EXPERIMENTAL STUDY OF THE ELECTROMAGNETIC FIELD IN THE NEAR ZONE OF EXPLOSIONS PRODUCED BY SOLID EXPLOSIVES

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A number of phenomena in the earth's atmosphere, of both natural and artificial origin (for example, the intrusion of meteoritic and other bodies), are accompanied by intense electromagnetic processes [1]. This same class of phenomena also includes the explosion of condensed explosives in the atmosphere, which leads to the appearance of an electromagnetic field. This effect was apparently first described by Kolsky [2] and was subsequently investigated experimentally in [3,4]. In [2–4] attempts were also made to determine the mechanism of occurrence of the electromagnetic fields associated with explosions.

One such mechanism was formulated in [3], where it is suggested that the electromagnetic field is associated with the discharge that occurs when the conductive region of the explosion, polarized in the external field (the earth's electric field), is grounded.

From this mechanism it follows, in particular, that an explosion occurring directly on the earth's surface does not create an electromagnetic field. This approach seems doubtful in a number of respects. So far the mechanism of occurrence of fields in connection with explosions remains uncertain.

Below we present certain results of an experimental study of the electromagnetic field accompanying the explosion of solid explosives with and without an external electric field, the object of the experiments being to establish the conditions and factors influencing the field-generation process and to obtain quantitative measurements of the nature of the interaction between spherical shock waves and an external electric field.

1. Experimental method and recording apparatus. In the experiments we used cast spherical charges of Composition B (50% TNT, 50% RDX) weighing 52, 225, and 660 g.

The explosion was initiated by a KD-8 blasting cap located in the center of the charge and detonated electrically or by means of a fuse. The explosions and measurements were conducted in a bell-shaped chamber 15 m tall and 12 m in diameter shielded from the earth's electric field.

The pulses of the electromagnetic field of the explosion were received by vertical rod antennas located at the level of the explosion directly in the explosion area at various distances from the center of the explosion within a range of 5 m. The antenna signals were fed through three amplifiers to an OK-17 recording oscillograph along an RK-1 cable 10 m long. Synchronization was achieved by means of a variable delay unit using the light pulse that occurred at the instant the detonation wave reached the surface of the charge. A general block diagram of the experiment is shown in Fig. 1, where ED is the electric detonator, F the fuse, EX the charge, CS the triggering contact sensor, PM the triggering photomultiplier, SU the synchronization unit, PT piezoelectric transducers, EP the electric probe, $A_1 \ldots$ $\ldots, A_4$ the rod antennas, M_1 and M_2 magnetic antennas, and P the antenna preamplifiers.

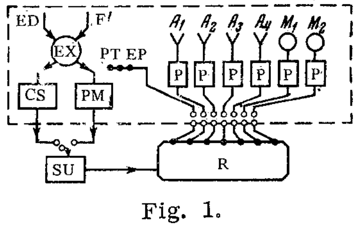

Fig. 1.

For the charges investigated the duration of the electric field pulse was 2–3 msec. A theoretical analysis of the transient responses of the equivalent circuit of a short rod antenna showed that for pulses of this duration to be recorded without distortion the input resistance of the preamplifier would have to be on the order of 10^{10} ohm (at an antenna self-capacitance of about 3 pF). Accordingly, as preamplifier we used two series-connected cathode followers, the first of which was connected in a "floating grid" circuit [5].

A direct experimental investigation of the transient response of the entire recording channel by registering the signal from a nearby antenna excited by a square current pulse lasting 3 msec showed that the receiving channel recorded such signals with an error not exceeding 15%. Below, this measuring circuit is referred to as the "broadband" circuit.

In addition, we used antennas in a "narrowband" variant with a preamplifier input resistance of the order of 1 Mohm, which, as an additional theoretical investigation and direct experimental verification showed, differentiate signals of the duration in question.

