SOME PROBLEMS OF THE POLARIZATION OF DIELECTRICS IN SHOCK WAVES

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It is well known that the passage of intense shock waves causes electrical polarization of polar dielectrics [1-2] and ionic crystals [3-6]. To observe this effect experimentally the electrical circuit shown schematically in Fig. 1 is used. The circuit consists of a plane-parallel capacitor through one of whose plates the shock wave travels into the material in question, and a load resistance R from which the electrical signal is picked off.

The dependence of the polarization current I(t) on the geometry of the specimen, the parameters of the shock wave, and also the electrical characteristics of the initial and shock-compressed material has been considered by Allison [7] and by Zel'dovich [8]. In both papers it is postulated that the shock wave front produces an initial polarization of the material $P_0$, which falls off with distance from the front. Allison [7] assumed that the decrease in $P_0$ with time occurs exponentially with a characteristic mechanical relaxation time $\tau$. Zel'dovich [8] studied the decay of $P_0$ in terms of compensation of the bound charges by the free current carriers.

A direct experimental determination of the mechanical relaxation time $\tau$ should in many respects facilitate the investigation of the electrical characteristics of the shock-compressed material, and should also enable an estimate to be made of the applicability of a theoretical approximation in each concrete case.

The value of $\tau$ can be obtained directly from the manner in which the polarization current increases after the shock wave has passed through the specimen, if the conditions are so arranged that the shock wave is not reflected from the second plate of the capacitor [5, 9]. This condition can be realized experimentally by using specimens in which the electrode (Fig. 1) is a thin metal foil held tightly between the two (the main and auxiliary) plates of the dielectric [9]. An oscillogram of the polarization and relaxation signals of plexiglas, obtained for a pressure of 150 kbar, is shown in Fig. 2a.

**1. Polarization of plexiglas in reflected shock waves.** When carrying out polarization experiments using the above setup (Fig. 1), after the shock wave reaches the metal electrode a reflected shock wave begins to propagate backwards through the compressed material. The polarization signal which occurs in the reflected wave will in this case be superimposed on the relaxation signal shown in Fig. 2a. For a given intensity of the forward wave $p_1$ the pressure in the reflected wave $p_2$ depends on the relationship between the dynamic rigidities of the material under investigation and the material of the electrode. By using electrodes of different metals (Cu, Mg) one can vary the value of this pressure.

Figure 2b shows typical oscillograms of the polarization signals of plexiglas which are produced by the forward ($p_1$ = 150 kbar) and reflected shock waves of different intensities.

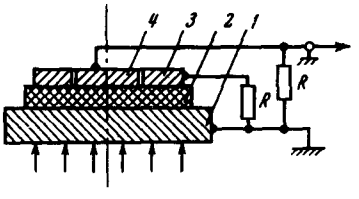


Fig. 1. Schematic diagram of the experimental arrangement: 1) metal plate-screen (the first plate of the capacitor), 2) dielectric, 3) guard ring, 4) electrode (the second plate of the capacitor). The arrows show the direction of motion of the shock wave front.

An unexpected fact is that the reflected wave, which propagates in a direction opposite to the direction of the forward wave, causes polarization of the plexiglas of the same sign as the forward wave. This can be seen particularly clearly if we separate in time the emergence of the forward wave at the electrode and the arrival of the reflected wave. To do this it is sufficient in the experiments for measuring $\tau$ [9] to place on the auxiliary layer of the dielectric a massive metal plate-reflector. The oscillogram obtained in such an experiment is shown in Fig. 2d. Note that, as follows from Fig. 2a, in the case in which the rarefaction wave arrives in the specimen in question from the side of the free surface of the auxiliary plate of the dielectric, a signal of opposite polarity is recorded.

