
0.39	0.67	0.08	36.8	0.004	$1.26\cdot10^{9}$	0.075	599.5
0.67	0.79	0.04	38.3	0.0035	$1.32\cdot10^{9}$	0.08	599.5
Powdered system							
16.62	28.02	0.0074	442	0.0060	$5.13\cdot10^{10}$	0.0073	646.5
22.6	38.1	0.0074	570	0.0061	$7.56\cdot10^{10}$	0.0075	646.5
27.05	46.03	0.0064	721	0.0064	$8.2\cdot10^{10}$	0.0075	646.5
30.62	52.10	0.003	940*	0.002	$9.6\cdot10^{10}$	0.003	686.5
63.87	108.7	0.0014	1960*	0.0009	$1.93\cdot10^{11}$	0.0014	686.5
Sodium chlorate (oxidizer) + diesel fuel (fuel)							
18.0	30.55	0.007	555	0.007	$5.69\cdot10^{10}$	0.008	537.6
Gunpowder							
7.88	8.76	0.04	319	0.08	$6.2\cdot10^{10}$	0.007	390.6

* Initiating the compositions was done with 3 g igniters.

Looking at these data from the point of view of possible progress of delagration to detonation (the principal criterion being the drain rate) one may note that the system staying the farthest from it is the stratified system. In contrast to that both calculations and experiments indicate that the system based on powdered polythene and sodium chlorate may proceed to explode. As for the system based on diesel fuel, increasing the power of its igniter and the mass of fuel may produce conditions for progress of deflagration into explosion.

The results presented indicate that the rate of drain from the burning surface may serve as one of the criteria for progress of deflagration into explosion.

On the other hand [2], the relationship between the rates of inflow of combustion components and their drain is the commonly accepted criterion to estimate the firing stability. In case the inflow of gases (defined by the firing rate) is less than the rate of products drain (their outflow under the critical conditions of gas dynamics), then the process of deflagration does not progress to detonation and vice versa. Now let us apply those criteria to our experiments and calculations.

With the linear firing rate, the charge density and the burning surface at hand we define the rate of components inflow. Consider the firing to be a butt propagating process, then deflagration products follow the equation for ideal gases.

Note that, first, we consider the process of drain of the firing products into the closed volume and, second, the process of deflagration for compositions based on sodium chlorate has an expressed autocatalytic nature instead of a common power function dependence. It means that the maximum firing rate is achieved not for the maximum pressure in the bomb but for its different value, defined by equations (2) and (3), i.e. at knuckle point of the inflow curve.

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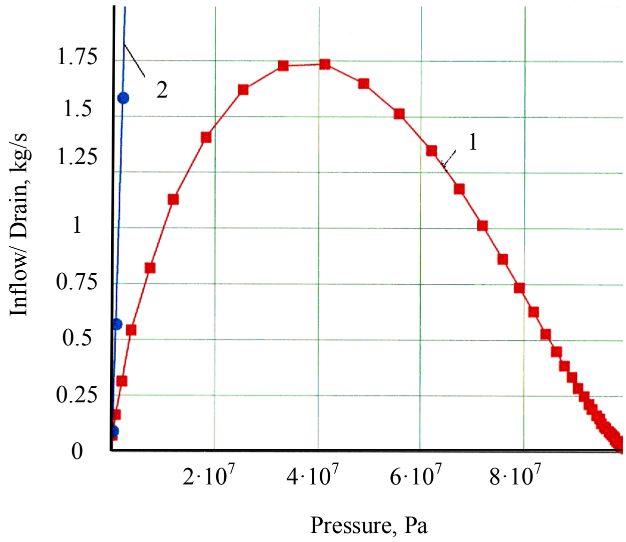

Fig. 1. Dependences of the mass firing rate / components inflow (1) and firing products drain (2) on bomb pressure for a stratified system

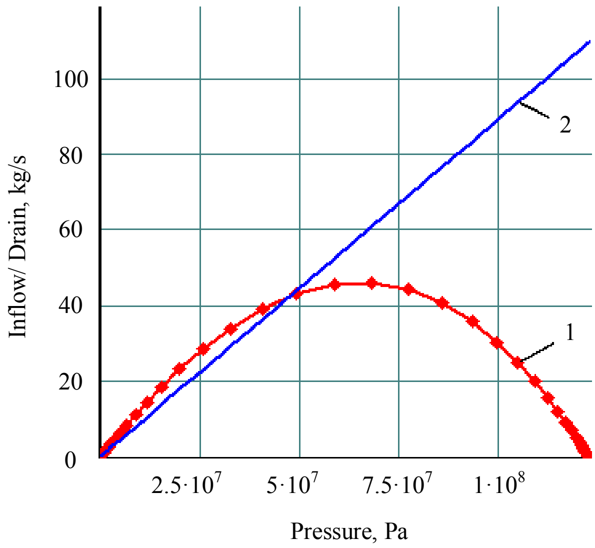

Fig. 2. Dependences of the mass firing rate / components inflow (1) and firing products drain (2) on bomb pressure for the system based on sodium chlorate and powdered polythene

