THE NATURE OF THE ELECTRICAL IMPULSE IN AN EXPLOSION

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The mechanism for the formation of an electric impulse on the explosion of ordinary explosive substances is analyzed. A double electrical layer with voltage of the order kT ~ 0.2-0.6 V is formed in the detonation wave. When the detonation wave passes to the outer surface of the charge, electrons adhere to molecules of air and explosion products. As the charged explosion products fly apart, the distance between the positive and negative charges increases and the voltage increases to a magnitude of the order of a kilovolt. The asymmetric separation of the charged explosion products is the cause of the impulse. Theoretical estimates are compared with experiments [1].

Recently a series of papers has examined the electromagnetic perturbations associated with the explosion of high explosives [1, 2]. It has been shown [1] that the application of external fields does not change the nature of the signal registered. This means that the perturbations are caused by internal processes occuring in the explosion. Estimates of the time and scales of the phenomenon show that the observed fields are quasistatic. Thus, the magnetic and electric components of the field can be considered independently. Estimates also show that the assumption concerning the magnetic nature of the impulse in the tests of [1] leads to unrealistically large currents (~ $10^8 a$ in the course of 1 msec) in the region of the explosion. Thus, an electrostatic mechanism for impulse formation seems the most probable.

Charge separation can occur in the shock wave [3, 4]. However, at distances of about 10 radii from the high explosive charge, the shock wave becomes spherical, independently of the form of the charge [5]. Spherically symmetrical motion of electric charges cannot lead to the appearance of a signal. Moreover, the time of appearance of the signal in [1] gives us reason to assume that the signal is not connected with processes in the shock wave. Thus, we shall assume, as in [1], that the appearance of a signal is determined by the asymmetric motion of the charged explosion products.

The following considerations can be added to confirm this assumption, in spite of those given in [1]. We can assume that the explosion products stop dispersing when their pressure becomes equal to atmospherical pressure. In order to estimate the time when they cease expanding we shall assume for simplicity that the cloud of explosive substances has a spherical form. Then the radius of the cloud at the moment when expansion ceases is

$$r \sim \left(\frac{M}{4\pi\rho_k}\right)^{1/3}$$

where M is the mass of the high explosive charge and ρ_k is the density of explosion products under normal conditions. The time interval between the moment when the detonation wave passes out of the surface of the charge and the moment when the explosion products cease to expand is

$$t \sim \frac{r}{v} \sim \frac{1}{v}\left(\frac{M}{\rho_k}\right)^{1/3}$$

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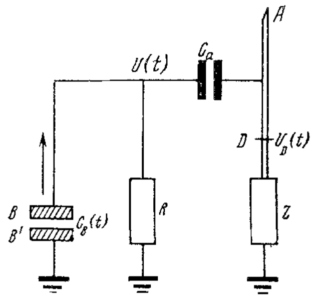

Fig. 1

where v is the mean velocity of expansion of explosive products, which can be taken to be ~ 1000 m/sec. Then for M = 1 kg, t ~ 1 msec., which approximately coincides with the time t_m between the start and the maximum amplitude of the electrical signal of the explosion registered in [1]. The function t ~ $(M)^{1/2}$ corresponds to the empirical function obtained in [1].

Consideration of the form of the signals obtained on the explosion of cylindrical charges with different ratios of cylinder height to diameter [1] also confirms this assumption about the nature of the electrical impulse of the explosion. The point is that for a cylinder which is exploded from the end, the backward (in the direction opposite to that from which the explosion starts) expansion of the explosion products occurs more slowly the longer the path traversed by the detonation wave along the explosive, i.e., the thicker the layer of compressed explosion products behind the wave the slower the explosion [6]. On the oscillograms given in Figs. 3 and 4 of [1], the positive half-wave of the signal, caused by the motion of the explosion products in the direction opposite to the direction of starting (from considerations of signal polarization), is shorter the smaller the ratio of cylinder height to diameter, i.e., the greater the velocity of motion of the explosion products in this direction.