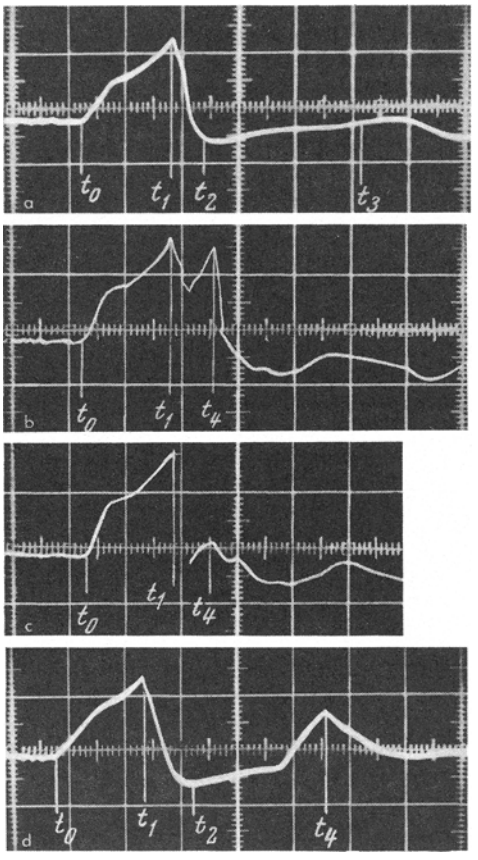


Fig. 2. Typical oscillograms of the electrical signals of plexiglas ($p_1$ = 150 kbar). The time scale is 0.25 μsec/division. The sensitivity is 7 V/division. The superposition on the relaxation signal of the polarization signals which occur: a) in the rarefaction wave and d) in the reflected shock wave. The signals which occur when using the arrangement shown in Fig. 1: b) copper electrode, c) magnesium electrode: $t_0$ is the beginning of the polarization signal in the forward wave; $t_1$ is the end of the polarization signal in the forward wave; $t_2$ is the beginning of the relaxation signal; $t_3$ is the beginning of the polarization signal in the rarefaction wave; and $t_4$ is the maximum polarization signal in the reflection shock wave.

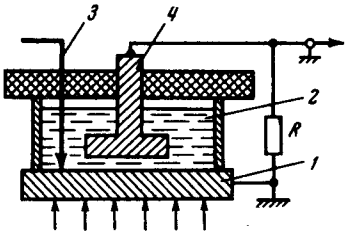


Fig. 3. Schematic diagram of the experimental arrangement to investigate the polarization of liquids: 1) aluminum screen of diameter 80 mm and thickness 8 mm, 2) material being investigated, 3) probe to indicate when the shock waves enters the material being investigated, 4) electrode made of various metals. The arrows show the direction of motion of the shock wave front. The gap between the screen and the electrode is approximately 3 mm.

**2. Electrical effects for dynamic loading of nonpolar materials.** An investigation of the polarization in reflected shock waves can give additional information on the properties of the shock-compressed material. The simplest and at the same time the most interesting subjects for investigation from this point of view are dielectrics whose molecules in the initial state do not have a constant dipole moment. It is well known [1] that such materials do not exhibit any polarization in the forward wave. Nevertheless, a preliminary investigation has shown that starting at a certain pressure in $CCl_4$, benzene, and certain other nonpolar materials, an electrical signal can occur after a shock wave has passed through the specimen at the instant the shock front reaches the second electrode [10]. The amplitude and sign of this signal depend on the properties of the electrode metal.

Experiment and results. We will describe experiments which were made in order to explain the nature of this effect in $CCl_4$. The main part of these experiments was performed with the arrangement shown schematically in Fig. 3. The active charge of explosive material, which produces in the $CCl_4$ an initial shock wave with a plane front and of the required amplitude, had a diameter of 60 or 80 mm and a height/diameter ratio of approximately 2.

To record the electrical signals which occur we used a double-beam OE-2 oscilloscope constructed by the Institute of Chemical Physics AN USSR, which had amplifiers with a rise time of 0.1 μsec and an input impendance of 100 ohm.

The velocities of the shock waves in $CCl_4$, which are required for the calculations, were calculated from the shock adiabat of $CCl_4$ [11] by means of the known state of the material of the screen, and also in separate experiments directly using a photorecorder which registered the illumination of the air gaps.

Figure 4 presents some oscillograms which show the change in the character of the electrical signals as the conditions under which the experiments were carried out changed: a change in the electrode material (Fig. 4a, b, c), the load resistance $R_e$ (Fig. 4c, d), the amplitude of the incident shock wave $p_1$ (Fig. 4c, e), and the electrode dimensions (Fig. 4e, f). We will consider a number of the characteristics of the recorded signals.

From experiments performed from the timed instant $t_0$ when the shock wave enters (for example, Fig. 4a) it follows that the signal occurs at a certain time $t_5$ after the shock wave starts to propagate in the $CCl_4$. At a pressure $p_1 = 180$ kbar, $t_5$ coincides with the time $t_6$ that this wave takes to pass through the screen and the electrode. For $p_1 = 100$ kbar, $t_5 > t_6$. In this case the appearance of the signal coincides fairly accurately with the instant at which triple compression begins, i.e., with the instant at which the wave reflected from the electrode reaches the screen. Special experiments, in which we used an additional UZ-5 amplifier, enabled us to establish that the possible polarization current density in the forward wave with $p_1 = 180$ kbar is less than $10^{-5}$ A/cm$^2$, which in our experiments is the limit sensitivity determined by electrical noise. In the usual experimental setup (Fig. 3) the polarization signal in the forward wave for an electrode diameter of 23 mm and a maximum sensitivity of the OE-2 (0.05 V/cm) is not recorded even for a pressure $p_1 = 320$ kbar.

