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MEMORANDUM REPORT NO. 1449
DECEMBER 1962

THE SHOCK-INDUCED POLARIZATION OF DIELECTRICS

F. E. Allison
A. B. Wenzel

Department of the Army Project No. 503-04-002

BALLISTIC RESEARCH LABORATORIES

ABERDEEN PROVING GROUND, MARYLAND

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Aberdeen Proving Ground, Md.
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ABSTRACT

In previous experiments it was shown that a displacement current is generated in suitable dielectric materials subjected to explosively produced shock waves. A theoretical description of the shock-induced displacement current, which takes into account the electrical properties of the dielectric and the shock propagation characteristics of the media, is used to interpret data obtained from experiments employing polystyrene as the dielectric. The theory predicts that the initial current is directly proportional to the area, inversely proportional to the thickness of the dielectric, and independent of the resistance, all of which agree with earlier experimental findings. The data show that most of the increase in the dielectric constant is due to an increase in the density of the specimen, with a rise in temperature playing a lesser role.

INTRODUCTION

In recent experiments, G. E. Hauver[1] showed that a displacement current is generated in a suitable dielectric material subjected to an explosively produced shock wave. The existence of the displacement current was established by placing the dielectric between conducting electrodes, one of which was in direct contact with an explosive charge. When the charge was detonated, a shock was transmitted into the dielectric material through the electrode next to the charge. The peak pressure was controlled by varying the thickness of the intervening electrode or buffer plate. As the shock entered the dielectric, an electric current was detected in a resistor connecting the two electrodes. Since there were no other sources of EMF in the circuit, the current in the resistor was proportional to a shock-induced displacement current in the dielectric.

It has been postulated[1] that the shock wave produces a net polarization of the dielectric by partially orienting the elementary dipoles of which the material is composed. It is now believed that preferential elongation or compression of the dipoles depending upon their orientation is a more plausible physical mechanism. A difference in the mass associated with the ends of the polar molecules has been suggested[2] as the most likely reason for the shock front to produce a preferential displacement of the positive and negative charges.

The research to be discussed in this report was conducted for the purpose of establishing the relation between the electric current generated, the electrica properties of the dielectric, and the shock propagation characteristics of the media. A theoretical description of the shock-induced displacement current is derived and used to interpret data obtained from experiments employing polystyrene as the dielectric material. As yet, results of the work have not been interpreted in terms of molecular mechanics describing the interaction of the shock front with the polar molecules of which the dielectric is composed.

THEORETICAL DESCRIPTION

A mathematical description of the shock-induced displacement current is based on the physical model illustrated in Figure 1(a). At a time t, the shock will have moved into the dielectric a distance Ut, and the rear surface will have moved forward a distance ut. Ahead of the shock, the electric properties are described by a dielectric constant K, an electric displacement $\underline{D}$, an electric polarization $\underline{P}$, and an electric field strength $\underline{E}$. It is assumed that the dielectric is isotropic ($\underline{D} = \epsilon_o\underline{E} + \underline{P}$) and that all vectors are oriented perpendicular to the shock front. Primed quantities are used to describe the electric properties behind the shock front, it being assumed that the properties are constant throughout the shocked region. Across any boundary between two dielectric media, the normal component of the electric displacement is continuous. Since the electric displacement vector is perpendicular to the shock front

$$D = D'. \tag{1}$$

Within a parallel-plate condenser,

$$D = Q/A, \tag{2}$$

where Q is the charge on the condenser and A is the area of the plates. Ahead of the shock, the electric displacement is related to the electric field strength by the relation

$$D = K\epsilon_o E, \tag{3}$$

where $\epsilon_o = 8.85 \times 10^{-12}$ farad/m. Behind the shock front, it is postulated that the polarization consists of an electrical contribution P' and a mechanical contribution P_s resulting from the shock wave. The electrical contribution to the polarization is proportional to the local electric field strength; i.e., $P' = \epsilon_o X'E'$ where X' is the para-electric susceptibility. On the basis of the preceding assumptions the electric displacement behind the shock is given by $D' = \epsilon_o E' + P' + P_s$ or

$$D' = K'\epsilon_o E' + P_s, \tag{4}$$

where $K' = (1 + X')$ and P_s is the net dipole moment per unit volume produced by the shock wave. When equations (1) through (4) are solved for the electric field strength, one obtains

$$E = Q/K\epsilon_o A, \tag{5}$$

$$E' = Q/K'\epsilon_o A - P_s/K'\epsilon_o \tag{6}$$

An examination of Figure 1(a) shows that the potential drop between the two plates is given by

$$V(t) = E(X_0 - Ut) + E'(U - u)t. \tag{7}$$

Since Kirchoff's law requires that $V(t) + IR = 0$, one obtains the following equation for Q:

$$IR + (Q/K\epsilon_0 A)\ (X_0 - Ut) + (Q/K'\epsilon_0 A - P_s/K'\epsilon_0)\ (U - u)t = 0, \tag{8}$$

after substituting the quantities for E and E' given by equations (5) and (6).

