time is large by comparison with τ_S) and also losses on account of nonconservation of the magnetic flux.

Figure 4 shows the secondary current I_2, the voltage on the fuse, and the current in the shunting foil (curves 1-3, respectively). The voltage across a fuse appears at the time when the foil resistance is increasing rapidly and rises to 20 kV on each fuse.

With a charging current of 54 kA, the current amplitude at the output of the store is over 2 MA. After the maximum the current decays exponentially with a time constant $\tau_2 \approx 10^{-3}$ sec.

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CONFINED EXPLOSION IN A POROUS MEDIUM

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UDC 622.235

1. Measurements have been made on the mechanical effects of confined explosions on monolithic rocks [1-5], and the maximal parameters of the explosion wave (mass velocity and pressure) have been related to the reduced distance, while information has been obtained on the damage zones. The results enable one to formulate relatively simple ways of forecasting the mechanical effects of explosion on monolithic rocks [1, 5]. On the other hand, the experimental data on explosions in porous media are restricted to laboratory results with sand [6, 7] and field studies [8, 9] with natural soft soils, which have enabled one to examine the damping of the compression waves [6, 8, 9] and the deconsolidating motion behind the front [7], which is responsible for the dilatancy [1, 5, 10]. It is extremely difficult to examine the damage zones in a material such as sand [11], and in laboratory experiments [3, 12] with pressed rocksalt the main attention was devoted to the decay of the mass velocities in the compression wave.

The available evidence on spherical explosion waves leads to the following conflict. For example, it is often asserted that the relationship between the maximum mass velocity and the reduced distance $\bar{r} = R/W^{1/3}$ (where W is explosion energy) for a monolithic rock (granite or rocksalt) is the same as for a porous medium such as sand. On the other hand, it is known [1,13] that there is a very low seismic performance in certain porous media (alluvium) surrounding an explosion focus.

This gives considerable interest to the mechanical effects of an explosion on a strong highly porous medium in which the damage areas can be identified quite simply. Artificial production enables one to select the properties to simulate actual rocks and also to locate measuring devices without disrupting the integrity.

2. The experiments on confined explosions were performed on blocks of artificial porous medium made from a mixture of KP-3 sand, lime flour, and waterglass. Heat treatment made the porous medium similar to strong but brittle rock. A cylindrical block of this medium had a height of 350 mm and a diameter of 300 mm and was contained in a metal vessel. The size of the block and the magnitude of the explosive charge were chosen such that the

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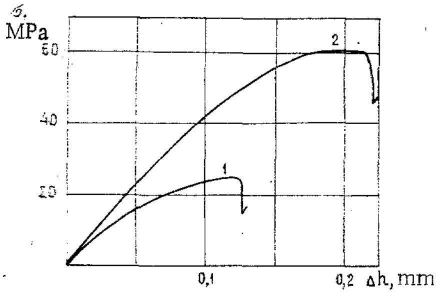

Fig. 1

cavity-development time was less than twice the transit time for compression waves moving up to the boundary on the model [1]. The explosive was TEN as spherical charges of diameters 12 and 8 mm and masses 1.34 and 0.4 g (trotyl equivalent W = 1.89 and 0.56 g). The charge was placed in the center of the model in a hole which was filled with epoxide resin.

The parameters of the medium constituting the block were as follows: density $\rho = 1.85 \cdot 10^3$ kg/m^3, porosity m = 25%, permeability k_0 = 150-300 mD, density of matrix material $\gamma = 2.64 \cdot 10^3$ kg/m^3, longitudinal-wave speed c = 3000 m/sec, Poisson's ratio $\nu = 0.22$, Young's modulus $E = 3.5 \cdot 10^3$ MPa, strength in uniaxial compression $\sigma^* = 25$ MPa, and strength in tension by the Brazilian method $\sigma_t = 4.5$ MPa. The data on the character of the failure (Konenkov's measurements) are given in Fig. 1. On the deformation data, the artificial material (curve 1) is similar to a sandstone (curve 2) but is weaker than the latter.

