# *ELECTRICAL CONDUCTIVITY OF DIELECTRICS IN STRONG SHOCK WAVES*

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The electrical conductivity of air, water, and certain solid dielectrics subjected to strong shock waves has been measured by an electrical contact method. The measured values of the specific conductivity in the shock front are as follows: air, $0.5\ \Omega^{-1}\ cm^{-1}$; water, $0.2\ \Omega^{-1}\ cm^{-1}$. At shock front pressures of approximately $1 \times 10^6$ kg/km$^2$ it is found that the electrical conductivity of Plexiglas or paraffin reaches 1 to $2 \times 10^2\ \Omega^{-1}\ cm^{-1}$, a value which approximates the conductivity of a metal.

## INTRODUCTION

In an earlier work[1] we have shown that there is a zone of high electrical conductivity in the front of the shock wave caused by the detonation of a high explosive. It is of great scientific and practical interest to investigate this effect in inert media which are subjected to strong shock waves. Present-day explosives provide a convenient means of producing transient pressures of several millions of atmospheres.[2] It is to be expected that at the high compressions and densities corresponding to these pressures there will be radical changes in the electrical properties of materials.

In 1948 — 1949 the present authors measured the electrical conductivity of air, water, paraffin and Plexiglas in strong shock waves produced by the detonation of charges of high explosives (HE). Under these conditions it is found that the electrical conductivity (in the shock front) is many orders of magnitude greater than the conductivity of the original material. Below we present the experimental data which have been obtained and discuss possible physical mechanisms for the formation of a zone of high electrical conductivity in dielectrics subject to strong shock waves.

## EXPERIMENTAL METHOD AND DATA

The rapidly varying electrical resistance in inert media subject to strong shock waves is measured by means of the electrical-contact method which has been described in reference 1. A shock wave in air is produced by placing an aluminum plate P, 2 mm thick, on the end face of the charge Ch (Fig. 1a). This plate prevents the explosion products from striking the measurement contacts $K_1$. On the far side of the plate there is a supplementary set of contacts $K_2$; the closing of these contacts is observed on an oscilloscope and denotes the time at which the shock wave passes the free surface of the plate.

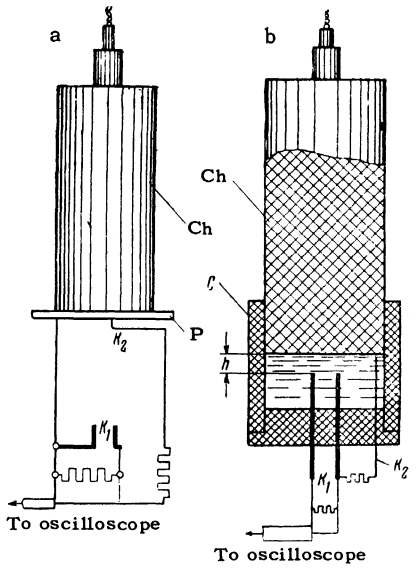


FIG. 1. Arrangement of the charges and contact devices used to measure the electrical conductivity in shock waves: a) in air, b) in water.

When the charge is detonated, the air shock wave, whose velocity is 10 — 15% greater than the velocity of the aluminum plate, reaches contact $K_1$ first; the oscilloscope is used to determine the electrical resistance in the shock front of the air wave. After a small time interval the contacts are closed briefly by the metal plate. The reference mark denoting the time at which the aluminum plate is set in motion and the marks denoting the change in electrical resistance are then used to measure the mean velocity of the aluminum and air shock wave.

A typical oscillogram obtained with the experimental arrangement of Fig. 1a is shown in Fig. 2. The numbers 1, 2, and 3 denote respectively the time at which the plate is set in motion, the arrival of the air shock wave at the contacts, and closure of the contacts by the metal plate. Analysis of such oscillograms indicates that the mean veloc-

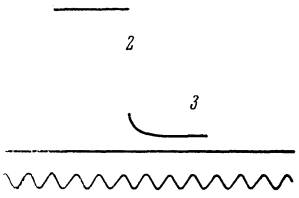


FIG. 2. Oscillogram of the contact measurements of the electrical conductivity in air (arrangement used in Fig. 1a). The frequency of the sinusoidal time markers is 1 Mcs.

ity of the air shock wave is 4.9 km/sec when the distance from the plate to the contact device is 5 to 10 cm. Under these conditions the velocity of the metal is 4.5 km/sec while the resistance of the air in the shock wave front is 2.2 to 2.6 Ω.