It is convenient to represent the behavior of the dielectric by the equivalent circuit shown in Figure 1(b). The current in the equivalent circuit is governed by the equation

$$Q/C_1 + Q/C_2 + IR = \mathcal{E}. \tag{9}$$

An examination of equations (8) and (9) shows that

$$\mathcal{E} = P_s\ (U - u)t/K'\epsilon_0, \tag{10}$$

$$1/C_1 = (U - u)t/K'\epsilon_0 A, \tag{11}$$

$$1/C_2 = (X_0 - Ut)/K\epsilon_0 A. \tag{12}$$

It is noted that the electromotive force is a saw-tooth wave having a period equal to the transit time of the shock through the dielectric. If the time constant of the circuit is much less than the period of the electromotive force; i.e., $RC \ll X_0/U$, it may be assumed that the entire potential drop appears across the capacitance. In this approximation equation (8) reduces to

$$(Q/K\epsilon_0 A)\ (X_0 - Ut) + (Q/K'\epsilon_0 A - P_s/K'\epsilon_0)\ (U - u)t = 0. \tag{13}$$

The initial current can be obtained by differentiating equation (13) and evaluating the derivative for t and Q equal to zero. It is found that

$$I_0 = (dQ/dt)_{t=0} = P_s\ (U - u)KA/K'X_0. \tag{14}$$

Equation (14) predicts that the initial current is directly proportional to the area, inversely proportional to the thickness of the dielectric, and is independent of the resistance, all of which agree with earlier experimental findings[2]. The experiments to be described in this report were conducted in an effort to confirm the theoretical model and evaluate the constants K' and P_s for polystyrene.

EXPERIMENTAL APPARATUS

The experimental apparatus used to study the shock-induced polarization in polystyrene is shown schematically in Figure 2. An explosive charge is used to produce a plane shock front in an aluminum buffer plate located between the explosive and the dielectric specimen. The thickness of the buffer plate is used to control the peak pressure to which the specimen is subjected. In order to remove electrostatic effects associated with the ionized detonation products, the buffer plate is maintained at ground potential. The dielectric is inserted between the buffer plate and a second electrode which has the same diameter as the specimen. The specimen and second electrode are enclosed in a Teflon receptacle, which is filled with carbon tetrachloride. The carbon tetrachloride reduces the impedance mismatch at the lateral surfaces of the dielectric thereby reducing the rarefaction wave that would otherwise result from a free boundary. The buffer plate is connected to the second electrode through a resistor. The shock-induced displacement current is observed by monitoring the voltage across the resistor using the upper beam of a type 555 Tektronix dual-beam oscilloscope. A representative voltage-time signal is shown in Figure 3. The duration of the signal corresponds to the transit time of the shock through the specimen. If the specimen is sufficiently thin, the attenuation of the wave while traversing the specimen will be negligible, and one can assume the shock velocity to be constant.

The shock parameters are determined experimentally by measuring the free-surface velocity of the aluminum buffer plate near the dielectric specimen. The arrival times of the free surface at four locations in space are detected by a set of probes connected to a suitable pulse-forming network and the lower beam of the dual-beam oscilloscope. The arrival times are indicated by the rapid vertical deflections of the lower trace illustrated in Figure 3.

DETERMINATION OF SHOCK PRESSURE

The pressure produced in the dielectric material is determined by a method similar to that outlined by J. M. Walsh and co-workers[3]. The particle velocity, u, resulting from the shock in the buffer plate is computed from the approximate relation

$$u = u_{fs}/2, \tag{15}$$

where u_{fs} is the free-surface velocity. The shock pressure in the buffer plate is determined from the p - u representation for the Hugoniot data of 2024 T3 aluminum. As shown in Figure 4, the curve for aluminum is reflected about a vertical line through the point representing the pressure and particle velocity existing in the buffer plate. The intersection of the p - u curve representing the Hugoniot data for polystyrene with the reflected p - u curve for aluminum defines the pressure and particle velocity existing behind the shock transmitted across the interface into the polystyrene. The shock velocity in the polystyrene is now determined from the conservation of momentum:

$$P = \rho_o Uu. \tag{16}$$

The shock velocity determined from equation (16) for the 1/8 in. polystyrene specimen was 5.26×10^3 m/sec. The shock velocity determined from Figure 3 by taking the ratio of the thickness to the transit time measured from the pulse duration is also 5.26×10^3 m/sec.

DETERMINATION OF CIRCUIT CAPACITANCE

In deriving equation (13), it was assumed that $RC \ll X_o/U$. To check the validity of this assumption, and consequently the validity of equation (13), it is necessary to measure the capacitance of the circuit. When an inductance, L, is inserted in series with the resistor, the current oscillates with a frequency whose period, T, is given by

$$T = 2\pi \sqrt{LC}. \tag{17}$$

A typical trace obtained from an experiment using an inductance is shown in Figure 5(a). The time between the first two peaks was measured to determine the period associated with each value of the inductance. As shown in Figure 5(b), the capacitance can be obtained by plotting the linear relation between T^2 and L, the slope of the line being $4\pi^2 C$.