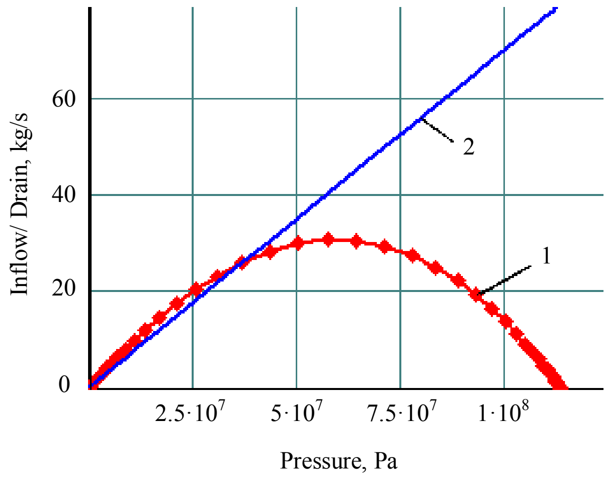

Fig. 3. Dependences of the mass firing rate / components inflow (1) and firing products drain (2) on bomb pressure for the composition based on sodium chlorate and diesel fuel

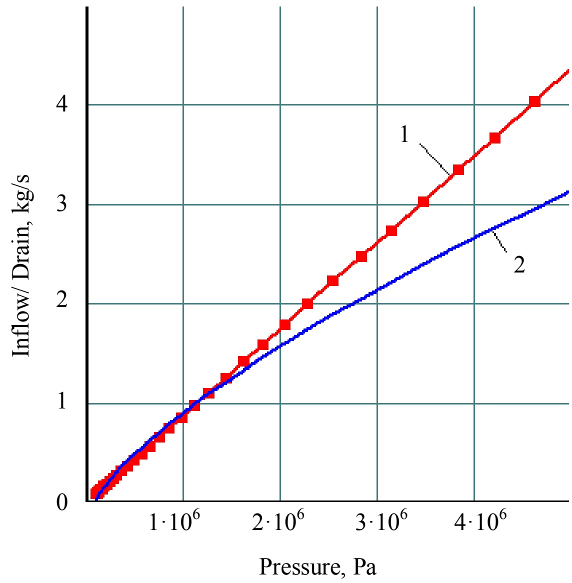

Fig. 4. Dependences of mass firing rate/ inflow (1) and drain (2) of deflagration products on bomb pressure for the system based on gunpowder in a closed volume

It follows from the data presented in Fig.1 that the stratified system burns steadily, and one cannot assume any possibility for it to proceed from combustion to detonation. The analysis of the process of deflagration for powder system is presented in Fig. 2. The inflow curve here goes above the drain curve, (cf. the stratified system, Fig. 1), that is at a higher rate and mass heat release, therefore that system has a possibility to proceed to detonation. Of certain interest from the point of view of models of deflagration stability are the data for the system based on sodium chlorate and diesel fuel, since it is easy and relatively cheap to produce (Fig. 3).

The analysis of dependences presented indicates that both curves practically coincide in their initial stage till the bomb pressure reaches about $3\cdot10^7$ Pa, but, since the inflow dominates over the drain such a composition may be considered a low-brisant explosive system.

To compare the obtained theoretical and experimental results for the studied systems we quote the data on the dependence of mass deflagration rate and inflow and drain of its products on pressure for gunpowder used to spall monolith blocks from rock massif (Fig. 4).

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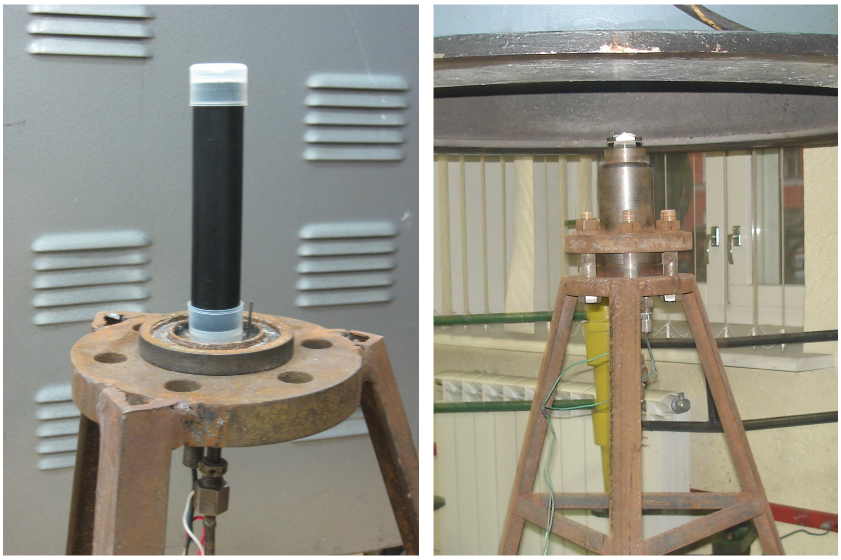

Fig. 5. The cartridge of gas generating composition prepared for the test (*a*) and placed into a permanent volume bomb (*b*)