To measure the electrical conductivity of water, a large container C filled with distilled water is located at the face of the charge Ch (Fig. 1b). As in the experiments with the air wave, contacts $K_1$ are used to measure the resistance in the shock front while the closing of the contacts serves to mark the time at which the shock wave is excited in the water. The measurements are carried out with the distance h set at 10, 30, and 50 mm. The functional relation is shown in Fig. 3. With h = 10 mm the resistance of the contact gap is 6.5 to 7.0 Ω; this value increases to 46 to 47 Ω when h = 50 mm.

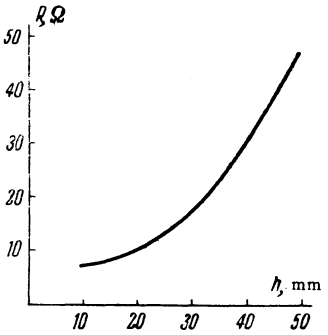


FIG. 3. The resistance R in a shock front in water as a function of the distance h.

The mean velocity of the shock wave in water under these conditions varies from 4 to 6 km/sec.

The measurements described here were carried out with distilled water (specific resistance, approximately $10^5$ Ω). In order to evaluate the effect of the initial resistance of the water similar experiments were repeated with ordinary water (initial specific resistance $7.5 \times 10^2$ Ω). Although the initial resistance is two orders of magnitude smaller, the electrical resistance in the shock front is the same as when distilled water is used.

The most interesting results have been obtained in measurements of the resistance of solid dielectrics subjected to the effect of strong shock waves. These experiments were carried out with paraffin and Plexiglas in the pressure range $1 \times 10^5 - 1 \times 10^6$ kg/cm$^2$. The results of these measurements are shown in Fig. 4. In the paraffin case an appreciable reduction in resistance is observed at pressures of $6 - 7 \times 10^5$ kg/cm$^2$. When the pressure in-

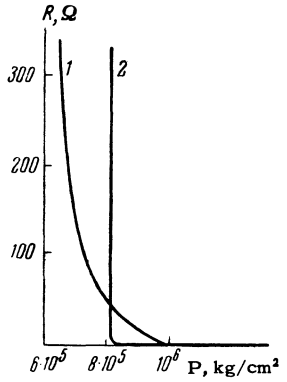


FIG. 4. The resistance R in a shock front as a function of pressure: curve 1 is for paraffin and curve 2 for Plexiglas.

creases to $9 - 10 \times 10^5$ kg/cm$^2$, the resistance drops rapidly to values of the order of hundredths of an ohm. In Plexiglas the reduction in resistance is observed at higher pressures than in paraffin ($8 \times 10^5$ kg/cm$^2$). In this case the resistance vs pressure curve drops suddenly; at a pressure of $8.2 \times 10^5$ kg/cm$^2$ the resistance is of the order of hundredths of an ohm.

The reduced data on electrical conductivity in the shock fronts for air, water, paraffin, and Plexiglas are shown in the table. Electrolytic-model measurements were used to convert the resistance of the contact gap to specific electrical conductivity γ. For shock waves of relatively small intensity in air and water the values of γ lie in the range $0.2 - 0.5$ Ω$^{-1}$ cm$^{-1}$. For paraffin and Plexiglas in the pressure range $6 - 10 \times 10^5$ kg/cm$^2$ the specific electrical conductivity increases to $100 - 200$ Ω$^{-1}$ cm$^{-1}$.

## DISCUSSION OF THE RESULTS

There are two possible mechanisms which can be responsible for the appearance of a region of high electrical conductivity in a strong shock front in dielectrics: thermal ionization, and enhancement of electronic transitions, resulting from the combined effects of high pressure and high temperature. An approximate calculation made on the basis of the Saha formula for the case of a shock wave in air gives values of the electrical conductivity which correspond, in order of magnitude, to the present experimental data. However, it is difficult to explain by thermal ionization alone the increase by 15 or 20 orders of magnitude of the electrical conductivity of such perfect dielectrics as paraffin and Plexiglas. The values obtained for these materials at shock pressures of approximately $10^6$ kg/cm$^2$, i.e., 1 to $2 \times 10^2$ Ω$^{-1}$ cm$^{-1}$ are only two orders of magnitude smaller than the electrical conductivity of metals.