The data shown in Figure 5(b) yields a capacitance of 8.8×10^{-12} farads for a 1/8 in. thick polystyrene specimen having a 1.0 in. diameter. The associated RC time constant is 8.2×10^{-10} sec. for a resistance of 93 ohms. On the other hand, X_o/U is 6.0×10^{-7} sec., which readily satisfies the condition $RC \ll X_o/U$.

DETERMINATION OF DIELECTRIC PROPERTIES

The displacement current was carefully measured for a series of four tests using 1 in. diameter polystyrene specimens. The experimental conditions associated with each test are summarized below:

Test	Specimen Thickness	Resistance	Pressure (from u_{fs})
1	1/8 in.	52 ohms	108 kilobars
2	1/8 in.	93 ohms	110 kilobars
3	3/16 in.	93 ohms	110 kilobars
4	1/4 in.	93 ohms	110 kilobars

As long as the resistance is sufficiently small, compared with the reactance of the stray capacitance, the charge on the stray capacitance can be neglected; i.e., $dQ/dt = I$ where Q is the charge on plates surrounding the specimen. For each test the current-time curves were integrated to obtain Q as a function of time; the resulting curves are shown in Figure 6.

To facilitate the determination of K' and P_s equation (13) was put into the following form:

$$F(Q) = Q(X_o - Ut)/K\epsilon_o A(U - u)t = P_s/K'\epsilon_o - Q/K'\epsilon_o A. \qquad (18)$$

It is noted that F(Q) is a linear function of Q whose slope is $-1/K'\epsilon_o A$ and whose intercept is $P_s/K'\epsilon_o$. Values for F(Q) were computed from the Q(t) curves presented in Figure 6 using experimentally determined values for U and u. Curves representing the function F(Q) are presented in Figure 7. It is noted that a linear relation exists between F(Q) and Q for both tests using 1/8 in. thick polystyrene specimens. An increasing departure from linearity exists for the 3/16 in. and 1/4 in. specimens respectively. For the thicker specimens, it is possible that the low-pressure tail following the shock results in substantial variations in the dielectric properties throughout the shocked region, which is contrary to the assumptions used in deriving equation (18). For the 1/8 in. specimens, the data follow the linear relation between F(Q) and Q predicted by the theory, and accurate values of K' and P_s can be obtained from the slopes and intercepts respectively. The results are summarized on the next page.

Test	P_s (coul/m^2)	K'	χ'	χ'/χ	ρ'/ρ
1	3.59×10^{-5}	3.29	2.29	1.5	1.6
2	3.75×10^{-5}	3.29	2.29	1.5	1.6

The susceptibility of the polystyrene behind the shock was computed from the dielectric constant using the relation $\chi' = K' - 1$. For the unshocked material the dielectric constant is 2.55; and the corresponding susceptibility, 1.55. Since shock compression of the polystyrene crowds more dipoles into a unit volume, the ratio χ'/χ should be approximately equal to ρ'/ρ provided the shock has not greatly increased the temperature of the specimen. An increase in temperature reduces the para-electric susceptibility and consequently the ratio χ'/χ is expected to be less than ρ'/ρ. However, it is interesting to note that the ratio χ'/χ is only 6% less than the ratio ρ'/ρ indicating that most of the change in susceptibility is accounted for by simple compression of the specimen.

SUMMARY

A theory has been developed which relates the shock-induced displacement current to the electrical properties and shock propagation characteristics of the dielectric. The theory predicts that the initial current is directly proportional to the area, inversely proportional to the thickness of the dielectric, and independent of the resistance, all of which agree with earlier experimental findings. The response of the dielectric to a shock wave is described in terms of a function F(Q), which, according to the theory, is a linear function of Q. Empirical curves representing F(Q) were obtained for polystyrene specimens. For sufficiently thin specimens, F(Q) was found to be a linear function of Q and the theory was used to evaluate P_s and K' for polystyrene subjected to a 110 kilobar shock. The data show that most of the increase in the dielectric constant produced by a shock wave is due to the increased density of the specimen with an increase in temperature playing a lesser role.

