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ELECTROPHYSICAL PROPERTIES OF A DETONATION PLASMA; HIGH-SPEED EXPLOSIVE CIRCUIT BREAKERS

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A plasma with an electrical conductivity of $\sim 1\ \Omega^{-1} \cdot cm^{-1}$ forms behind the detonation front (DF) of condensed explosive materials (EM) [1]. The conducting region is divided into two parts [2, 3]: nonequilibrium (the chemical-reaction zone with a width of ~1 mm) and equilibrium. The equilibrium electrical conductivity can be on the order of the nonequilibrium value or much lower and it declines rapidly in the expansion waves.

The motion of the conducting zone behind a DF with a velocity of 5-8 km/sec can be used to break a high-current circuit in a time of $\lesssim 1$ μsec. Such circuit breakers can find application in powerful energy sources. The speed of the existing methods of explosive circuit breaking (~10 μsec [1]) is limited by the formation of arcs during the breaking of the circuit.

In the proposed method the conducting zone moves behind a DF between two electrodes. The current flows through the plasma and ceases when the EM between the electrodes has reacted and the electrical conductivity declines. The considerable electric strength of the detonation products [5] prevents the breakdown of the gap and the formation of an arc. Therefore, the breaking time is determined by the decline in electrical conductivity behind the DF, and with a minumum conducting zone (the reaction zone) it comprises ~0.1 μsec. The volt–ampere characteristics of the plasma at high current densities are required for the application of the new method of circuit breaking. These data can also be useful in clarifying the mechanism of plasma conduction.

Experiments. The voltage source was a capacitor battery (25 μF, 30 kV). The midpoint of the battery was grounded and the two halves were charged to voltages of opposite polarity. Such a scheme made it possible to reduce the demands on the voltage leads to the explosive chamber.

A cross section of the charge is shown in Fig. 1. The explosive material 1 (3 × 5 mm, length 12-15 cm) lay between copper electrodes 2 with a length of 10 cm. The voltage on the charge and the current were oscillographed with compensation of the inductive leads [6, 7]. Photographic recording was carried out with a high-speed photographic sweep through the plastic wall.

The charge was connected to the battery by arresters following the contact of the electrodes with the conducting zone behind the DF. The electrodes were protected from breakdown ahead of the DF by two to four layers of Dacron film 25 μ thick. Under the action of the high pressure the resistance of the film became low behind the DF in comparison with the resistance R of the plasma.

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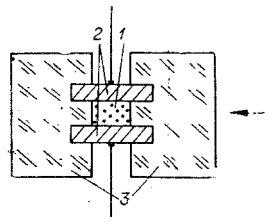
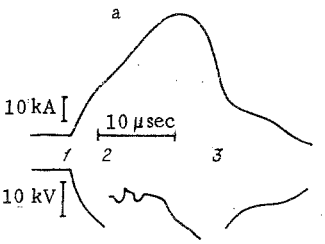


Fig. 1



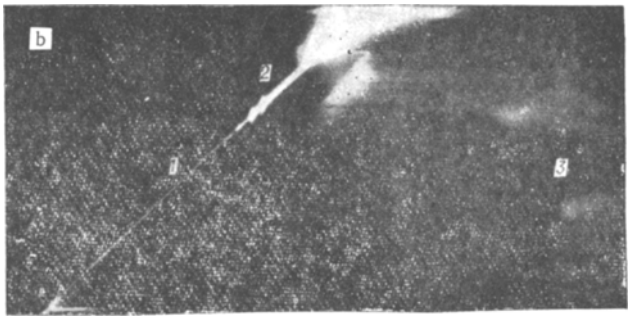


Fig. 2

TABLE 1

EM	ÉVV 8G	Semtex	Hexogen
R, Ω (at U, kV)	1,1 (0,01) 1,0 (5—12)	3,3 (0,01—5) 2,0 (27)	20 (0,05) 20 (10)
E, kV·cm^{-1}	40	90	>70

Following the connection of the battery the current and voltage on the charge grew in a time of ~L/R (L = 4 μH is the inductance of the circuit). The volt–ampere characteristic was determined on this section. Breakdown took place at a certain voltage between the electrodes. Then a conductor connected in series with the charge exploded with a certain delay. This was used to coordinate the photographic sweep and the oscillograms with no worse than 1 μsec accuracy (the breakdown is not always seen on the photographic sweep).