In considering the mechanism of signal formation, the following questions arise:

1) Why does a microscopic separation of electrical charges occur in a quasineutral medium like expanding explosion products?

2) What causes these expanding charges to spread to distances over which the fields which arise are so large as to be registered at comparatively large distances?

3) Why are the charges which arise not neutralized in spite of the large attractive electric field between them?

We can consider the formation of a double electrical layer in the detonation wave as one of the most probable separation mechanisms for electric charges in the initially neutral high explosive. For a shock-wave propagating in a plasma, the discontinuity of potential at a distance equal to the mean free path (in the case of incomplete ionization, at a distance of Debye radius) is ~ kT/e [3]. As a result of their large mobility, the electrons can outstrip the shock wave. A similar mechanism can also occur in the propagation of the detonation wave. In this case, the explosion products furthest removed from the center of the explosion will be negatively charged. The comparatively low temperature in the front of the detonation wave (~ 10^3°K) cannot be the reason why this treatment is unsuitable, since the electrical conductivity of the explosion products according to [7] is determined basically by the density and pressure in the front of detonation wave and exceeds by several orders of magnitude the corresponding values determined by thermal ionization. It was also shown in [7] that the zone of high electrical conductivity is situated in a comparatively narrow layer adjacent to the wavefront.

At the moment when the detonation wave passes out to the surface of the charge, the electrical conductivity of the explosion products falls sharply. This is caused, firstly, by the fall in pressure at the surface of the charge, and secondly, by the adherence of free electrons to oxygen, molecules, forming negative ions, which can occur both in the air as well as inside the contact layer between the explosion products and the air. Under these conditions, a peculiar "hardening" of state apparently occurs, characteristic for a double electrical layer.

When the detonation waves passes to the surface of the high explosive charge, the explosion products begin to disperse into the atmosphere. The outer layers of explosion products expanding in the air carry away with themselves the excess negative charges. The velocity of the explosion products decreases to the velocity of sound in a time ~ 10^{-3} sec, while the corresponding decrease of velocity for explosion products behind the detonation wave front occurs after a time ~ 10^{-6} - 10^{-5} sec [8]. Consequently, the time for the charges to be dispersed coincides in order of magnitude with the time observed in [1] for an electrical signal to arise from the explosion.

The process of negative ion formation plays an important part in the mechanism under consideration, since the conductivity is strongly dependent on the mass of the charge carriers. The characteristic time for electrons to adhere to oxygen molecules in air at normal pressure does not exceed $\tau_+ = 4 \cdot 10^{-8}$ sec [9].

Rough estimates give $\tau_+ \sim 10^{-9}$ sec for electrons with $T_e \approx 2 \cdot 10^3$°K, entering the air compressed by the shockwave ($\rho = 8\rho_0$, where ρ_0 is the density of air under normal conditions). The relaxation time for free charges is $\tau_0 = (4\pi\sigma)^{-1}$. During the expansion time, the pressure of explosion products is small, and so

$$\sigma = \frac{e^2 N}{m\nu}, \qquad \nu = nvq, \qquad v = \left(\frac{2kT}{m}\right)^{1/2}$$

Here m is the mass of the charge carrier, N is the concentration of carriers, ν is the effective collision frequency, q is the effective momentum-transfer cross section, and n is the concentration of molecules. Finally, for τ_0 we have

$$\tau_0 = \frac{nq\,(2mkT)^{1/2}}{4\pi e^2 N} \sim \frac{\sqrt{m}}{N}$$

The ratio of the "ion" (subscript i) and "electron" (subscript e) neutralization time is

$$\frac{\tau_{0i}}{\tau_{0e}} = \left(\frac{m_i}{m_e}\right)^{1/2} \frac{N_e}{N_i}, \qquad \left(\frac{m_i}{m_e}\right)^{1/2} > 10^2, \qquad \frac{N_e}{N_i} \gg 1$$

Consequently, the formation of negative ions increases the lifetime of free electric charges, and affects the process leading to the appearance of free charges. Thus, the signal amplitude from the explosion of a high explosive charge in a gas atmosphere (or in a material envelope) which readily forms negative ions should be larger than in air.

