UNDERGROUND EXPLOSION IN A LOW-POROSITY SOLID

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1. Formulation of the Problem. Experimental studies conducted in the field and the laboratory [1, 2] have established that underground explosions in such hard-to-fracture, nearly monolithic media as granite lead to a gigantic increase in permeability due to the creation of a system of cracks. The study findings were used as a basis for recommendations on the practical use of explosions in ore bodies to facilitate subsequent leaching operations.

On the other hand, powerful explosions in porous reservoirs containing low-pressure gas have not led to an increase in gas flow [4], while large-scale hydraulic fracturing conducted in the same bed has proven clearly effective [5]. Powerful explosions in petroleum resevoirs [6] appreciably changed the distribution of output by well and evidently resulted in a moderate increase in oil recovery from the bed.

Laboratory explosions in high-porosity models of fluid-saturated media confirmed that permeability increases slightly in distant zones and changes nonmonotonically in nearby zones [2, 7]. At the same time, an explosion in a dry medium with a porosity $m_0 = 25\%$ led [2, 8] to a sharp reduction in permeability due to shock closure of the pores followed by shear closure. An analysis [2, 8] established that the changes in permeability are due to small subcritical plastic strains and that dilatation, leading to an increase in porosity in the immediate vicinity of the cavity, is offset by the accompanying crushing of the material and, hence, a reduction in the effective diameter of the pore channels. These conclusions were supported by published data from laboratory explosions in specimens of natural sandstones ($m_0 = 26\%$). Investigators also noted annular compaction and dilatation zones [9], while studies with a scanning electron microscope [10] revealed that all of the cracks undergo dilatational opening. However, these cracks are short and do not form the crack network necessary for an effective increase in permeability.

In this connection, it was suggested that an explosion may lead to an increase in the permeability of resevoirs — but only low-porosity resevoirs [2]. Theoretical calculations of the mechanical effect of an explosion in the nearby zone [2, 11, 12] in which subcritical plastic strains were ignored to simplify the problem established that only porosity, not permeability, may change nonmonotonically. This finding made necessary the laboratory experiment described in the present article.

2. Experimental Method. Tests were conducted under laboratory conditions with blocks modeling rocks and made of a mixture of coarse sand (grain size to 2 mm), Portland cement (grade 500), and water. These materials were carefully mixed and poured into a metal container 300 mm in diameter and 350 mm in height. Pressure transducers were placed in the container at the same time. The filled container was compared by vibration for 2-3 min. Then stainless steel tubes (well models) were inserted into the container through special holes in its body to study the filtration properties of the medium. The assembled model was placed in a steam chamber for 9 h at 90°C and then held at room temperature for 7-10 days.

The medium was determined to have the following physicomechanical properties: strength in uniaxial compression $\sigma \simeq 35$ MPa; density $\rho \cdot 10^{-3} \simeq 2.15$ kg/m^3; velocity of longitudinal elastic waves $c \simeq 4000$ m/sec; porosity $m_0 \simeq 10\%$; gas permeability $k_0 \simeq 5$-10 mD. A cylindrical rod from 10 to 16 mm in diameter and up to 180 mm in length was placed in the center of the model before the latter was heat-treated. The rod was extracted after the medium cooled and the channel that was left was used as a blasthole.

We used a spherical charge of pentaerythrityl tetranitrate in the tests. The charges weighed 0.4, 0.76, and 1.34 g and had diameters of 8, 10, and 12 mm, respectively. The density of the explosive was 1.6 g/cm^3. The space above the charge in the blasthole was tempered with a material based on epoxy resin. The charges were detonated from the center with lead

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azide. Two conductors were placed in the charges in parallel and directed toward the detonation point to trigger the recording equipment. The model was clamped from above and below the explosion to create a preliminary static compression of 0.15-0.3 MPa. This prevented the model from being separated in two parts by a transverse crack created in the plane of the charge by the shock waves.

The mechanical effect of the explosion in the medium was evaluated by several methods: a) recording of the parameters of the shock waves; b) study of changes in the filtration properties of the medium from the explosion cavity to the periphery; c) visual observation of the character and size of fracture zones in the medium after the explosion (cavity size and sizes of fractures and cracks); d) study of the condition of the medium around the explosion cavity by acoustic and density techniques.