In order to measure the magnetic field we used ferrite antennas (ten turns of insulated conductor on a core consisting of several cylindrical ferromagnetic rods) with a preamplifier and integrator. Calibration of the magnetic antennas in Helmholtz coils showed that when an integrator is used the minimum measurable magnetic field strength does not exceed 10^{-3} Oe. The instants of arrival of the shock wave and explosion products at different distances were registered by means of a system of piezoelectric transducers and electric probe. Where necessary a constant electric field was created between the ground and a horizontal grid $2a = 1.5$ m in diameter charged to a potential on the order of (−10 to +3) kV. The effective field E_{eff} on a vertical axis through the center of the grid can be found from the relation

$$\frac{E_{eff}}{E_0} = \left(1 - \frac{z}{\sqrt{a^2 + z^2}}\right) \qquad \left(E_0 = \frac{\varphi}{h}\right)$$

Here, z is the distance from the grid to the point in question, φ is the grid potential, and h is the distance between the grid and the surface of the earth (h = 3 m).

Although the experimental conditions were not favorable (effect of chamber walls), nevertheless the results make possible a number of specific conclusions relating to the physics of the processes involved.

2. Experimental results. The full set of measurements of the electromagnetic field of the explosion with simultaneous registration of the motion of the shock front and the boundary of the explosion products can be divided into two groups. The first comprises the series of explosions without an external electric field. In this case the explosive was detonated both electrically and with a fuse. It was found that in the case of electrical detonation the presence of the conductors had an important influence on the phenomenon. After this was discovered all the experiments were conducted with a fuse. Both narrowband and broadband recording apparatus were employed.

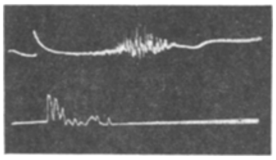

Fig. 2

Figure 2 presents a typical oscillogram of a field pulse (upper trace) from the explosion of a charge weighing 225 g at a height of 30 cm above the earth's surface recorded using the narrowband apparatus. The lower trace is the signal from a piezoelectric transducer located 43 cm from the charge (sweep time 500 μsec). Clearly, at the instant the shock wave touches the earth an electric pulse occurs, even in the absence of an external electric field.

A series of oscillograms and their copies are presented in Figs. 3 and 4:

a) copies of oscillograms of field pulses in volts from broadband antennas without an external electric field; oscillogram of pulses from broadband antenna (lower trace) and narrowband antenna (upper trace), m = 225 g R = = 250 cm;

b) copies of oscillograms of pulses from broadband antennas with an external electric field; oscillogram of pulses from broadband antennas, m = 225 g, +3 kV, R = 250 cm (upper trace), R = 330 cm (lower trace);

c) copies of oscillograms of pulses from broadband antennas with an external electric field, m = 52 g; oscillograms of pulses from broadband antenna (lower trace) and narrowband antenna (upper trace), m = 52 g, +5 kV, R = 250 cm.

As may be seen from Figs. 3 and 4, the pulse is characterized by a relatively stable shape. The polarity of the of the pulses varies from experiment to experiment. A characteristic feature of the pulses from all the explosions without an external field is the absence of a signal until the shock wave reaches a distance $20r_0$, where r_0 is the initial radius of the charge (this occurs for explosions of different energies.* The pulses have maxima (see Figs. 3a and 4a) reached at times t_1^0 and t_2^0 (here and in what follows t^0 is understood to represent the ratio of time t_{sec} to $(m_{kg}^{1/3})$; for charges weighing from 50 to 660 g $t_1^0 = 7.4 \cdot 10^{-4}$ and $t_2^0 = 2.1 \cdot 10^{-3}$.

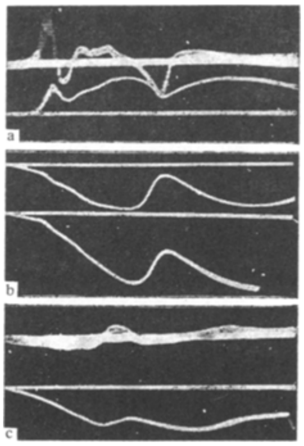

Fig. 3

The second maximum is clearly expressed in all the experiments. However, the first maximum together with the subsequent minimum in some cases degenerates into a point of inflection. We note that under the experimental conditions the shock wave reached the ground at time t = 1.6 msec and that this time coincides only by chance with the minimum at $t = t_3$ (m = 225 g).

