sure of the gas at infinity p_∞. Averaging the normal component of the stress along the zone of fractured coal, we obtain a discontinuity in the stress–strain diagram of the normal stresses in the cross section x_2. The value of this discontinuity δ, determined by the relationship

$$Ax_2 + B = P + \delta,$$

will lie within the limits

$$0 < \delta < p_\infty - \sigma_x|_{x=x_2}.$$

For the selected values of the discontinuity δ, the initial parameters of the process of sudden ejection can be determined by the method proposed in [3].

The gas–coal mixture expelling the plug is situated in a tube of variable diameter v(x) (see Fig. 4). In the case of a breakdown of the plug, the gas–coal mixture will be carried out through the opening into the working space. The gasdynamic stage of the course of the ejection, before and after the breakthrough of the plug, must be considered, taking account of the contracting form of the working space, formed by the action of the stressed state around the working, varying during the course of the process.

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HEAT AND MASS TRANSFER DURING AN EXPLOSION IN SOLIDS

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UDC 622.235.5

The pressures in the detonation products of explosives have a magnitude of the order of 100 kbar, and the temperature of the gases at the initial instants reaches several thousands of degrees. Many actual solids, soils, and rocks contain in their structure a considerable amount of pores, micro- and macroscopic cracks, and gaps separating the medium into individual blocks. With these conditions, a gas having a high velocity can penetrate into these defects of the medium without performing any mechanical work in general on the deformation of the material or, with defined conditions, producing a "wedge" effect in the cracks. Since the freshly formed surfaces of solids have an enhanced sorption capability, part of the gas may be adsorbed into the medium and may undergo capillary condensation. The quantity of gas "absorbed" by the medium can be different depending on the total surface area of the cracks and pores and, in certain cases, can reach very considerable magnitudes. From a formal point of view, the entrainment of detonation products by solid media amounts to a nonadiabatic process of expansion of the explosion cavity in soils and rocks, while from the factual point of view it amounts to a reduction of the explosion efficiency or of its mechanical action.

In the Institute of Terrestrial Physics, Academy of Sciences of the USSR, under the directorship of I. L. Zel'manov, over the period of a number of years systematic experimental investigations have been conducted of microexplosions in sand with a different density of

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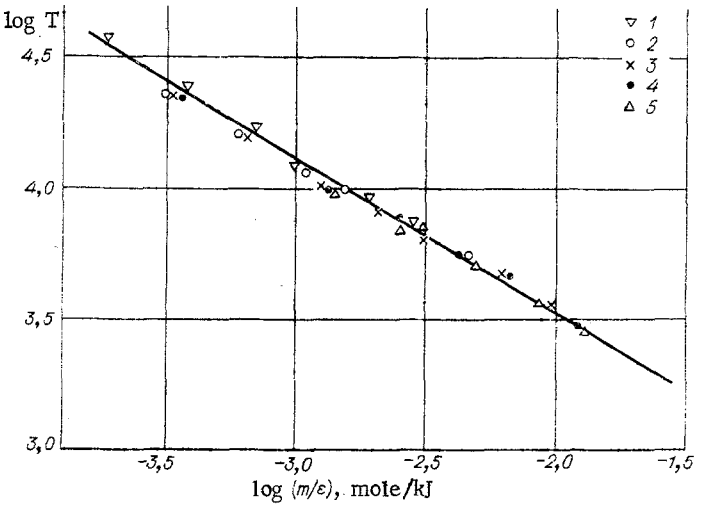

Fig. 1

energy release [1, 2]. This was achieved by means of electroexplosions, combinations of an electric discharge with chemical explosives, dilution of explosives with easily vaporized additives, explosions in air cavities, and, finally, "explosions" simply of compressed air. The experiments were performed in such a way that the essentially varying (approximately by two orders of magnitude) parameter was the initial temperature of the gases. By choosing in an appropriate manner the volume of the air cavity, it is possible to obtain approximately identical initial pressures, almost without varying the initial temperature of the gases, so that the nature of the expansion isentrope remains one and the same in all experiments. By means of induction sensors, the mass velocity field was measured as a function of the distance and time. As usually accepted in explosion experiments, the data obtained were processed in scaled coordinates $\bar{r} = r\beta E^{1/3}$, where r is the distance from the center of the explosion and E is the energy. For single-temperature explosions (for example, for one and the same type of explosive), the principle of geometric similarity with respect to energy was verified. If, for example, the maximum mass velocity v_m is written in the form $v_m = f(\bar{r})$, then for explosions of different scales the function $f(\bar{r})$ has one and the same form.