The pressure transducers were placed in the plane of the charge so that it was possible to record the radial component of stress σ_{11} in the shock wave in the range of corrected distances from 0.2 to 1 $m/kg^{1/3}$. As the transducers we used a semiconducting crystal of silicon based on a KS 133V stabilotron measuring 1 × 1 mm. A 3 × 3 mm plate was soldered onto the positive lead of the diode to increase the area of contact of the transducer with the medium. The working frequency range of such transducers is from 0 to 10 mHz.

The transducers were calibrated on an MP-2500 hydraulic press. The dependence of the sensitivity of the transducer on pressure $p \sim f(u)$ is linear. According to the results in [13], where semiconductor silicon transducers were dynamically loaded with a laser beam, the function $p \sim f(u)$ is linear in the pressure range $0\text{-}2 \cdot 10^3$ MPa. To evaluate the measured pressures, we conducted tests in sand. The resulting data on stresses agree satisfactorily with the results in [14]. The readings of the transducers in the tests were recorded with S8-11 and S8-14 oscillographs.

The filtration parameters were studied by using 8 tubes (3 mm in diameter) placed in the model at corrected distances of 0.162-1.94 $m/kg^{1/3}$ from the charge. The ends of the tubes were perforated over a length of 8-10 mm, while the opposite ends projecting from the model were flared and connected with adapter nuts to the measurement circuit.

The measurements were obtained with an AKM-core unit. In the tests, we determined the steady-state flow rate Q of air and the corresponding pressure drop Δp in the model between a pair of tubes before and after the explosion. The measure of the resistance of the medium was the ratio $R = Q/\Delta p^2$, which will henceforth be referred to as the fluid conductivity of the medium. We thus determined the fluid conductivity of the medium for the sections between wells.

The change in the filtration parameters of the medium as a result of the explosion was evaluated from the equation

$$R/R_0 = \frac{(Q/\Delta p^2)}{(Q_0/\Delta p_0^2)},$$

where R and R_0 are the fluid conductivities of the medium after and before the explosion.

Visual observation amounted to the following. After the post-explosion filtration characteristics of the medium were determined, the model was removed from its metal shell and cut in the transverse direction in the plane of the charge; the size of the cavity and the fracture and crack zones was determined from the cut surface.

The condition of the medium around the explosion cavity was studied by determining the change in the velocity of elastic waves in the medium and in its density. Here, we used a serially made UKB-1M unit to measure wave velocity in conjunction with an UGGP-1 universal gamma—gamma densitometer. The velocity of the longitudinal waves was determined with small transducers having a natural resonance frequency of 150 and 800 kHz. We used the method of through sounding of the model before the explosion. Here, the sounding was done over radii from the center to the periphery, with measurement points located every 0.5 cm. To determine changes in the properties of the medium after the explosion, we cut out a disk of material from the model in the plane of the charge (4-5 mm thick) and used the method of thickness sounding over different radii to determine the velocities of the longitudinal waves (across the disk). The measurement points were again 0.5 cm apart (i.e., there were 100 measurement points on each disk).

The change in the density of the medium around the explosion cavity was determined by the densitometric method of recording scattered gamma radiation (GGM-I) and a modification of

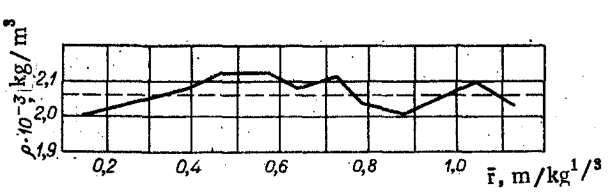

Fig. 1

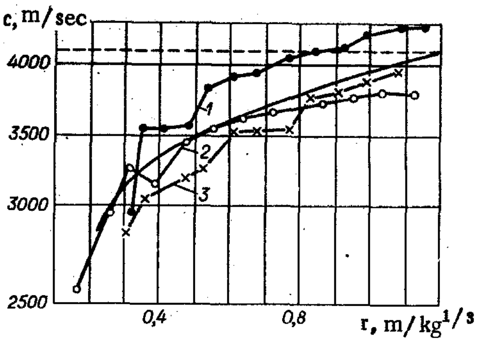

Fig. 2

TABLE 1

Weight of PETN charge, g	Radius of cavity r_c, mm	Radius of color-change zone r_*, mm	Corrected radius $\bar{r}_c$, m/kg$^{1/3}$	Corrected radius r_*, m/kg$^{1/3}$
1,34	10,5	30	0,083	0,245
0,76	8,1	26	0,08	0,255
0,40	6,7	25	0,081	0,30