We used stress transducers made from semiconducting silicon crystals to measure the parameters of the stress waves. The transducers were oriented in the models in relation to the point of charge placement in such a way that it was possible to record the radial component of the stress in the compression wave. The transducers were calibrated with an oil press up to 250 MPa and on explosion in moist sand before insertion in the medium.

The medium was released after the explosion from the mechanical shell for visual examination and was cut in a cross section in the plane of the charge. We determined the size of the cavity, the mode of damage around it, and the extent of the cracks.

A densitometric method of recording scattered γ rays (GGM-p) was used with a narrow γ-ray beam (MPG) to measure the density of the medium from the explosion cavity out to the periphery. The basis of the γ–γ density method is that γ rays from the source are scattered in the material. The density distribution in the medium was measured by zones on disks of thickness up to 5 cm cut from the model after the explosion in the plane of the charge. The measurements were made along five rays from the center; the pitch in the measurements varied from 1.0 cm at the periphery to 0.5 cm at the central part of the disk (the method was developed and the measurements were performed jointly with G. I. Khovrin and L. B. Prozorov).

The acoustic method of examination involved determining the push-wave speed in the medium before and after the explosion. We used a UKV-1M apparatus, for which we made small transducers with natural resonant frequencies of 150 and 800 kHz. The initial properties of the medium were determined by passing the ultrasound along the generator along three lines from the center at angles of 120° to one another, with measurement points at 0.5-2.0 cm intervals; here we used the transducers with the natural resonant frequency of 150 kHz. To detect the changes in acoustic parameters after the explosion, the measurements were made on a disk already used for measuring the density along the same lines. The profile and thickness measurements were made with transducers with the natural resonance frequency of 800 kHz with a 0.5-cm step (the method was developed and the measurements were performed jointly with Yu. F. Trofimov and N. I. Seleznev).

We inserted eight tubes of diameter 3 mm at distances from 2.2 to 14 cm from the charge in order to examine the change in filtration parameters; the ends of the tubes were perforated over a length of 18-20 mm, while the opposite ends emerging from the model were joined to a measurement system. We determined the steady-state flow rate of air and the corresponding pressure difference between pairs of tubes in the model before and after the explosion. The filtration characteristic was taken as the ratio $\Gamma = Q/\Delta p^2$, i.e., we determined the conductivity of the medium in a particular area (method developed jointly with K. S. Konenkov).

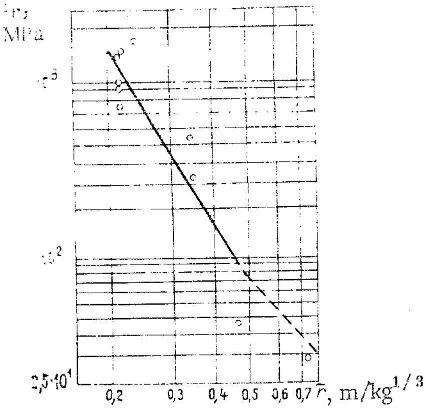

Fig. 2

TABLE 1

Zones	R, mm	R/a_0	$\bar{r}$, m/kg$^{1/3}$
R_0	15	2,5	0.12
R_p	37,5	6,25	0,3
R_{cr}	45	7,5	0,365

3. The mechanical effects of the confined explosion were as follows. The cavity was nearly spherical. Around it was a zone with an altered color, which was identified as a pressed but weakly bound powder. Cracks colored by the explosion gases could be traced out from the boundary of the cavity. These pass through the zone of pressed powder, but their lengths were 30% greater than the radius of this zone, while the widths were <0.5 mm. The total number was three to five. The size R_0 of the cavity, the size R_p of the zone of pressed powder, and the size R_{cr} for the crack zone are given in Table 1 (for W = 1.34 g of TEN, charge radius a_0 = 6 mm).