However, for explosions with different initial temperatures of the explosive, the experimental $f(\bar{r})$ curves were different, and in order to reduce them to one curve it was necessary in each of the cases described above to introduce a correction factor to the quantity E. As this universal curve, the function $v_m = f(\bar{r})$ was chosen. Thus, over the whole range of variation of energies and temperatures investigated the unified formula

$$v_m = f(\hat{r}),\ \hat{r} = r/(\eta E)^{1/3} \tag{1}$$

was established for explosions in sand.

The quantity η, in this sense, is called the PETN equivalent. For PETN in Eq. (1), $\eta = 1$.

The magnitude of the temperature in the experiments was not measured, but was determined in an indirect way. For all types of explosives, one of the standard characteristics is the volume of gases per 1 kg of explosive, reduced to normal conditions. Denoting by m* and dividing by 22.4 liters, we obtain the number of moles of gas per 1 kg of explosive:

$$m = m^*/22.4. \tag{2}$$

The dependence of the temperature of the explosion products on the specific energy ε and the quantity m can be estimated by using the equation of state of air [3]. Figure 1 shows the relation $T = f(m/\varepsilon)$ for different energy densities (1 corresponds to E/V = 0.460, 2 to 0.286, 3 to 0.143, 4 to 0.0715, and 5 to 0.0357 kJ/cm^3). This dependence can be approximated by the relation

$$T = 480(m/\varepsilon)^{-0.6}\ \text{mole/kcal}.$$

On the other hand, according to the data of the above-described experiments, we construct the function $\eta = f(m/\varepsilon)$ plotted in Fig. 2 (1 corresponds to PETN, 2 to electroexplosion, 3 to mixed charges, 4 to a mixture of PETN and air, and 5 to compressed air), which is described with good accuracy by the equation

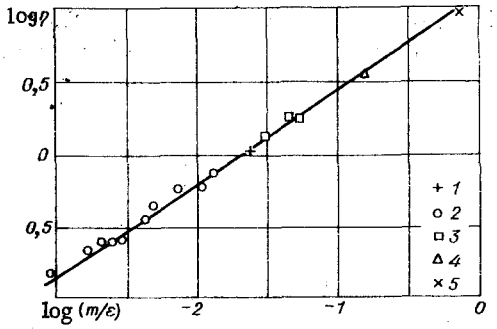

Fig. 2

$$\eta = 10(m/\varepsilon)^{0.6}. \tag{3}$$

Combining these two expressions, we obtain

$$\eta = T_0/T, \; T_0 = 4800\,^{\circ}\mathrm{K} \tag{4}$$

The value of T_0 corresponds to the temperature of the detonation products of PETN [4]. It is interesting that this relation can be obtained from the following simple, but somewhat formal, considerations. Suppose that at the initial instant m moles of gas were formed with temperature T_0 and Δm moles "disappeared" instantaneously, having penetrated into the pores of the sand and been adsorbed on the surface. Since for this process it is necessary to surmount a certain potential barrier U, it can be supposed that the quantity Δm is determined by the Boltzmann factor, so that

$$\Delta m = m \exp(-U/kT).$$

Since Δm moles of gas so not perform mechanical work, the efficiency of the explosion ζ, understood as the ratio of the mechanical work (together with the accompanying thermal losses) to the total explosion energy, is equal to

$$\zeta = (m - \Delta m)/m = 1 - \exp(-U/kT) \approx U/kT.$$

The latter equation occurs because the quantity ζ for explosions in sand is small and amounts to only a few percent, according to the experimental data of [1]. If we introduce the relative efficiency (or the PETN equivalent), then, obviously,

$$\eta = \zeta/\zeta_0 = UT_0/U_0T. \tag{5}$$

If the explosions are conducted in one and the same medium, then $U = U_0$ and formula (4) follows from the last expression. The role of the gas cavity as a factor, together with the energy of a defined efficiency of the explosive, has been noted by a number of researchers. One of the methods which is characteristic for the efficiency of explosives is the method of the lead bomb or the Trautz test [4, 5].