We studied powdered hexogen, which has an electrical conductivity of about 0.2 $\Omega^{-1}\cdot cm^{-1}$ in a zone of ~1 mm, and two plastic EM: ÉVV 8G and Semtex L (product of Czechoslovakia). The width of the conducting zone was ~3 mm for the plastics under the experimental conditions and the electrical conductivity was 1.2 and 0.71 $\Omega^{-1}\cdot cm^{-1}$, respectively. The results of the measurements are presented in Table 1 (the voltage corresponding to the measured resistance is given in parentheses).

For the plastic EM the volt–ampere characteristic of the conducting zone is close to a straight line. The electric strength E of the plasma was determined for these EM from the voltage of the breakdown, which took place in the conducting zone. In the process the arc moves together with the DF, slightly intensifying its emission. In Fig. 2 we present an oscillogram (a) and a photographic sweep (b) of a test with ÉVV 8G. In this and succeeding figures the number 1 denotes the time of application of the voltage, 2 is the breakdown, and 3 is the explosion of the conductor; the marks on the photographic sweep are every 1 cm.

The breakdown could occur between the ends of the electrodes at lower voltages if the detonation products were able to expand to this point and the electric strength fell [5] to ≤ 10 kV·cm^{-1}. For Semtex, for example, such a breakdown set in at a voltage of from 14 to 25 kV at the moment when the detonation wave had traveled 7-8 cm along the electrodes. The breakdown took place in the conducting zone if the voltage had increased to 27 kV by this time. A photographic sweep of a test with Semtex is presented in Fig. 3.

For hexogen the time L/R was small and the measurements were made with a constant voltage. The resistance did not depend on the voltage in the range of 50 V–10 kV. At a voltage higher than 10 kV the air in pores is ionized for several millimeters ahead of the DF at the moment the charge is connected (Fig. 4). This is associated with distortions of the field ahead of the DF. Since the Dacron film conducts behind the DF, the electric field is close to uniform; ahead of the front a field of the same magnitude arises in the hexogen powder. This leads to breakdown of the powder when U > 10 kV (E > 30 kV·cm^{-1}). Far from the DF the

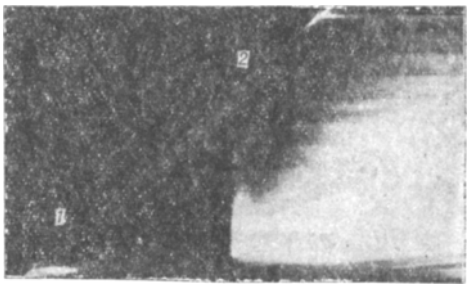


Fig. 3

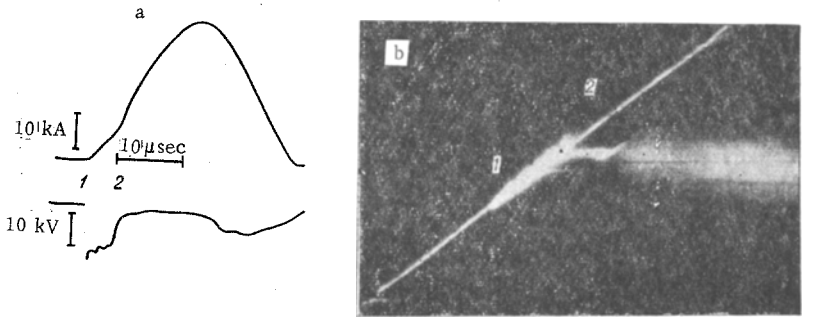


Fig. 4

TABLE 2

U_0, kV	15	20	25	30
U, kV	13	13	18	21
t, μsec	7,5	4	2	1
R, Ω	2,4	1,7	4,5	3,5
σ, $\Omega^{-1} \cdot cm^{-1}$	0,07	0,2	0,15	0,4