Figure 2 gives the maximum radial stresses σ_r in the compression wave. In the near zone, $R < R_\tau$, the results are described by

$$\sigma_r = A(R/W^{1/3})^{-n},\ [\sigma_r] = \mathrm{MPa}\ ,\ n = 3.5,\ A = 6.4, \qquad (3.1)$$
$$0.21 \leqslant \bar{r} \leqslant 0.47.$$

Only one measurement ($\bar{r}$ = 0.73) was made at somewhat larger distances, but in another series of experiments we made measurements from which one could establish reliably the value n = 1.96 for $\bar{r} \geqslant 0.47$; the corresponding line passes through the measurement at $\bar{r}$ = 0.73 (broken line in Fig. 2). Also, the same series of experiments implied n = 0.6 for the maximal measured stresses σ_φ for $\bar{r} \leqslant 0.47$, and this implies that in the region $R < R_\tau = 0.47\ W^{1/3}$ there were considerable maximal shear stresses $\tau = (1/2)(\sigma_r - \sigma_\varphi)$ of the order of the strength of the medium. High shear stresses are evident also from the residual radial stresses σ_r^∞ and azimuthal ones σ_φ^∞, which could be seen on recordings of the stresses. Figure 3 shows the distribution of the residual stresses from the cavity out to the periphery, which indicates that from R = 0.25 $W^{1/3}$ to R = 0.4 $W^{1/3}$ (from 3 to 5.25 cm) there is a zone of elevated residual stresses of both types with the maximum values at the level R = 0.33·$W^{1/3}$ (4.1 cm). The anomalously large residual stresses recorded near the wall of the cavity (at R < 2.25 cm) were not borne in mind, since the transducers could have been affected by the hot detonation products. On the whole, the residual-stress distribution agrees with the data of [14].

Figure 4 shows the density measured by zones from the cavity to the periphery as averaged over the various measurement rays. In the distance range from R = 0.125 $W^{1/3}$ to R = 0.29 $W^{1/3}$ the density after the explosion was reduced by a maximum of 16%, while from R = 0.29 $W^{1/3}$ to R = 0.49 $W^{1/3}$ it increased by 6-10%. No density changes were found outside these limits.

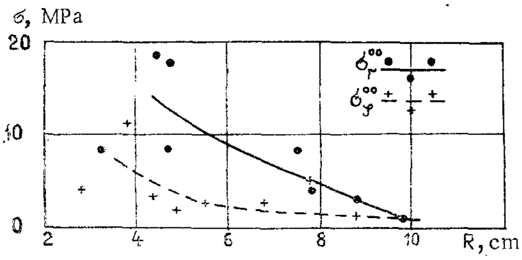

Fig. 3

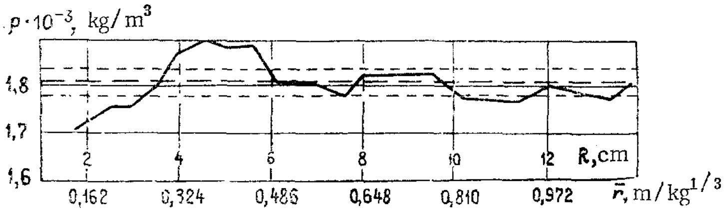

Fig. 4

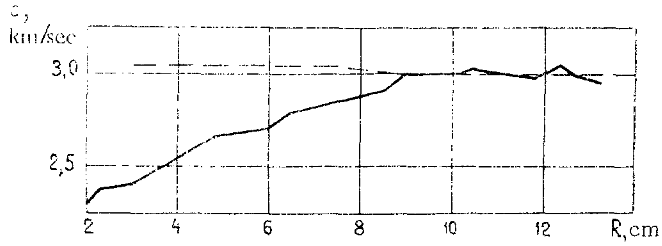

Fig. 5

The solid line in Fig. 5 shows that the elastic-wave speed increases away from the center of the explosion on average from 2430 m/sec to the initial values of 3000 ± 100 m/sec at $R = 0.8\ W^{1/3}$ (broken line in Fig. 5). Longitudinal profiles taken along the same radii gave the following results (Fig. 6). Near $R = 0.31\ W^{1/3}$, the wave speed after the explosion was reduced by about 30%. In the section from $R = 0.31\ W^{1/3}$ to $R = 0.42\ W^{1/3}$ there was an increase in the speed, with a peak value of 4000 m/sec (30-35% above the initial value) at $R = 0.365\ W^{1/3}$.