The standard bomb is a cylinder with height and diameter 20 cm with an axial opening of 2.5 cm and a height of 12.5 cm. The charge of mass M = 10 g being investigated is placed on the bottom of the bomb channel and is covered with dry quartz sand. The increase of volume of the cavity ΔV (in cm^3) is taken as a measure of the efficiency. All explosives issued by industry have as tabular characteristics, together with the specific energy ε (kcal/kg), the "gassiness" m* (liter/kg) and also the efficiency ΔV (cm^3). Figure 3 shows graphically the data for the dependence of ΔV on ε for a few tons of types of explosives. It can be seen that the spread of the experimental points is very large. Since part of the surface of the explosives is in contact with the sand, it cannot be excluded that the heat—mass loss mechanism described above also functions here. We shall introduce a correction factor and we shall find the dependence of ΔV on $\eta\varepsilon$ (Fig. 4). It can be seen that the spread of the points is reduced significantly, so that a curve can be constructed from them (solid line in Fig. 4), which we shall consider as the experimental calibration of the lead bomb.

Approximate calculations can be carried out. For this, we make the following assumptions:

1) We replace the cylindrical bomb by a spherical layer of equivalent volume with inside radius a_0 and outside radius R_0;

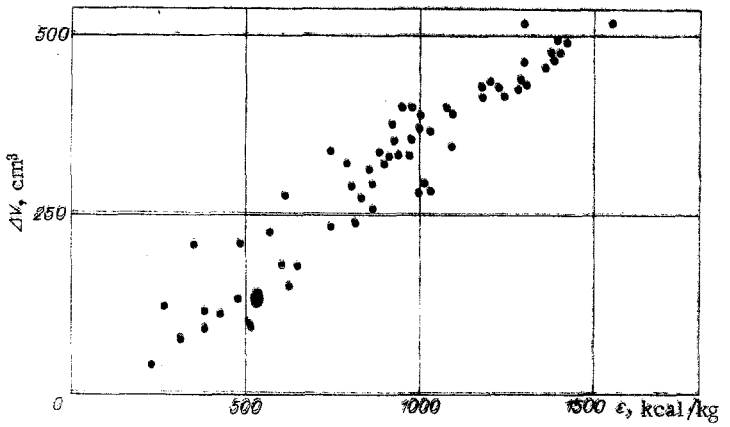

Fig. 3

2) we assume the material to be incompressible and to satisfy the Tresca–Mises condition of plasticity

$$|\sigma_r - \sigma_\theta| = 2\tau_s.$$

With these assumptions, the equations of motion

$$\rho(\partial v/\partial t + v\partial v/\partial r) = \partial\sigma_r/\partial r + 2(\sigma_r - \sigma_\theta)/r$$

and continuity

$$\rho = \text{const}, \quad v = a^2\dot{a}/r^2$$

with the boundary conditions

$$\sigma_r = -p(a), \; r = a; \quad \sigma_r = 0, \; r = R$$

can be integrated and reduced to a form which expresses the law of conservation of energy:

$$\int_{a_0}^{a} p(a)\,4\pi a^2 da = \int_{a_0}^{a}\left(4\tau_s \ln\frac{R}{a}\right)4\pi a^2 da + 2\pi\rho(a^2\dot{a}^2)\left(\frac{1}{a} - \frac{1}{R}\right), \tag{6}$$

where σ_r and σ_θ are the components of the stress tensor; τ_s is the yield point (shear strength); ρ is the density of lead; v is the radial velocity; r is a coordinate; $\dot{a}$ is the rate of expansion of the cavity; $p(a)$ is the gas pressure in the cavity; a is the running value of the radius of the cavity; and R is the running value of the outside radius.