the method of examination by a pencil beam of gamma rays (MPG). The gamma—gamma densitometric method is based on the recording of primary gamma radiation. By recording the counting rate on the disk cut from the model after the explosion and used for the above-mentioned measurements of wave velocity with allowance for its thickness at the point of examination, we could determine the volume weight of the medium around the explosion cavity. The density of the medium was measured over radii from the center of the disk at points 0.5-1.0 cm apart.

3. Experimental Results. We visually studied the blast zones in five of 11 tests of a series. In three of the tests, disks were cut out to measure the velocity and density of the medium subjected to the explosion. The changes in the filtration properties of the medium and the stresses in the shock wave were recorded in all 11 tests explosions.

After the metal shell was removed and the model was separated into two parts (upper and lower) in the plane of the charge, it was found that the nearly spherical explosion cavity had been burnt by detonation products and was surrounded by a region of compacted material. This material, however, was still less coherent than the original medium. Its color had also changed. Isolated vertical cracks could be seen passing from the cavity through the color-change zone. The number of cracks was small (up to 5), and their length over the radius from the cavity was about 0.8 m/kg$^{1/3}$. Table 1 shows the radial dimensions of the cavity and the color-change zone r_* for three charge weights. Here, the mean size of the explosion cavity is 0.08 m/kg$^{1/3}$, the size of the crushed zone (color-change zone) around the cavity has a radius of about 0.27 m/kg$^{1/3}$, and the length of the newly formed cracks ranges up to 0.8 m/kg$^{1/3}$.

Figure 1 shows the change in the density of the medium from the cavity to the periphery according to the experimental results. It is evident from this data that zones of loosening and compaction alternate around the cavity. The loosened (dilated) zone extends to distances $\bar{r} \cong 0.32$ m/kg$^{1/3}$ from the center of the explosion, while the compaction zone extends to the range of distances $\bar{r} \cong 0.32-0.88$. The UGGPI-1 did not detect any changes in the density of the medium at distances greater than $\bar{r} \cong 0.88$ m/kg$^{1/3}$. The loosening and compaction of the medium average 5-6%.

The data on the velocity of the elastic waves was averaged for each of three disks over points corresponding to the same corrected distances. This gave us experimental curves 1-3 (Fig. 2), which show the change in velocity in the corresponding models investigated. Figure 2 also shows the monotonic curve $c = 1758.7 + 4127\bar{r} + 1912.6\bar{r}^2$, corresponding (with a confidence level of 0.92) to the expectation value of longitudinal wave velocity and obtained by averaging data for all three disks. The greater changes in c (60-80% of the original values) are seen at distances up to 0.3-0.5$\bar{r}$. General disturbances in the medium are seen up to distances of 1.2$\bar{r}$.