Figure 7 shows the filtration results (H_a is the hydraulic conductivity after the explosion, and H_b is that before it, namely the initial value). In all cases the filtration parameters were reduced after the explosion. The conductivity gradually increased outwards from the cavity, but it remained below the initial value throughout the distance range out to $R \geqslant 2\ W^{1/3}$.

4. We now analyze these results on spherically symmetrical explosive motion in porous media. A difference from the failure zones in brittle monolithic solids [3, 15], where the material is fragmented by cracks, is that a porous brittle medium has only a few cracks. The region of vigorous mechanical action is $R_0 < R < R_\tau = 0.47\ W^{1/3}$ and consists of two zones. In the internal zone, directly adjoining the cavity, the main effect is reduction of the material to a weakly bound powder. On the other hand, this powder was fairly tightly compacted. The density was less than the initial density of the medium by 16%, while the longitudinal-wave speed was reduced by 20%, i.e., this zone can be called a zone of deconsolidation in relation to the initial state: $R_0 < R < R_d \doteq 0.3\ W^{1/3}$. This zone coincides with the zone of the pressed powder ($R_d = R_p$). This state is produced by high shear stresses τ, so this deconsolidation related to crushing was of limiting dilatancy type [1, 10]. The permeability of the pressed powder was no higher than the initial permeability of the medium, since the dilatancy does not result in an increase in the permeability when high pressures act at the same time and merely reduces the rate of decrease [16]. There was an appreciable improvement in the hydraulic permeability in this zone in some experiments, but this was accidental and was due to individual cracks as reported above.

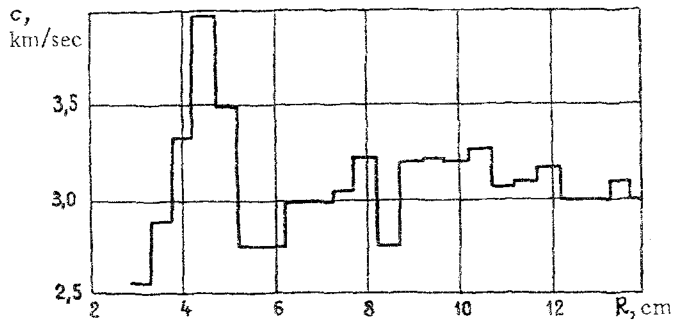

Fig. 6

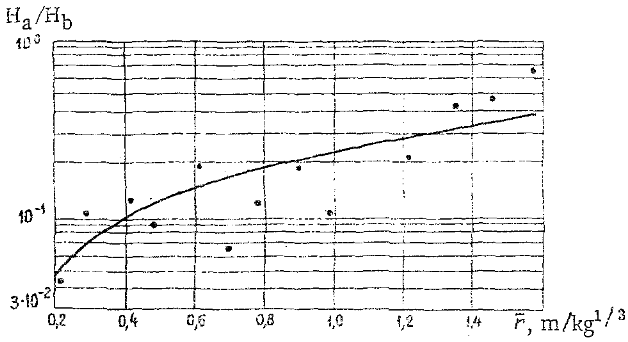

Fig. 7

In an explosion in sand [11], pressed powder is formed near the cavity, which at later stages of the explosive motion is penetrated by radial cracks. Not much is known about the effects of residual stresses on the hydraulic conductivity of the radial cracks.

The second (external) part of the region of extensive mechanical action was $R_d = 0.3\ W^{1/3} \leq R \leq R_\tau = 0.47\ W^{1/3}$ and constituted the consolidation zone. In this zone the density was 5% above the initial value, and the speed of longitudinal elastic waves in the radial direction was above the initial level by up to 35%. The maximum residual stresses also occurred in this zone.

The maximum in the residual stresses corresponds to the second stress peak in the spherical explosion wave found [17] by numerical calculation for dilating rocks (the first corresponds to the wave front). In fact, the second stress peak is displaced only slightly in time, and the amplitude, although decreasing, remains above the stresses at larger and smaller distances from the center. The second peak, or the maximum in the residual stresses, is to be identified with a ring zone around the cavity. It follows from calculations [18] that this is a compression effect, and that it occurs to a smaller extent also in plastic incompressible media.