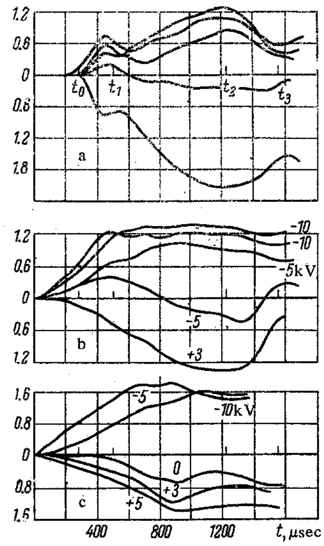

Fig. 4

The results of the measurements with a magnetic antenna indicate that the amplitude of the magnetic field did not exceed 10^{-3} Oe. The second group of experiments consisted of explosions in an external electric field created by means of a charged grid located at a height of 3 m. The magnitude and direction of the external field were varied by varying the potential on the grid in the range (−10 to +3) kV.

*On this time interval the amplitude of the electric pulse is negligibly small as compared with the amplitude of the pulse at the maximum of the same oscillogram or as compared with the amplitude of the pulse on the same time interval for explosions in an external electric field.

The electric pulses were recorded by four rod antennas (length 20 cm) located at distances of 250, 330, 430, and 490 cm. Oscillograms of the pulses recorded at various distances, for various charges,and at different values of the external field are presented in Figs. 3b, c and 4b, c.

Clearly, in the time interval $0 \le t \le t_0$ a nonstationary electric field is recorded. In every case without exception (total of 60 explosions) on this time interval the polarity of the signal was opposite to that of the external field. Outside this time interval the pulses are practically the same as the pulses without an external field.

Experimental values of the electric field E, measured at different values of the external field E_{eff}, different explosion energies, and different distances R on the time interval $0 \le t \le t_0$ are presented in Fig. 5 in the form of the dimensionless combination

$$\Phi(t^\circ) = \frac{R^3 E(t^\circ)}{2 r_0^3 E_{eff}}.$$

In calculating E (t°) it was assumed that the effective height of the antenna was equal to half its length. In the same figure we have plotted the relations

$$\Phi''(t^\circ) = \left[\frac{r''(t^\circ)}{r_0}\right]^3, \qquad \Phi'(t^\circ) = \left[\frac{r'(t^\circ)}{r_0}\right]^3$$

characterizing the law of variation in time of the volume of the regions encompassed by the shock wave and the leading boundary of the explosion products, respectively.

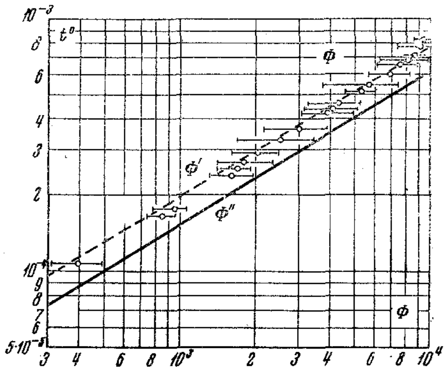

Fig. 5

The time dependences of the radius of the shock front r″ (t°) and the explosion products r′ (t°) were calculated from the empirical formulas obtained in [6]:

$$\frac{r''}{r_0} = [3\cdot10^5 (t^\circ - t_d^\circ) + 1]^{0.603}, \qquad 1 \leqslant \frac{r''}{r_0} \leqslant 12$$

$$\frac{\Delta}{r_0} = 0.045\left[\left(\frac{r''}{r_0}\right)^{1.4} - 1\right], \qquad 1 \leqslant \frac{r''}{r_0} \leqslant 35$$

Here, Δ is the distance between the shock front and the leading edge of the explosion products. These relations were obtained in [6] for Composition B charges weighing 50–135 g. As our measurements showed, these relations are also applicable to charges weighing 225–600 g.