We see from Fig. 4a, b, c that with $p_1 = 180$ kbar for copper and silver electrodes the signal has positive polarity, while for magnesium and zinc it has negative polarity.

The maximum amplitude of the signal $U_{max}$ for a constant pressure $p_1$ depends on the metal of the electrode, but in the pressure range from 100 to 180 kbar does not exceed 1.2 V in absolute value.

For $p_1 = 180$ kbar the amplitude $U_{max}$ remains practically constant when the load resistance is changed from 35 to 510 ohm.

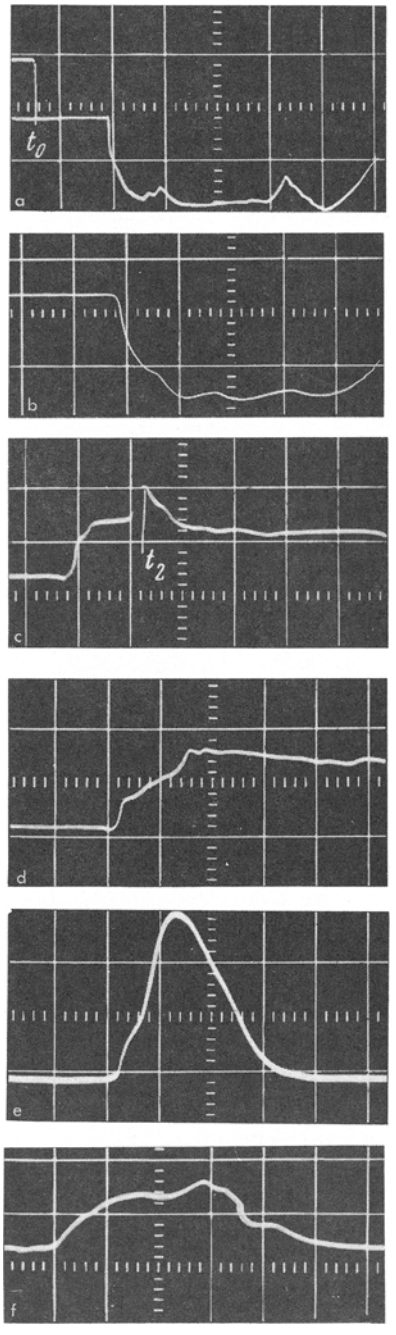


Fig. 4. Oscillograms of the electrical signals which occur when $CCl_4$ is shock loaded in experiments employing the arrangement of Fig. 3. The time scale is as follows: a, b, e, and f) 0.5 μsec/division, c and d) 0.25 μsec/division. Sensitivity: a) 0.5 V/division; b) 0.4 V/division; c, d) 0.3 V/division; e) 0.4 V/division; f) 0.6 V/division. $R_e$: a, b, c, e, f) 50 ohm; d) 510 ohm. Electrode diameter: a, b, c, d, e) 23 mm; f) 40 mm. Electrode material: a) Mg, b) Zn; c) Cu, Ag; d, e, f) Cu. $p_1$: a, b, c, d) 180 kbar; e, f) 100 kbar.

In all cases the signal does not change its polarity during an observation time sufficient for several reflections of the shock wave from the electrode and screen to occur.

Discussion of the results. The screen, electrode, and also the shock-compressed layer of $CCl_4$ between them (henceforth called the compressed layer) can be considered as a certain equivalent generator which has an internal resistance $R_i$ and an emf E. This generator is connected across the resistance of the input circuit of the device $R_e$. In this case for a recorded voltage U we have

$$U = E/1 + \alpha \qquad (\alpha = R_i/R_e). \tag{1}$$

Assuming that $R_i$ is equal to the resistance of the compressed layer, it can be calculated from the well-known dependence of the conductivity of the dynamically loaded $CCl_4$ on the pressure [12].

With $p_1$ = 180 kbar, during all the observation time $\alpha \ll 1$. (From the data given in [12] in this case the resistance of the compressed layer of diameter 23 mm is on the order of 0.5 ohm, which corresponds to $\alpha \sim 10^{-2}$, and there is no reason to assume that with successive reflections the resistance of the layer may increase.) Hence it follows from (1) that $U \simeq E$.