On the other hand, the residual density changes, which are excluded in traditional elastoplastic calculations [18], are characteristic of dilating media. While the residual consolidation can be ascribed to effects at the shock-wave front, the deconsolidation can be explained [10] only by dilatancy.

The maximum consolidation occurs not at the front of the spherical explosion wave in a sand but a certain time later [19], which is also due to dilatancy accentuation of the consolidation behind the front arising from the shear stresses [20].

The differences in the speed of sound along the radius and in the azimuthal direction after the explosion indicate anisotropy in the residual volume changes and the corresponding changes in Young's modulus. This result is in agreement with the data [21] on the marked anisotropy occurring in processing metal powders with explosion waves.

The reduction in the hydraulic conductivity H extends outside the region of marked mechanical action, i.e., to the region where the changes in acoustic properties and porosity hardly exceed the spread in the data, which indicates minor plastic strain in the pore space [22]. Here we may note the study of [23], according to which the outer boundary of the weak

TABLE 2

Rock	$\rho\cdot10^{-3}$ kg/m³	c, km/sec	$\rho c^2\cdot10^{-2}$, MPa	n	A·10	Range	Source	Note
				3,4	36,5	$0,7<\bar{r}<3$		Laboratory
Sand	1.7	0,215	0,786	1,8	9.5	$3<\bar{r}<10$	[6]	expts.
Sandy soil	1,5	0,08	0,096	3,3	2.8	$0,5<\bar{r}<2$	[8]	Field expts.
Alluvium	1.6	1.2	23	3,035	9.3	$\bar{r}<0.15$	[4, 26]	»
Tuff	1,85	2.14	84,7	2,084	140,7	$\bar{r}<0.8$	[4, 26]	»
Rocksalt	1,72	3.04	159	2,6	110	$1<\bar{r}<9$		Laboratory expts.
(porous)	1.87	3,56	237	2,6	140	$1<\bar{r}<9$	[12]	
				1,25	187	$1<\bar{r}<1.5$		
Rocksalt	2,12	4.42	414	2,5	297	$1.5<\bar{r}<9$		Field
	2.14	4,5	433	1,6	122,5	$\bar{r}<1,5$	[26]	expts.
				2,16	364,5	$\bar{r}<0,6$		
Sodium thiosulfate	1,8	4,5	364	1,7	421,2	$\bar{r}>0,6$	[25]	Laboratory expts.
Granite	2,67	5,4	778	1,9625	620	$\bar{r}<1$	[4]	Field expts.
»	2,7	5,0	675	2	700	$1<\bar{r}<20$	[2]	»

mechanical action (irreversible bulk strains of the order of 10^{-3}) extends out to $\bar{r}_c = 5$ in a dry loam.

Therefore, the reduction in H (permeability) in a porous medium is due to reduction in the pore volume (closure of some of the pores). A competing mechanism is an increase in permeability arising from the generation of new cracks, but this is virtually absent in a highly porous medium. On the other hand, in a brittle medium of low porosity such as a grit, the cracking mechanism is predominant, and the permeability increases monotonically from the periphery to the center [24] apart from the area directly adjoining the cavity, where there is a decrease in accordance with the above situation for the pressed-powder zone.

5. Table 2 compares the results of (3.1) with the data from other studies; the shock waves in our porous medium had a dampening index n = 3.5, which is larger than the corresponding values for dry sand on alluvium. Table 2 also shows appreciable discrepancies over the coefficient A from the laboratory data [6] of sand (water content 5%), in which measurements were made on the mass velocity v_m, while the stresses were found by calculation from $\sigma_r^m = \rho_0 v_m c$ and field data [8, 9] with direct stress measurement in the explosion wave (water content 3-6%).

Strictly speaking, the geometrical similarity in the cube root of the explosion energy requires the use not of the reduced radius $\bar{r} = R/W^{1/3}$ but the dimensionless one $\bar{r}_0 = R(\rho c^2/W)^{1/3}$ [1]. The reduced radius satisfies the requirements of the theory of similarity only on transferring the mechanical effects of an explosion at one energy to another in the same medium.