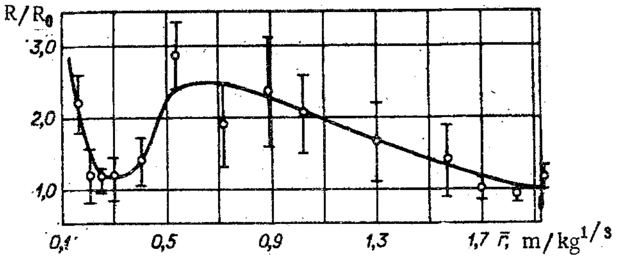

Fig. 3

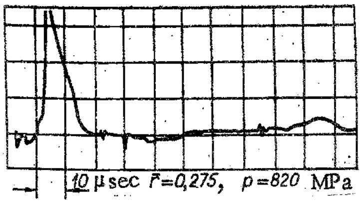

Fig. 4

Figure 3 shows changes in the filtration properties of the medium as a result of the explosion.* Three zones with different types of change in filtration properties are observed in succession going away from the cavity. In the first zone, with a radius $\bar{r}$ of about 0.25 m/kg$^{1/3}$, fluid conductivity increases from the external boundary to the explosion cavity by a factor of approximately 3-4. On the boundary itself $\bar{r} \simeq 0.25$ m/kg$^{1/3}$, the permeability of the medium is roughly equal to the initial permeability. In the second zone (0.25-0.65 m/kg$^{1/3}$), fluid conductivity increases by a factor of 2.6. The third zone, beginning at $\bar{r}$ equal to about 0.65 m/kg$^{1/3}$, has an external boundary at $\bar{r}$ equal to about 2.0 m/kg$^{1/3}$ and corresponds to a gradual reduction in fluid conductivity to the initial value. The mean improvement in permeability in this zone is associated with a factor of 1.5.

Figure 4 shows a typical oscillogram of the stresses in the wave. We should note that even at the points nearest the charge the wave front is different from a shock front and constitutes a continuous compression wave. The velocity of the maximum of the wave front up to distances $\bar{r} \simeq 0.6$ m/kg$^{1/3}$ is below the speed of sound in the medium, i.e., the maximum of the blast wave corresponds to a plastic wave.

Statistical analysis of the dynamic measurements gives us the dependence of the maximum stresses in the wave $\sigma_{11}^{\max} = 33.2(\bar{r})^{-n}$ ($n = 2.13$, $0.26 \leqslant \bar{r} \leqslant 1.0$) on the corrected distance. The exponent n turns out to be lower than for high-strength media [2, 15, 16], which is consistent in terms of order of magnitude with the measurements [17].

Table 2 shows the radii of characteristic explosion-affected zones.

4. Analysis of Results. The change in fluid conductivity after the explosion is due primarily to subcritical changes in the structure of the pore space — in the present case, the creation of new microcracks. However, a gradual increase in fluid conductivity up to the cavity is suppressed by general compaction of the medium (see Fig. 1), and only the presence of long macrocracks ($\bar{r} \leqslant \bar{r}_f$) penetrating the compact zone ensures that the level of permeability ($R \geqslant R_0$) is maintained.

The subsequent transition to the loosened zone ($\bar{r} \leqslant 0.32$) ensures a new increase in fluid conductivity toward the cavity. The size of this zone, meanwhile, coincides with the size of the zone in which the medium has undergone cataplastic crushing to the powdered state and a change in color.

The complex character of the change in pore space in the range $0.3 \leqslant \bar{r} \leqslant 0.52$ and the alternation of compaction and loosening are also reflected by the nonmonoticity of individual curves of ultrasonic velocity $V_p \simeq f(\bar{r})$ for each disk studied. The presence of local maxima ($\bar{r} = 0.48$-0.55) and minima ($\bar{r} \simeq 0.63$) was noted in acoustic studies of the zone affected by a full-scale underground explosion [18] with a charge of 500 kg.

Comparison of the data obtained here with the results in [2, 7, 8] leads to the following conclusions. With a reduction in porosity by a factor of 2.5 (from 25 to 10%), the linear size of the cavity decreases by a factor of 1.5. The fluid conductivity of the new cracks in this case approximately doubles, while the size of the fracture zone determined by ultrasonic studies increases by a factor of 1.5. The external boundary of the compact zone has a linear size almost twice as great for low-porosity medium as for a medium with $m_0 = 25\%$. This can be attributed to a lesser degree of decay of $\sigma_{11}^{\max}$ in the wave: $n = 2.13$ for low-porosity media with $m_0 = 10\%$, versus $n = 3.5$ for $m_0 = 25\%$ [2, 8, 15]. The changes in the filtration properties of the medium with a reduction in its initial porosity from 25 to 10% are qualitatively

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*The tubes — the well models — were undamaged after the explosion; this means that all changes caused by the explosion occurred in the porous medium.