Note that $R_i$ can be included by itself and is even determined by the resistances of the junction which arise at the boundary of separation of the shock-compressed phases of the metal and the material under investigation. It is possible that the drop in voltage which is always observed for a certain time for $t > t_2$ for copper and silver electrodes with $p_1$ = 180 kbar and $R_e$ = 50 ohm (Fig. 4c) is connected with this. For a sufficiently large value of $R_e$ the resistances of the junctions turn out to be unimportant and the voltage drop does not occur (Fig. 4d). However, for further consideration it is important to estimate only the maximum possible E, and, as already noted, $U_{max}$ does not depend on $R_e$. Therefore, for the pressure considered the maximum value of the emf, which depends on the nature of the metal, does not exceed 1.2 V in absolute magnitude.

Generally speaking, the emf of order 1 V which arises when a shock wave propagates through an electrically conducting medium with an arbitrary type of conductivity can be determined by the polarization at the shock wave front in the volume of the material, and also by the thermoelectric or electrochemical effects at the boundary of separation of the shock-compressed phases of the metal and the material being investigated [10,13]. However, both when there is polarization in the volume and when thermoelectric emfs occur at the boundaries of separation of the phases, the signal in the general case must change sign when the direction of propagation of the shock wave changes. The fact that the sign of the signal is independent of the direction of the shock wave and also the correlation of the change in sign of E with the position of the electrode metal in the potential series suggests that the observed phenomenon is electrochemical in nature.

On the basis of this idea it is not difficult to explain the experimental dependence U(t) for $p_1$ = 100 kbar of Fig. 4e. In fact, for a single compression up to a pressure of 100 kbar the value of $\alpha \sim 10^2$, i.e., the electrical conductivity of the material is too low to record an electrochemical signal. It occurs when the electrical conductivity is increased due to multiple compression of $CCl_4$ in the gap between the screen and the electrode. Indeed, the duration of the observed pulse (Fig. 4e) agrees well with the calculated time taken for the multiply compressed layer to unload down to the original pressure, produced by a single compression, and increases when electrodes of larger diameter and greater thickness are used (Fig. 4f).

A further confirmation of the electrochemical nature of the recorded signal is the change in the polarity of the signal for a zinc electrode when the aluminum screen is replaced by a magnesium screen ($p_1$ = = 195 kbar) and the occurrence of a signal (Fig. 5) when a strip of copper foil of thickness 0.05 mm and width 20 mm placed perpendicular to the screen is used as an electrode. In the latter case, despite the fact that there is no reflected wave, the signal preserves a practically constant amplitude during the whole time of observation.

It should be noted that electrical signals can also arise in the experiments when the screen and the electrode are made of the same metal, for example, aluminum. However, in this case the value and

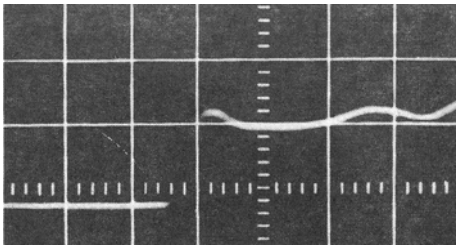

Fig. 5. Oscillogram of the electrical signal when the shock wave ($p_1$ = 180 kbar) reaches the electrode of copper foil. The time scale is 0.5 μsec/division. The sensitivity is 0.25 V/division.

shape of the signals change from experiment to experiment. This phenomenon is obviously connected with the possible electrochemical nonequivalence of the two boundaries of separation of the shock-compressed phases of the metal and the $CCl_4$.

In conclusion we will discuss the general aspect of the problem of polarization in shock waves. To explain the value of the polarization current which appears when certain polar dielectrics [1-2] and ionic crystals [3-6] are shock loaded up to pressures of 100-200 kbar, it is necessary to introduce into the equivalent measuring circuit a voltage source which has an emf greater than $10^4$ V [3]. This polarization can be called high-voltage polarization as distinct from low-voltage from low-voltage polarization which is observed when a shock wave propagates through semiconductors [14]. In this case for a shock wave amplitude of approximately 200 kbar the emf is approximately 0.4 V. As was shown in the example of $CCl_4$, a signal of this order is also observed when certain other materials which become electrically conducting in the shock-compressed state are dynamically loaded.

It is not obvious that the physical nature of low-voltage polarization can be explained by phenomena which only occur at the shock front (in the volume of the material), for example, by activation of impurities in the semiconductors [6]. The recorded signals can be explained to a considerable extent by thermoelectric or electrochemical effects at the boundary of separation of the shock-compressed phases of the metal and the material under investigation. In particular, we can conclude on the basis of our experiments that the electrical signals which arise when $CCl_4$ is dynamically loaded are electrochemical in nature and, therefore, are due to the presence of ions in the shock-compressed materials.

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