If we transfer to the dimensionless radius, then the coordinate of the kink point $\bar{r}_\tau = 0.47$ corresponding to the outer boundary of the dilatancy zone becomes the dimensionless coordinate $\bar{r}_{0\tau} = R_\tau(\rho c^2/W)^{1/3} = 12$ $(\mathrm{m\cdot kg^{-1/3}\cdot MPa^{1/3}})$, with $\rho c^2 = 16.7\cdot10^3$ MPa.

The kink point for sand [6] $\bar{r}_\tau = 3$ has the corresponding coordinate $\bar{r}_{0\tau} = \bar{r}_\tau(\rho c^2)^{1/3} = 12.8$ in the same units. For sodium thiosulfate, which simulates a monolithic rock [25], the value $\bar{r}_\tau = 0.6$ becomes $\bar{r}_{0\tau} = 19.5$. Therefore, the kink points for porous media have virtually the same dimensionless coordinate, whereas the failure zone is 1.6 times larger (in dimensionless radius) in a monolithic rock, where the explosion energy is dissipated less rapidly.

The outer boundary of the zone of reduced permeability is shown by Fig. 7 as having a coordinate $\bar{r}_c \geqslant 2$, which corresponds to the dimensionless coordinate $\bar{r}_{0c} \geqslant 50.5$; the same

TABLE 3

Material	m, %	σ^*, MPa	c, m/sec	k, mD
Model	25	25	3000	200
Sandstone	22	60	4500	150
Carbonates	20	70	4500	100

dimensionless coordinate applies to the boundary of the irreversible bulk deformations in explosion in a loam (for $\rho = 1.65 \cdot 10^3$ kg/m^3, c = 600 m/sec, $\rho c^2 = 5.94 \cdot 10^2$ MPa), which corresponds to $\bar{r}_c = 6$, which is very close to the measured value [23].

Therefore, we can take it as established that the residual reduction in the permeability is due to irreversible deformation in the pore space.

6. The artificial porous medium used in the experiments is not an exact analog of any particular rock, as Table 3 shows, which compares the porosity m, strength in uniaxial compression σ^*, speed of sound c, and permeability k for the model material and for characteristic strong porous rocks.

Table 3 indicates that the model medium is weaker than natural materials of the same porosity, and therefore the reduction in the permeability and the absence of cracks are more prominent than would be expected from the explosions in these rocks. Therefore, under field conditions it is possible that there would be some quantitative deviations from our results. On the other hand, our results reveal clearly the characteristic features of the mechanical effects of explosions in porous media. The competing effects from cracking (and the corresponding increase in permeability) will increase as the porosity is reduced and as the strength of the material rises. Also, there will be appreciable corrections from the level of the lithostatic pressure.

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HEAT AND MASS TRANSFER IN A TWISTED GAS—LIQUID LAYER

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The traditional method of organization of the processes of heat and mass transfer upon direct gas phase—liquid contact on bubble disks has definite advantages. Using this method as the basis, numerous types of heat- and mass-exchange equipment have been created which are widely used in different areas of technology [1, 2]. However, increasing the effectiveness of foam—bubble devices encounters fundamental difficulties associated with a limitation on the velocity of the gas phase.

A further development of the indicated method is the organization of the processes of heat and mass transfer in twisted gas—liquid layers formed in special vortex chambers [3-5]. According to the data of [3], the effectiveness of the transfer processes is higher in vortex gas—liquid devices than in the usual foam—bubble devices. However, one should state that there is no sufficiently reliable procedure for the calculation of heat and mass exchange in such devices.

An important stage in the creation of a procedure for the calculation of vortex gas—liquid devices is the establishment of the hydrodynamic laws of a gas—liquid layer — its structure, the rotational velocity, the average gas content, the specific contact surface of the phases (CSP), etc.

It has been established as a result of preliminary hydrodynamic investigations of a vortex gas—liquid chamber [6] that a uniform bubble structure is realized in the centrifugal force field in a twisted layer with a bubble diameter d significantly smaller than in the traditional bubble systems. The average gas content φ depends weakly on the velocity of the gaseous phase w referred to the total area of the guiding device. The relationship

$$a = 6\varphi/d, \quad (1)$$

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