TABLE 2

Radius of cavity $\bar{r}_c$, $m/kg^{1/3}$	Radius of new cracks $\bar{r}_f$, $m/kg^{1/3}$	Radius of fracture $\bar{r}_p$, $m/kg^{1/3}$*	Radius of subcritical strain $\bar{r}_s$, $m/kg^{1/3}$†	Dilation radius $\bar{r}_{di}$, $m/kg^{1/3}$	Compaction range $\bar{r}_c$, $m/kg^{1/3}$	Improvement in filtration properties
0,08	0,8	1,2	2,0	0,3	0,3–0,9	from $\bar{r} \simeq 2{,}0$

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*According to data from ultrasonic studies.

†According to data on the change in the filtration properties of the medium.

different. Thus, whereas an explosion in a medium with m_0 = 25% leads to a deterioration in permeability only up to distances $\bar{r} \simeq 2.0\ m/kg^{1/3}$ (with a maximum reduction by a factor of more than 10^2 near the cavity), an explosion in a medium with $m_0 \simeq 10\%$ causes nonmonotonic changes in post-explosion permeability. The fluid conductivity from the cavity to the periphery has local maxima and minima and turns out to be higher than the original value everywhere in the mechanically affected zone.

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REACTION OF A THREE-LAYER HYDROELASTIC CYLINDRICAL SHELL TO AN AXISYMMETRIC INTERNAL EXPLOSION

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A relatively small number of publications has been devoted to the experimental study of the elastic deformation of shells under explosive loading. The first studies in this area [1-3] examined the dynamics of closed metal shells to obtain estimates of the strength of blast chambers. The status of these investigations was analyzed in [4] and a fairly complete survey of the literature was made. It was apparent from the survey that most of the studies examined the dynamics of one-layer shells with a monolithic wall. It was shown (in [4, 5], for example) that the dynamic reaction of the shell depends not only on the energy released by the explosion but on features of the natural vibration-frequency spectrum of structures. In particular, an increase in the amplitude of the vibrations ("buildup") was noted. In the opinion of the authors, this phenomenon is due to interaction of natural modes of vibration and it leads to a significant increase in shell deformation compared to the strains calculated on the basis of the simplest model of a shell as a system with one degree of freedom.

There is almost no data on the dynamics of elastic shells with a more complicated structure, such as multilayer shells with a combination of dissimilar materials. Results were presented in [8] from an experiment with a three-layer shell subjected to shock loading. The dependence of the strain of the external layer on the parameters of the filler material was determined. The inside and outside layers of the shell were made of steel, while the material of the intervening layer was varied — water, sand, or concrete (only data on the amplitudes of the maximum strains was presented, and no information was given on features of the vibration process).

Here we study the dynamics of a three-layer (metal—liquid—metal) shell loaded by the detonation of a linear explosive charge on the axis. The study is conducted within the elastic range of deformation of the bearing layers. We determine the dependence of the shell strains on the thickness of the liquid layer and obtain data on features of the vibration process which develops in the system.

The test model (Fig. 1) consisted of two cylindrical shells 1 and 2. The space between the shells was filled with water 3. The model was loaded by the detonation of an explosive charge 4 in air. The charge was placed along the geometric axis of the system. The internal cavity and the annular volume between the shells were enclosed by flat monolithic heads 5. The joint between the cylindrical shells and flanges corresponded structurally to a scheme of rigid fastening. The thickness of the layer of liquid filler H was changed gradually by replacing the external shells. The number of values of H studied was not large, which had to do with technical difficulties. As a result, the range of thicknesses was chosen to be rather large: $H/R_1 = 0.23-0.66$ (R_1 and R_2 are the radii of the internal and external layers). The shells were made of flat-rolled steel Kh18N10T of the thickness $h_1 = h_3 = 3$ mm and had the following dimensions: $D_1 = 234$ mm, $D_2 = 294$, 334, and 394 mm; length $L = 1200$ mm. The chosen dimensions of the system made it possible to prevent the strains measured in sections L/2 from being affected by perturbations reflected from the ends (at least during the first half-period of the circumferential vibrations). We used linear charges with the same weight of explosive. The charges consisted of three tightly packed detonating fuses of the DSh-A type (detonation velocity $v_D = 6500$ m/sec, the explosive was pentaerythrityl tetranitrate, and the linear weight of explosive for one fuse was $1.2 \cdot 10^{-2}$ kg/m). The charge was detonated from one end. The arrow in Fig. 1 denotes the direction of propagation of the detonation wave.

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