distortions of the field are small, and the detonation wave drives a bounded ionization region ahead of it. The current grows linearly with time from the moment of supply of the voltage (Fig. 4a). This means that the ionization ahead of the DF leads to the appearance of equilibrium conduction of the detonation products, which does not decline during the expansion. Therefore, the conducting zone expands with the detonation velocity from the time of application of the voltage and the resistance of the charge declines as $\sim t^{-1}$. The voltage on the charge is less than that on the battery by an amount LdI/dt, i.e., almost always. The current flowing through the powder ahead of the DF is small in comparison with the current through the conducting region behind the DF: The current line should intersect the DF twice because of the insulation ahead of the front. The energy release ahead of the wave does not exceed a fraction of a percent of the detonation energy release. Breakdown with an almost stationary arc occurs behind the DF with a certain delay. By this time the conducting zone has expanded by 5-50 times. The voltage on the charge, the breakdown delay time, the resistance up to the moment of breakdown, and the average electrical conductivity in the extended breakdown are presented in Table 2 as functions of the voltage U_0 on the battery. This electrical conductivity is on the same order of magnitude as the intrinsic value for hexogen.

A voltage of 21 kV is held for 1 μsec. One can suppose that the leading ionization reduces the electric strength; when the voltage is applied after the EM enters into the reaction, the electric strength must be no lower than 70 kV $\cdot$ cm^{-1} (see Table 1).

The values of E obtained near the DF are on the same order as those measured in [5] during expansion of the detonation products.

Acceleration of the Detonation Wave. For Semtex the Joule heat release reached 40% of the detonation value while for ÉVV 8G it was 15%. This did not significantly affect the detonation process. For Semtex an increase of 3-4% in the wave velocity D was observed at the maximum warm-up (see Fig. 3). The small amount of acceleration is connected with the distribution of the internal energy into elastic and thermal parts, which varies during the heating. From the increase in the velocity of the wave one can estimate the Grüneisen constant of the detonation products ($\Gamma \approx 0.4$ for Semtex). In this case the thermal component of the pressure is

~6% while the thermal part of the energy is about 25% of the total (without warm-up). The release of Joule heat raises the temperature twofold (by estimate); a luminous zone with a width of ~6 mm develops behind the DF.

An increased detonation velocity (13 km · sec^{-1}) was observed in [8] when the hexogen powder was ignited by a foil explosion. This phenomenon is connected not with the Joule warm-up of the products (the effect is small) but evidently with a discharge through the powder in advance of the wave, which could ignite the EM at a sufficient power. In Fig. 4b, at the time of application of the voltage the emission front leads the DF, also with a velocity of ~13 km · sec^{-1}. In the given case ignition did not occur (a weak source) and the detonation passes through the luminous region "without noticing" it.

Conduction Mechanisms. The twofold rise in temperature, as seen from Table 1, has a weak effect on the electrical conductivity of the plastics. The magnitude and the weak temperature dependence of the equilibrium electrical conductivity could have been explained by the total ionization of a small admixture, such as NO. But then the ionization potential should decrease by 8-9 eV. Estimates like those presented in [9] give 2-4 eV. Therefore, an electron–ion composition is unlikely for the charged component of the plasma. The equilibrium conduction is either ionic [10] or is connected with the condensation of free carbon [3].

Small energetic effects have a strong influence on the conductivity of hexogen, which testifies in favor of electron–ion conduction. It should be emphasized, however, that the reason for the appearance of equilibrium conduction during the motion of a wave through ionized matter is unclear. Expansion of the products does not lead to a rapid decline in conductivity, which distinguishes this effect from the well-known effects of [11] (the conducting zone is an order of magnitude larger than the thickness of the charge in the presence of a weak envelope).