ACKNOWLEDGEMENTS

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F. E. Allison

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A. B. WENZEL

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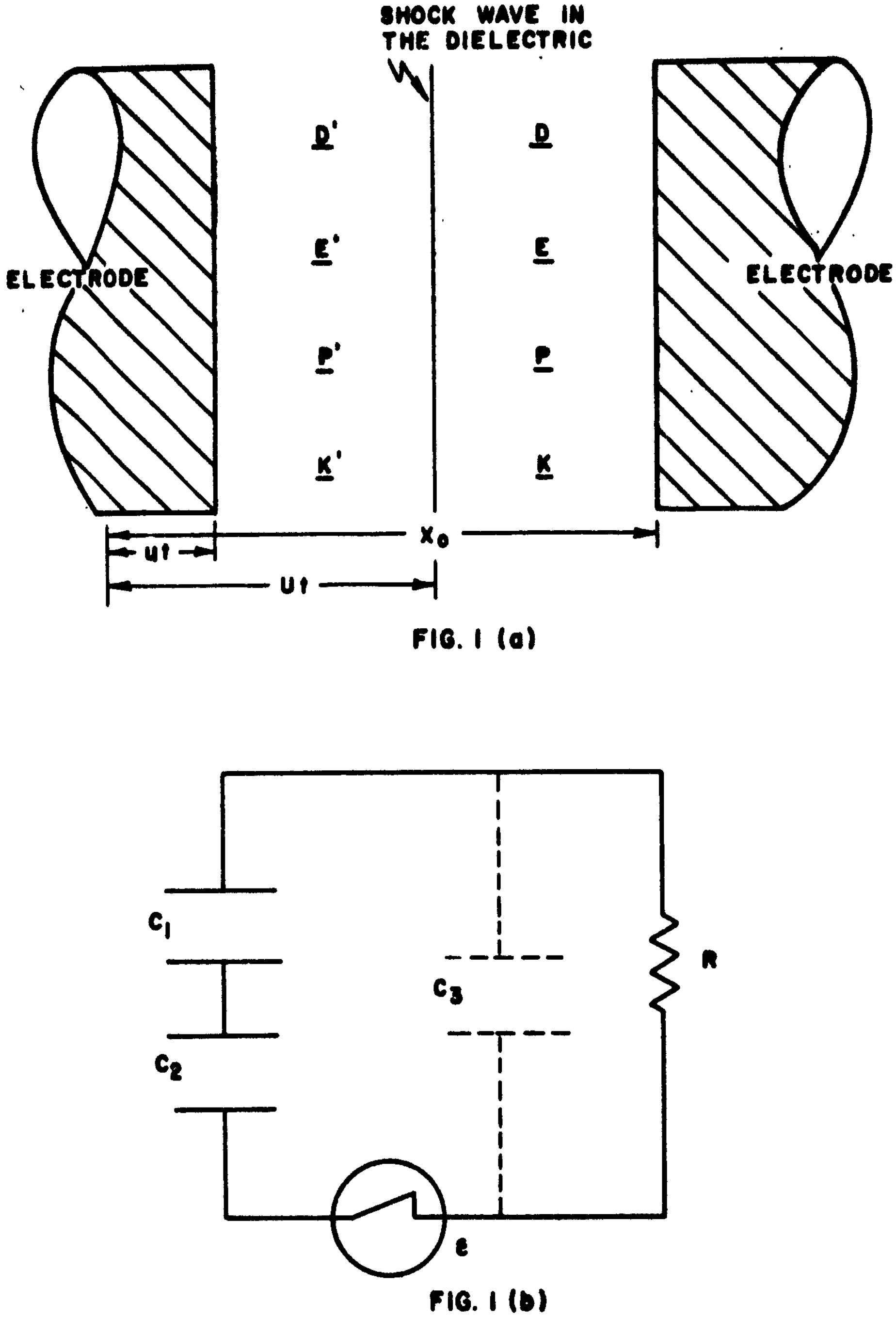

FIG. 1 (a)

FIG. 1 (b)

FIG. 1 - DIAGRAM ILLUSTRATING (a) THE PHYSICAL MODEL USED TO DESCRIBE THE NET POLARIZATION PRODUCED BY A SHOCK WAVE IN A DIELECTRIC, AND (b) THE EQUIVALENT CIRCUIT RESULTING FROM AN ANALYSIS OF THE MODEL. C_3 REPRESENTS THE STRAY CAPACITANCE ASSOCIATED WITH THE CIRCUIT.

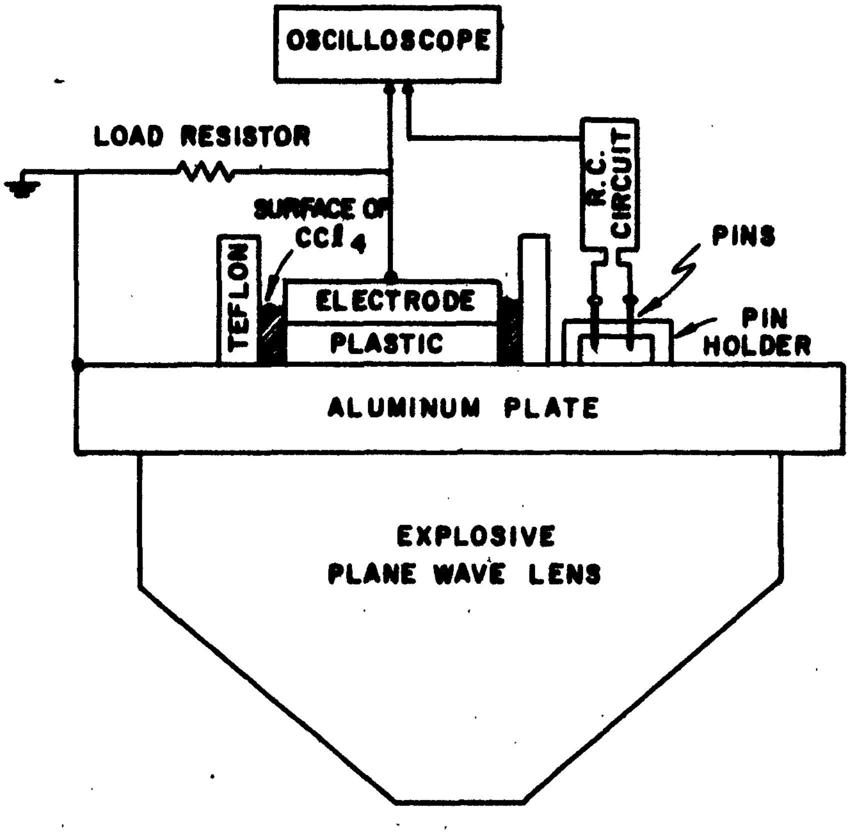

FIGURE 2: EXPERIMENTAL APPARATUS USED TO STUDY THE SHOCK-INDUCED POLARIZATION IN POLYSTYRENE.