The macroscopic separation of electrical charges, after the electrons expand into the air, is apparently impossible, since the ratio of the density ρ_* in the shock wave to that in air ρ_0 is $\rho_*/\rho_0 = 8$. At the same time, considerations of the structure of the detonation wave-front show that the region of high electrical conductivity cannot reach the surface of the high explosive charge as the result of the finite width of the front (~ 0.1 mm [10]). Thus, the dispersion of charges will be determined by the ratio of density $\rho_{**}/\rho_k \sim 10^3 - 10^4$, where ρ_{**} and ρ_k are the density of explosion products in the detonation wave and at the moment when expansion ceases, respectively. (The density of explosion products at the moment when expansion ceases can be noticeably lower than the density of normal air.)

The electrical processes involved in the formation of the impulse can be described with the help of the equivalent circuit given in the figure. In Fig. 1, B and B' are the plates of the variable condenser formed by the expanding explosion products, C_a is the capacity of the link with the antenna A, Z is the impedance of the device registering the voltage U at the point D, and R is the leakage resistance of the capacitance C_b due to the conductivity of the explosion products. An analysis of this circuit shows that for $R = \infty$ the maximum value of the registered voltage is attained roughly at the time when the expansion of explosion products is greatest, which agrees well with the considerations given above and with experimental results [1]. As the capacitor plates are separated, the voltage on the capacitor increases. For a plane capacitor

$$U(t) = U_0 \frac{l(t)}{l_0} = U_0 \frac{\rho_{**}}{\rho(t)}, \qquad U_0 = \frac{kT_e}{e}, \qquad U_k = U(t_m)$$

For $T_e = 2000$°K, $U_0 \approx 0.2$ V and so $U_k \simeq 0.2\,(10^3 - 10^4)$ V. However, in the case under consideration the the electron gas in the detonation wave is apparently degenerate [3]. Rough estimates based on data concerning electrical conductivity [7] give a Fermi energy of $E_f \gtrsim 0.6$ eV. In this case, $U_0 \gtrsim 0.6$ V and $U_k \gtrsim 0.6\,(10^3 - 10^4)$ V.

These estimates refer to the case of two-dimensional expansion of explosion products. In any real case the values of U_k will be less because of the three-dimensional nature of the expansion. The values of U_k obtained characterize only the maximum values of the voltage.

To obtain a rough estimate of the emf induced in a vertical antenna of effective height b, we can treat the field which arises as a dipole [1] field of moment D_0. This leads to the expression

$$U_D = 2\frac{D_0 b}{R_0^3} = 2\left(\frac{S}{4\pi R_0^2}\right)\frac{b}{R_0} U_k$$

where S is the horizontal cross section of the cloud of explosion products, and R is the distance to the antenna. For $R_0 \sim 5$ m and $S \sim 1$ m^2, we obtain $U_0 \approx (0.1 - 4)$V.

The appearance of a double electric layer in the detonation wave can also be regarded as the result of the formation of a distinctive "contact potential difference." The sharp change in conductivity behind the detonation wave-front [7] creates conditions close to those occuring at the boundary between a metal and a semiconductor (with electron conductivity). Estimates of U_k in this case roughly coincide with those given above. However, this treatment reveals an effect which can be varied experimentally.

The external electric field affects the dimensions and the resistance of the contact layer. If the external electric field is in the direction from the layer with the smaller electrical conductivity to that with the larger electrical conductivity, the thickness of the double layer and its resistance increase. If the external field is in the opposite direction, the thickness of the double layer and its resistance decrease. Thus, it follows that if the charge is exploded in the direction of the earth's electric field, the amplitude of the signal registered should be somewhat larger than for an explosion in the opposite direction.

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