At the instant of maximum expansion ($a = a_m$, $R = R_m$), the rate $\dot{a} = 0$ and the last term in Eq. (6), expressing the kinetic energy of the medium, are equal to zero,

$$\int_{a}^{a_m} p(a)\,4\pi a^2 da = \int_{a_0}^{a_m}\left(4\tau_s \ln\frac{R}{a}\right)4\pi a^2 da; \tag{7}$$

the work of the gases is accomplished on the plastic deformation of the material, i.e., ultimately on heating it up.

This expression (exact within the bounds of the assumptions made) can be integrated (right-hand side) if two quite obvious assumptions are made:

$$R^3 \gg a^3, \quad a_m^3 \gg a_0^3.$$

The left-hand side of Eq. (7), by the definition of the efficiency, is written in the form ηE, where $E = Mc$ is the total explosion energy. Using Eq. (5), we finally obtain

$$\eta\varepsilon = \frac{4}{3}\frac{\tau_s}{\rho_0}\frac{1}{M}\left(\ln\frac{V}{\Delta V} + 1\right)\Delta V,$$

where V is the volume of the bomb and ΔV is the expansion of the explosion cavity.

This relation is shown in Fig. 4 by the dashed line for the following values of the parameters: $V = 6\cdot10^3$ cm³, mass of explosive M = 10 g, and $\tau_s/\rho_0 = 300$ kg/cm². According to reference book data, $\tau_s = 60$–85 kg/cm² for lead.

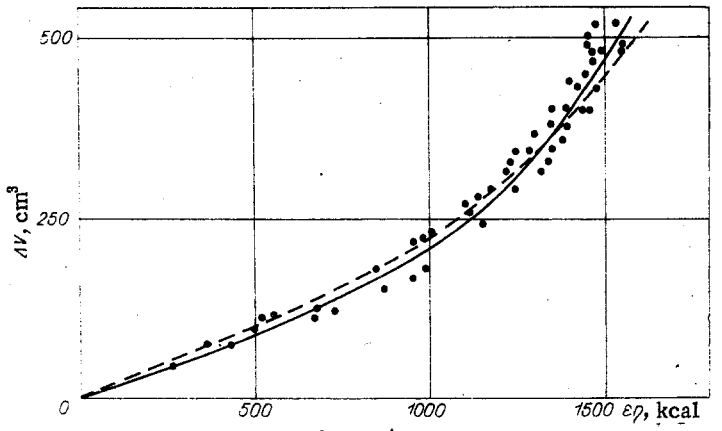

Fig. 4

Thus, the efficiency of a charge of PETN in the Trautz bomb ζ_0 has a value within the limits of 20 to 28%. If it is assumed that the whole deficit of energy is expended on the kinetic energy of the sandy stemming, then, as the calculation shows, its velocity should be about $2.5 \cdot 10^3$ cm/sec, which exceeds the observed values by more than an order of magnitude. Moreover, the factor $\eta \sim (m/\varepsilon)^{0.6} \sim T^{-1}$, for adjusting the experimental data, defines the thermal losses during the explosion, which must be taken into account for an adequate description of the phenomenon. From Eqs. (1)-(3) we obtain that the relative (with respect to PETN) energy of the explosive ε_0 is defined by the following combination of the energy ε and the specific volume of the gases m*:

$$\varepsilon_0 = 1.6 m^{*0.6} \varepsilon^{0.4}.$$

It is clear from what has been said that it is possible to increase the explosion efficiency if the gases are not allowed to penetrate into the medium in the early stage of expansion. Experiments were mounted in sand, with the explosive enclosed in a ductile casing (lead, rubber, plasticine). In this case, the explosion efficiency increased by a factor of two to three. It is characteristic that if the compact casing were cut into two parts, the result obtained would be the same as for the explosion without the casing. Brittle shells (cement) showed no effect on the explosion efficiency.