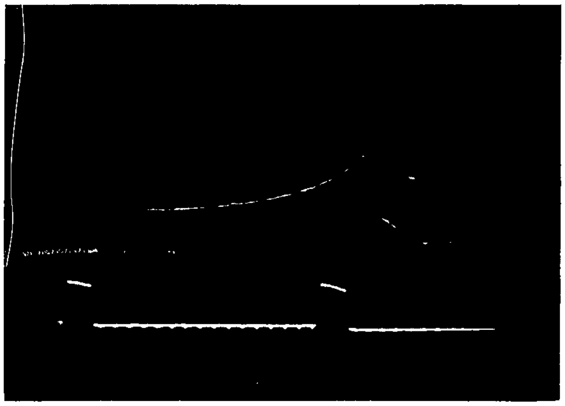

FIGURE 3. - TYPICAL OSCILLOGRAM OBTAINED FROM A TEST USING A 1/8 INCH POLYSTYRENE SPECIMEN. SINCE THE SPECIMEN ACTS AS A CONSTANT CURRENT GENERATOR, THE VERTICAL DISPLACEMENT IS PROPORTIONAL TO THE LOAD RESISTOR. THE ARRIVAL TIMES OF THE FREE SURFACE AT FOUR LOCATIONS IN SPACE ARE DETECTED BY A SET OF PROBES CONNECTED TO A SUITABLE PULSE-FORMING NETWORK AND THE LOWER BEAM OF A DUAL-BEAM OSCILLOSCOPE. THE ARRIVAL TIMES ARE INDICATED BY THE RAPID VERTICAL DEFLECTIONS OF THE LOWER TRACE. THE FREQUENCY OF THE REFERENCE SINE WAVE IS 50 MC FOR THE UPPER BEAM AND 10 MC FOR THE LOWER BEAM. THE TRACES ARE DISPLACED ALONG THE TIME AXIS BECAUSE THE LOWER BEAM IS TRIGGERED ABOUT 0.2 μSEC LATER THAN THE UPPER BEAM.