3. Discussion of the results. In our experiments we observed, on the one hand, a field pulse when the shock wave touched the earth's surface in the absence of an external field and, on the other, a field pulse in an external electric field before the conductive region of the explosion was grounded (see previous section). These two observations do not confirm the mechanism proposed in [3] to explain the formation of a field in connection with the explosion of solid explosives.

The occurrence of a field pulse at the instant the shock wave touches the surface of the earth is evidently associated with the presence of an ambipolar radial field in or beyond the strong front, where a considerable ionization gradient exists. Until the shock wave reaches the underlying surface, this field is localized in a certain spherical double layer. Henceforth from the instant of contact the conditions of ambipolar-field formation due to the gradients at the "explosion products-earth" interface are different. For this reason the entire region of explosion acquires a certain effective dipole moment, which leads to the appearance of a field in the external region.

The appearance of an electromagnetic field associated with an explosion in an external electric field is obviously a consequence of the polarization of the conductive region of the explosion in that field.

The coincidence of the slopes of the functions $\Phi''(t^\circ)$, $\Phi'(t^\circ)$, and $\Phi(t^\circ)$ indicates the presence of an expanding spherical volume, within which the external field does not penetrate and whose boundary moves in accordance with the law of motion of the shock front and the explosion products. As seen from Fig. 5, this boundary is always located between the shock front and the explosion products. It should be noted, however, that this fact was established with less certainty, since it was obtained on the basis of certain additional assumptions (for example, concerning the effective height of the receiving antenna in the near zone of the radiator) which require further study.

The spherical volume with compensated external field creates a field at small distances above the flat surface of the earth, which for the given frequencies may be assumed perfectly conducting,

$$E(t^\circ) = 2E_{eff} \frac{r^3(t^\circ)}{R^3}$$

which corresponds to the relation $\Phi(t^\circ)$ in Fig. 4. It is perfectly understandable that the radius r(t) of a conducting sphere with compensated electric field should be located between the shock front and the explosion products on the time interval in question, since, for example, at $r'' = 20r_0$ the temperature directly behind the shock front is about 800° K and is insufficient to create appreciable thermal ionization, while the air temperature near the leading edge of the explosion products is about 3800° K, which leads to an electron density of about 10^{13} 1/cm^3 (see [7–9]).

The law of motion of the boundary surface is more correctly determined by the condition that by the time t in question the external field E_{eff} is attenuated in a region with conductivity $\sigma(r, t)$ to, say, 0.1 of its initial value

$$\int_0^t \sigma(r, t')\, dt' \approx 2.3$$

Obviously, in the case of a strong shock $r(t) \sim r''(t)$; for a weak shock $r(t) < r''(t)$. The space-time distribution of conductivity behind the spherical shock front, which determines the relation r(t), is affected by the temperature distribution, the nonequilibrium character of the ionization process, and a number of other factors.

A subsequent, more detailed experimental study of the law of motion r(t) for explosions in an external electric field may make it possible to obtain additional data on these processes. Difficulties may arise in connection with the effect of the electric field that occurs even at $E_{eff} = 0$. Obviously, the relative influence of this factor can be made as small as desired by increasing the external field.

In this connection it might be possible to use the considerable fields occurring in storm clouds. Suppose an explosion carried out at a height of 10 km in a field $E_{eff} = 10^5$ V/m compensates the field in a volume of radius 10 m. Then at the earth's surface the quasi-static component (the induction and wave components are much less) will be E = = 0.1 mV/m, which is perfectly measurable.

As for the field pulse at $t > t_0$, not associated with an external electric field or with the interaction of the shock wave and explosion products with the earth's surface, its nature remains obscure and requires further investigation.

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