The volume of the pores in dry poured sand is very large — up to 40%. It is obvious that with pressures of the order of 100-10 kbar the explosion products can penetrate inside the medium to considerable distance, while with temperatures of several thousands of degrees the heat—mass transfer can be so large that it plays the predominant role in the entire process. In rocks (expecially fractured rocks), the essence of the phenomenon is preserved, and only the quantitative aspect of the matter is changed. Experimental and pilot-industrial data are available [6] concerning the penetration of the explosion detonation products to distances of 12.5 to 25 charge radii for monolithic and fractured trachyliparites with a compressive strength of 800 kg/cm², and there are also data on the fact that up to 40% of the gases is retained by the rocks surrounding the site of the explosion during the breaking down of ores in underground conditions. Special experiments were mounted on the explosion of a mixture of PETN and iodine in blocks of rock salt (V. M. Komir and V. G. Nazarenko, Khar'kov Polytechnic Institute). Quantitative analysis showed that up to 33% of the total content of iodine was contained in the cracks inside the block after the explosion. The penetration of gases inside rocks has a twofold importance. On the one hand, the efficiency of an explosion is reduced in consequence of the reasons considered above. On the other hand, the gases exert a wedge effect on the existing cracks and also reduce the strength of the material. The latter is due to the resistance to explosion in the mechanics of brittle fracture [7] and is determined by Griffiths formula

$$\sigma_{res} = \sqrt{E'\sigma/\pi(1-\nu^2)l},$$

where E' is Young's modulus, σ is the specific surface energy, ν is Poisson's coefficient, and l is the half-length of the crack.

In the case of penetration (adsorption) of the gases inside the medium, the quantity σ is decreased, which leads to a reduction of strength.

The problem considered in explosion physics, despite the considerable amount of empirical data from explosive practice, is presented as new by the authors. Because of this, there is still a large number of obscure questions here, and, in the first place, the role of scaling and time factors is unexplained.

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EXPERIMENTAL VERIFICATION OF THE DRUCKER POSTULATE

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UDC 539.4.001

The Drucker postulate can be formulated as the condition that the work of additional stresses with loading is not a negative value:

$$d\sigma_{ij}d\varepsilon_{ij} \geqslant 0. \tag{1}$$

This postulate is of great importance in the theory of plasticity; specifically, there follows from it the law of plastic flow [1, 2], as well as the fact that the creep surface must be convex. The postulate has been verified experimentally for a number of metals at room temperature [3, 4]. Since a great number of processes of plastic deformation of metals take place at high temperature, it is of interest to verify the postulate under precisely these conditions. Such a verification was carried out for a monaxial stressed state (elongation and compression) in a special device, i.e., a plastometer [5]. The following metals and alloys were tested: technical-grade copper; brass (B90, B68, B62); nickel (NPA1 and NPAN), Monel metal (NMZh, MTs-28-2.5); nickel silver (MNTs 65-15-20); German silver (MN19); carbon steels 20, 3, 45, 6 and U8; alloy steels 40Kh, 40KhN, 45G2, 12KhNZA, 35KhGS, 15KhSND, ShKh15, 14GN, 60S2, 1Kh13, 4Kh13, Kh17N2, Kh18N12M2TO, and R18; heat-resistant chrome–nickel alloys ÉI435, ÉI602, and VZh98; zinc; and lead. The samples for the elongation tests (diameter 6, length 30 mm with screw clamps) were heated simultaneously in four electric furnaces, in which the temperature was monitored by thermocouples. The elongation of a sample, arranged in the electric furnace, was effected using a cam, whose profile determines the law of deformation. The cam was driven through a flywheel, a reducer, and a chain clutch from a direct-current electric motor. The speed of the electric motor decreased during the deformation by not more than 2%. This speed was monitored by a tachogenerator.

The samples for compression tests (diameter 6 and height 9 mm) were heated together with the container in furnaces; they were then mounted in the plastometer and the test was carried out. The temperature was monitored by a thermocouple; during a test it did not vary by more than 5°C in view of the considerable mass of the container. The thermocouples were introduced into the furnaces through openings and were forced tightly to the middle of the sample using a spring.

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