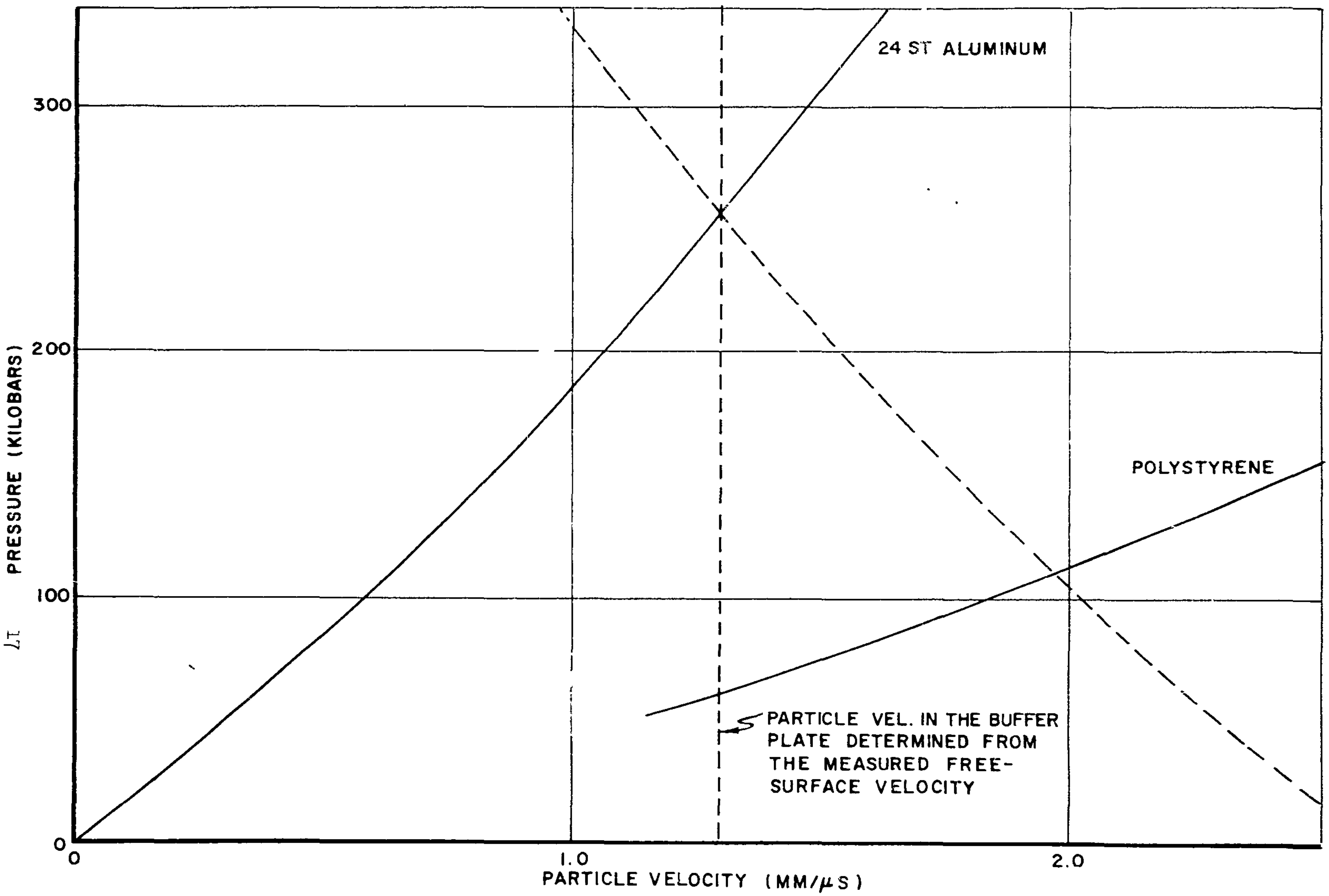

FIGURE 4. GRAPH ILLUSTRATING THE METHOD USED TO DETERMINE THE PRESSURE IN THE POLYSTYRENE SPECIMEN. THE INTERSECTION OF THE p-u CURVE REPRESENTING THE HUGONIOT FOR POLYSTYRENE WITH THE REFLECTED p-u CURVE FOR ALUMINUM DEFINES THE PRESSURE AND PARTICLE VELOCITY BEHIND THE SHOCK TRANSMITTED INTO THE POLYSTYRENE.