Circuit Breakers. In model experiments a Semtex charge 3 mm thick and 55 mm in diameter was located between electrodes 40 mm in diameter and was ignited at the center. A voltage of up to 15 kV was applied to the electrodes from a capacitor battery of 75 μF; the inductance of the circuit was ~2 μH. After the detonation emerged from the interelectrode space the dispersal of the products and the decline of the conductivity began. The current of 15 kA was cut off after 2 μsec, the maximum voltage was 30 kV, and the weight of the charge was about 10 g. Perforation of the charge accelerates the break. In an analogous arrangement [12] a current of 10 kA was cut off after 0.75 μsec by a hexogen charge with a weight of 100 g.

The results of the present work allow one to estimate the possibilities of circuit breaking using the motion of the conducting zone behind a DF. When the width of the conducting zone is $\Delta \approx 1$ mm (the reaction zone), the minimum breaking time is ~0.1 μsec. The minimum amount of EM (for a cylindrical layer with a thickness Δ) is $m \sim \rho U/E \cdot I/\sigma E$, where UI is the power being switched; σ and E are the electrical conductivity and electric strength of the plasma. For Semtex with $UI \approx 10^{12}$ W we have $m \approx 300$ g. In this case the initial resistance of the circuit breaker is $r \approx U/I$. One can reduce r and the voltage before the break by increasing the radius and weight of the charge ($m \sim r^{-1}$). Such a circuit breaker is useful as a peaker, facilitating the operation, before the decline in conductivity, of an explosive circuit breaker (quenching arcs at a low voltage).

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INVESTIGATION OF FLOW IN THE CHAMBER AND CHANNEL OF A VARIABLE-AREA SHOCK TUBE

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One factor which affects the flow uniformity in a shock tube is the noninstantaneous nature of the diaphragm-opening process. Several investigators [1, 2] have calculated the flow in a shock tube channel in one-dimensional formulation, allowing for this factor.

In this paper the problem is considered two-dimensionally. The flow parameters were calculated on a BÉSM-6 computer using the Lax–Wendroff numerical method. The following dimensionless parameters were used: D is the semidiameter of the tube; p_0, ρ_0 are the initial pressure and density in the shock tube channel; $\sqrt{p_0/\rho_0}$ is the characteristic velocity; and $D/\sqrt{p_0/\rho_0}$ is the characteristic time. The gas is taken to be inviscid, non-heat-conducting, with constant specific heat ratio $\varkappa$. The governing parameters of the problem are

$$P = p_1/p_0;\ R = \rho_1/\rho_0;\ \varkappa;\ t_*$$

(t_* is the dimensionless diaphragm opening time). The subscripts 0 and 1 denote the gas parameters to the right and left of the diaphragm.

The two-step Lax–Wendroff method used here is based on a difference approximation to the Euler equations of motion, written in divergent form. The smoothing introduced for strong detonations [3] allows us to avoid the characteristic oscillation of the solution. The method has second-order accuracy and affords a continuous computation of the flow field without isolating strong discontinuities. In the shock tube sections with curved boundaries the transition to a design field of rectangular shape is accomplished by the coordinate transformation

$$X = x;\ Y = y/y_c(x),$$

where $y_c(x)$ is the function giving the wall shape.

The structure of the equations of motion does not vary, but the new dependent variables differ from the old by factors which depend on the channel shape [4]. The flow field is covered by a rectangular mesh. To calculate the flow parameters at each node we deal with a nine-point cell, having the node to be considered at its center.

For the computations the flow in the tube with the diaphragm is modeled as follows. The diaphragm is replaced by a transverse membrane of zero thickness, separating the gases with different initial parameters. At time $t = 0$ the membrane begins to open from the center to the walls according to a given time law. The presence of the membrane requires a nonpermeability condition, similar to the channel walls. The nonpermeability condition is achieved by means of a fictitious flow which, interacting with the computed flow, makes the normal velocity component zero at the points on the solid boundary. In order to satisfy the boundary condition on the moving membrane, the calculation uses two columns of points spanning the membrane. The flow parameters at pairs of points are distinct as long as the membrane separates them. When this is not true identical values are given to each, and the point pairs are regarded as a single point. For this reason the relative position of the ends of the opening membrane and the computational cell belonging to it are analyzed

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