Fig. 6. The sequence of fragmenting boulders with gas generators in the course of constructing an oil terminal

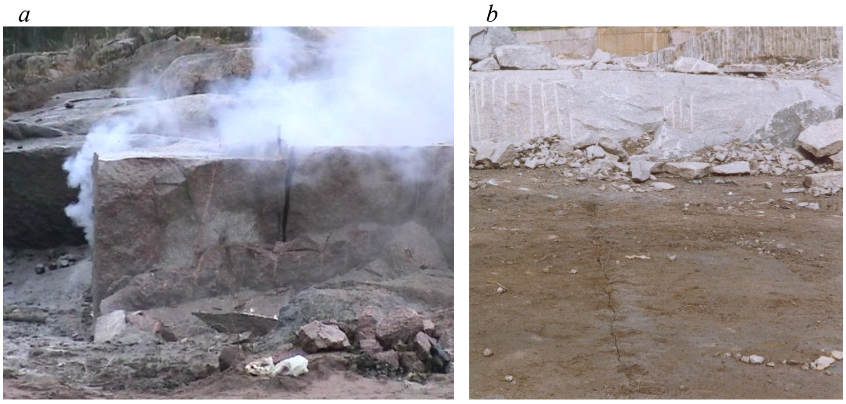

Fig. 7. Using gas generators in quarries for construction materials: *a* – prior to spalling a granite block from rock massif in the "Tervajarvi" quarry, block volume is 72 m^3; *b* – producing a mainline fissure to spall the monolith in moderation mode

As seen from calculation results the deflagration rate of inflow firing products exceeds the mass drain rate of burned out products, which may under certain conditions bring that system into the mode of low rate explosive transformation. Hence, using gunpowder may result in the formation of large zone of induced spall and degrade the quality of spalled blocks.

Therefore, using both techniques to assess stability of deflagration process both benchmarking the drain rate from the firing surface by the speed of sound in burnt products, and comparing the rates of inflow (the firing rate) and product drain, one may assess reliably the stability of deflagration process and its capability to proceed to detonation (explosion).

As demonstrated by experimental studies and calculations, the energy of substance charge in the gas generator depends strongly on the type of fuel mixed with oxidizer (powdered vs. stratified system). Technologically that means the need for a well-founded choice of pipes (polythene orpropylene) and their thickness for the stratified system. To that end studies were conducted in a permanent volume bomb. Pipe parameters were estimated by the factor of excessive oxidizer (Fig. 5).

Processing the experimental data made it possible, first, to identify the range of stable deflagration for stratified system; second, to retrieve regression dependences of the linear deflagration rate on the factor of oxidizer excess and define the maximum values of linear deflagration rates; third, to assess the effect of film thickness for fixed diameter pipes on deflagration rate.

To test operation stability of gas generators in stratified sys-

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tem, industrial tests were run fragmenting boulders (Fig. 6) and mining construction materials in quarries (Fig. 7).

Theoretical calculations and experimental industrial tests yielded the parameters for positioning blast holes for gas generator cartridges used to spall granite blocks from rock massif and specific consumption of gas generating composition (Table 2).

Table 2

Experimental values of specific gas generator charges consumption to spall granite in dependence of distance between blast holes of various depth, kg/m^3

Blast hole depth, m	Hole to hole distance, m								
	0,25	0,3	0,35	0,4	0,45	0,5	0,55	0,6	0,7
1	0.06	0.07	0.08	0.09	0.1	0.11	0.12	0.13	0.15
1.25	0.07	0.08	0.1	0.1	0.12	0.13	0.15	0.16	0.18
1.5	0.09	0.1	0.12	0.13	0.15	0.16	0.18	0.19	0.22
1.75	0.1	0.12	0.136	0.15	0.17	0.19	0.21	0.22	0.26
2	0.12	0.14	0.16	0.18	0.19	0.21	0.23	0.25	0.29
2.25	0.13	0.15	0.17	0.2	0.22	0.24	0.26	0.29	0.33
2.5	0.15	0.17	0.19	0.22	0.24	0.27	0.29	0.32	0.37
2.75	0.16	0.19	0.21	0.24	0.27	0.3	0.32	0.35	0.4
3	0.17	0.2	0.23	0.26	0.29	0.32	0.35	0.38	0.44
3.25	0.19	0.22	0.25	0.28	0.32	0.35	0.38	0.41	0.488
3.5	0.2	0.24	0.27	0.31	0.34	0.38	0.41	0.45	0.5

Comment. Blast hole diameter 32 mm.

Conclusions

1. The results of experimental studies and calculations following the two criteria have demonstrated that firing of the stratified system may only occur in deflagration mode. Proceeding of deflagration to detonation is hardly possible and practically excluded.
2. The gas generator powder system belongs to weak brisant class of explosives and is explosion-prone.
3. The composition on the basis of sodium chlorate and diesel fuel may also be rated an explosive, however a much weaker one.
4. The relationship is assessed between the technological parameters of mining operations (blast hole to hole distance, hole diameter and depth) along the block spalling line and specific consumption of gas generators.

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