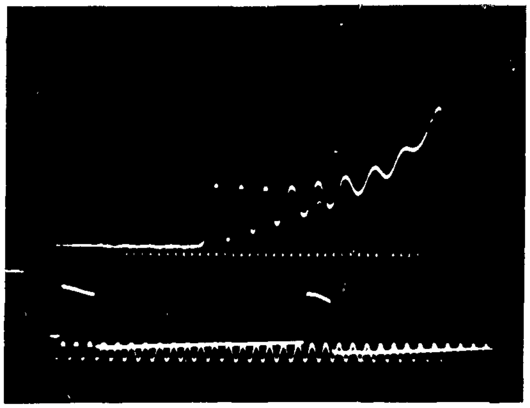

FIGURE A

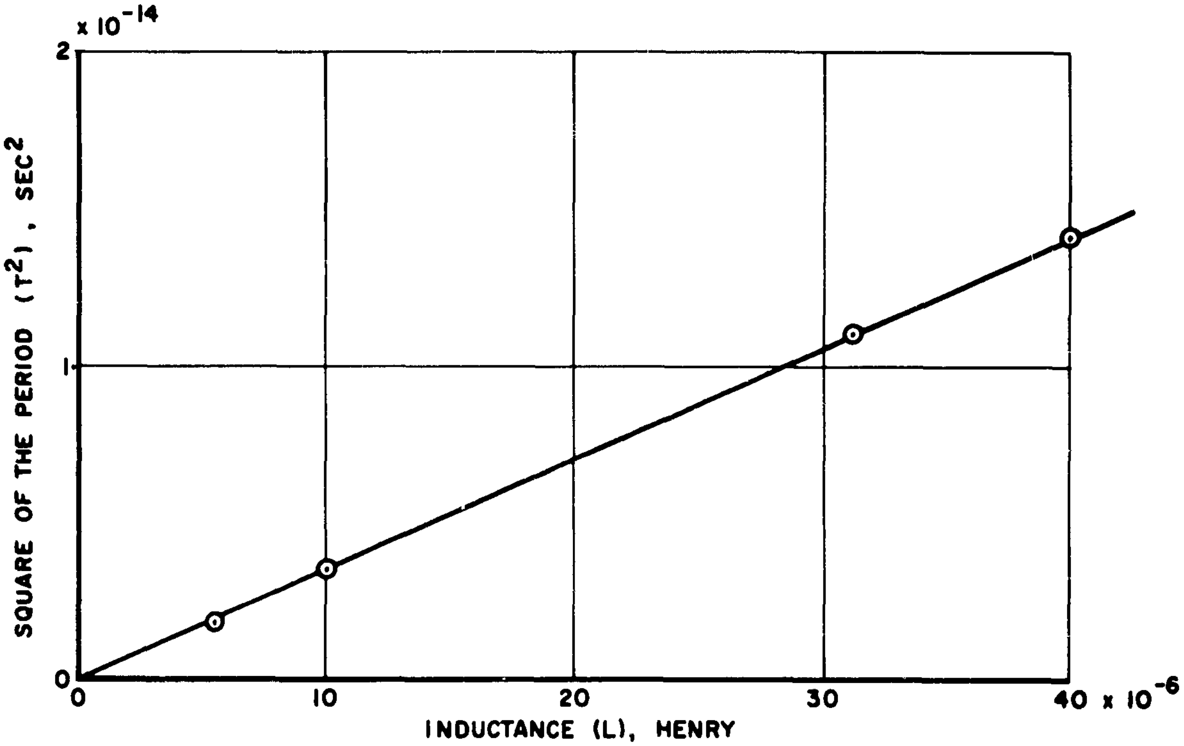

FIGURE B

FIGURE 5 - (a) TYPICAL OSCILLOGRAM OBTAINED BY PLACING AN INDUCTANCE L IN SERIES WITH THE LOAD RESISTOR. THE INITIAL CAPACITANCE IN THE CIRCUIT IS OBTAINED FROM THE PERIOD OF THE FIRST OSCILLATION. SINCE THE PERIOD IS GIVEN BY $T = 2\pi\sqrt{LC}$, T^2 IS A LINEAR FUNCTION OF L WITH A SLOPE OF $4\pi^2 C$. (b) THE LINEAR RELATION BETWEEN T^2 AND L FOR A 1/8 INCH POLYSTYRENE SPECIMEN.

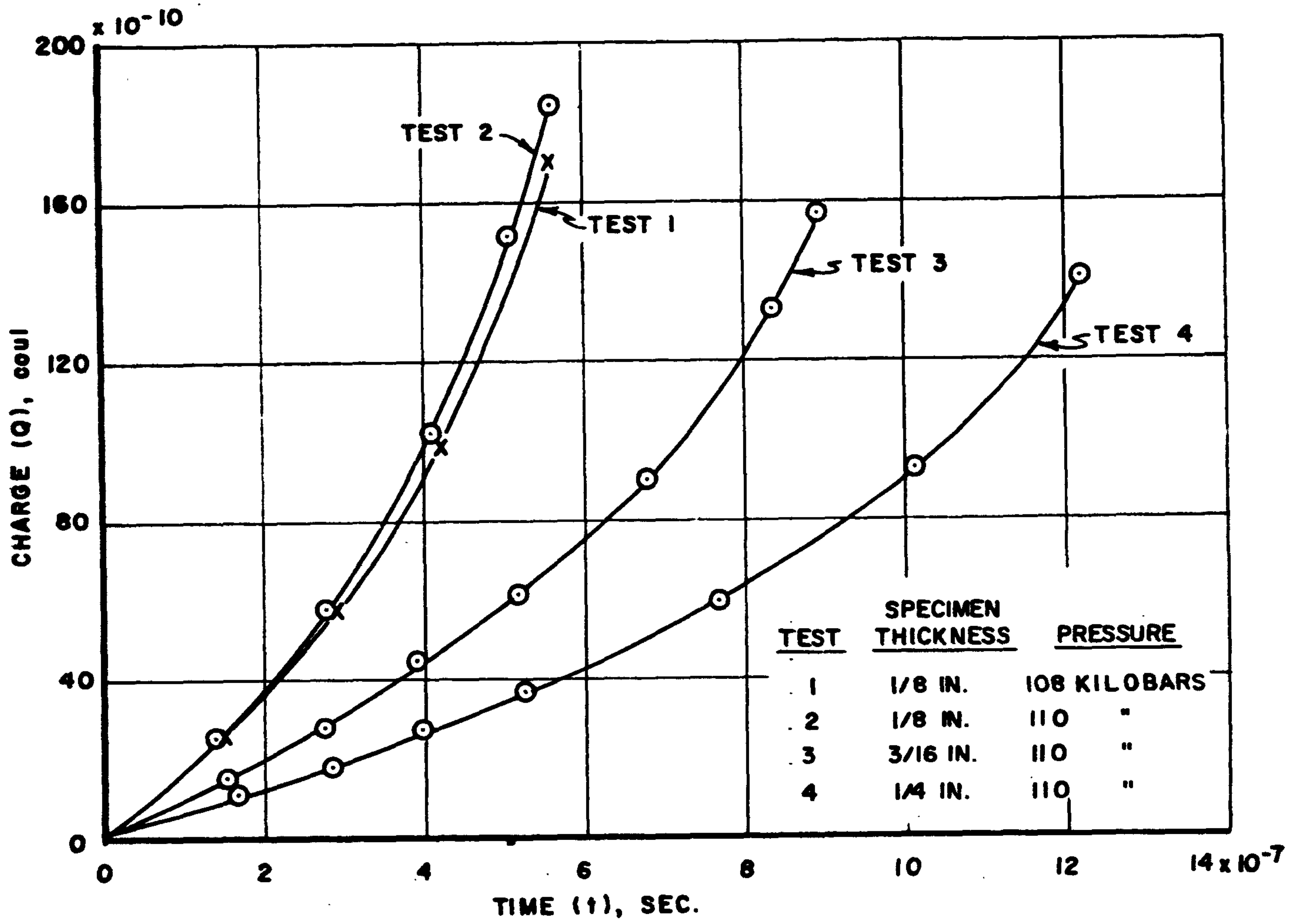

FIGURE 6. CURVES ILLUSTRATING THE BUILD UP OF ELECTRIC CHARGE ON THE PLATES SURROUNDING THE POLYSTYRENE SPECIMENS. VALUES FOR THE CHARGE, Q, WERE OBTAINED FROM THE TIME INTEGRAL OF THE CURRENT THROUGH THE LOAD RESISTOR.