The effect of high and ultra-high pressures on electrical conductivity of dielectrics has been discussed at length in the literature. For example,

| Material | Initial density, $\delta_0$ g/cm$^3$ | Initial electrical conductivity $\gamma_0$, $\Omega^{-1}$cm$^{-1}$ | Pressure in the wave front P, kg/cm$^2$ | Electrical conductivity in the wave front $\gamma$, $\Omega^{-1}$ cm$^{-1}$ |
|---|---|---|---|---|
| Air | 0.0012 | — | $3 \cdot 10^2$ | 0.5 |
| Water | 1 | $10^5$ | $1 \cdot 10^5$ | 0.2 |
| Paraffin | 0.8 | $10^{-18}$ | $1 \cdot 10^6$ | $10^2$ |
| Plexiglas | 1.18 | $10^{-15}$ | $8.2 \cdot 10^5$ | $2 \cdot 10^2$ |

Bridgman[3] has shown that at pressures of 12 or 13 $\times 10^3$ kg/cm$^2$ and temperatures of 200° yellow phosphorus becomes black phosphorus. This new form has a density 1.4 times greater than the original form, and has an electrical conductivity characteristic of a metal, whereas yellow phosphorus is an insulator. Similar transformations, characterized by an increase in density and the appearance of a high electrical conductivity, are observed in tin and arsenic.

In 1944, Zel'dovich and Landau,[4] in analyzing the transition of metals into the gaseous state, reached the conclusion that at sufficiently strong compression any material will exhibit metallic properties. One of the latest theories concerning the structure of our planet proposes that the core of the earth consists of olivine, and not iron and nickel, as had been thought earlier. At the pressures of $1.4 \times 10^6$ kg/cm$^2$ which exist at the boundary of the earth's core, olivine has a density of about 10 g/cm$^3$, becomes metallic, and should have a high electrical conductivity.

In 1956, Alder and Christian[5] applied shock waves to CsI crystals and pressed samples of $I_2$, CsBr, $LiAlH_4$ and certain other dielectrics and found that the resistance in the shock front of the wave was reduced to several hundred ohms (the original resistance of the samples was higher than $10^8$ Ω). The shock pressure in these experiments was approximately $2.5 \times 10^5$ kg/cm$^2$. For this reason the "metallization" of the dielectrics was relatively weak. In the present experiments with paraffin and Plexiglas the pressure in the shock front is four times greater and the values of the electrical conductivity are found to be four orders of magnitude greater than those obtained by Alder and Christian.[5]

The general nature of the phenomena which occur in a strong shock front in dielectrics may be explained as follows. The high temperature and compression in the wave front stimulates atomic interactions and "squeezes" the electronic levels. These effects enhance electronic transitions, and materials which are originally dielectrics acquire an electrical conductivity characteristic of the metal state.

The temperature in the shock front has a strong influence on this effect. It is hoped that further work will make it possible to delineate the individual effects of high pressures and temperatures in the formation of a region of high electrical conductivity in dielectrics. However, the experimental data which are already available indicate that the strong shock waves produced by high explosives offer a convenient way of studying the transformation of dielectrics into "metals" under laboratory conditions.

[1] Brish, Tarasov, and Tsukerman, JETP **37**, 1543 (1959), Soviet Phys. JETP **10**, 1095 (1960).

[2] Al'tshuler, Krupnikov, and Brazhnik, JETP **34**, 886 (1958), Soviet Phys. JETP **7**, 614 (1958).

[3] P. W. Bridgman, Physics of High Pressures, Macmillan, New York, 1935, Russ. Transl. ONTI, 1935.

[4] Ya. B. Zel'dovich and L. D. Landau, JETP **14**, 32 (1944).

[5] B. J. Adler and R. H. Christian, Phys. Rev. **104**, 550 (1956).

Translated by H. Lashinsky