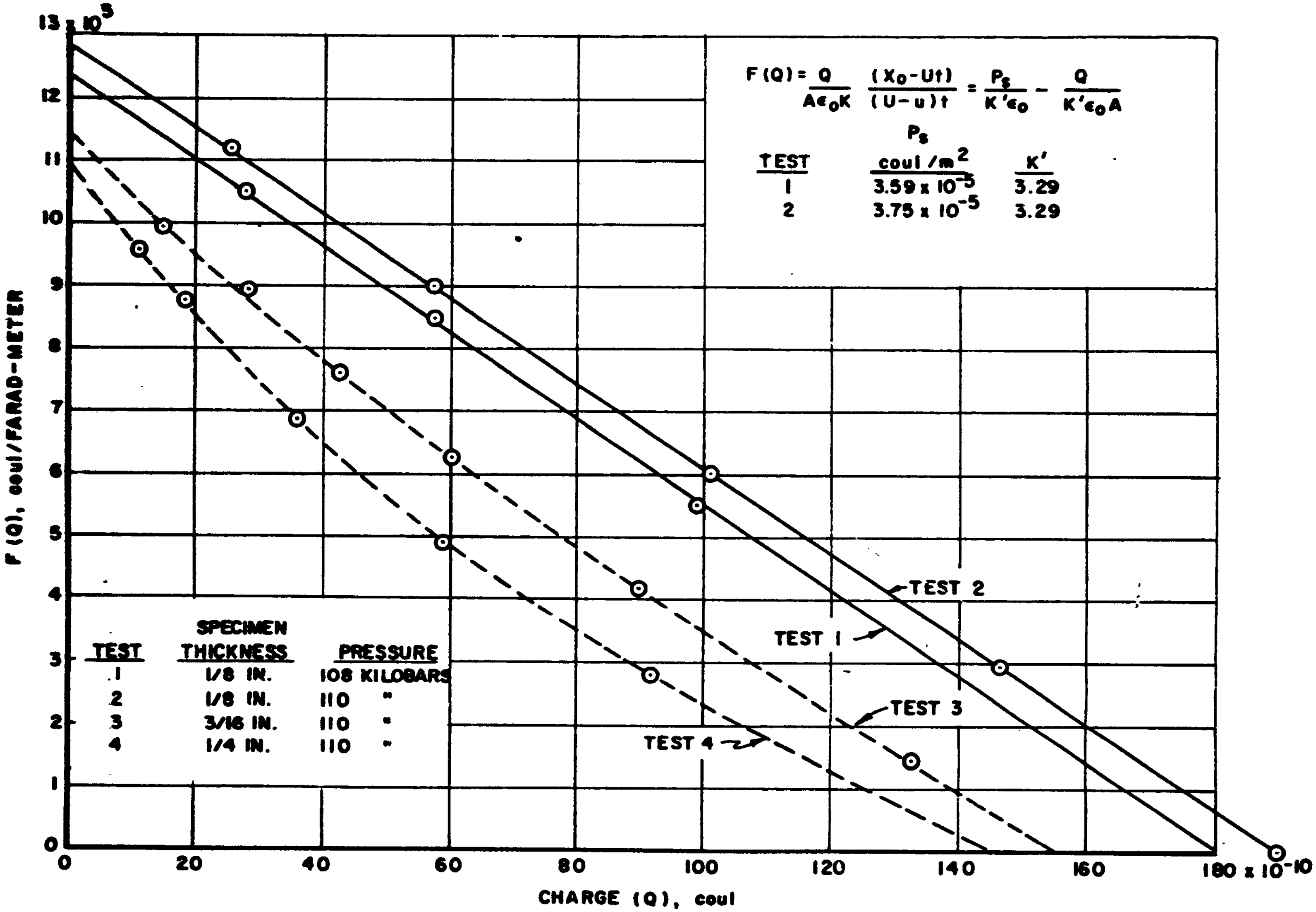

FIGURE 7. GRAPHS ILLUSTRATING THE METHOD USED TO DETERMINE NUMERICAL VALUES FOR THE ELECTRICAL PROPERTIES OF POLYSTYRENE BEHIND THE SHOCK FRONT. DATA FOR THE 1/8 IN. SPECIMENS AGREE WITH THE THEORY, WHICH PREDICTS THAT F(Q) IS A LINEAR FUNCTION OF Q.

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Shock Waves - Electrical Effects in Plastics
Electric Polarization - Produced by Shock Waves in Plastics

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In previous experiments it was shown that a displacement current is generated in suitable dielectric materials subjected to explosively produced shock waves. A theoretical description of the shock-induced displacement current, which takes into account the electrical properties of the dielectric and the shock propagation characteristics of the media, is used to interpret data obtained from experiments employing polystyrene as the dielectric. The theory predicts that the initial current is directly proportional to the area, inversely proportional to the thickness of the dielectric, and independent of the resistance, all of which agree with earlier experimental findings. The data show that most of the increase in the dielectric constant is due to an increase in the density of the specimen, with a rise in temperature playing a lesser role.