On the Electromotive Force and the Electric Conductivity Accompanied with the Detonation of Explosives

By

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The electromotive force and the electric conductivity in the ionized gases produced by the detonation of Sakura dynamite were investigated in this study. This investigation was carried out to obtain several fundamental data for developing a method by which the detonation rate of an explosive could be estimated.

As to the electromotive force, the maximum values ranging from 1 V to 2 V were obtained and these electromotive forces were generally observed in the negative signal against the ground.

In the majority of records, between 10 micro-seconds and 20 micro-seconds after detonation, the conductivity was observed to attain to its stationary value which was ranged from 5×10^{-2} mho/cm to 30×10^{-2} mho/cm.

1. Introduction

There are many phenomena accompanied with the detonation of an explosive which are not yet well understood, and the electric phenomena accompanied with the detonation of explosives, such as an electromotive force and an electric conductivity in ionized detonation gases, may be considered to belong to one of these. These phenomena may vary according to the kind, shape and loading density of explosives, and have hardly been measured in boreholes drilled in rocks or in the ground.

It may be considered that the electric phenomena accompanying the detonation of explosives are all due to the ionized detonation gases, and the study of these phenomena may be considerably difficult because of extremely high pressure produced in detonation gases comparing with the ordinary electric discharge in gases. Owing to this reason, only a few studies of these electric phenomena have been made, and therefore there may exist a good many facts which have not yet been appreciated.

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The electromotive force generated in explosives has been hardly observed, and we can only estimate the magnitude of the electromotive force as about from 1.5 V to 2 V for an alloy of TNT with RDX from the study by A. A. Brish and his co-workers[1)].

As to the electric conductivity, more studies than for the electromotive force have been made and their results show that the conductivity in detonation gases of TNT, Tetryl and 20/80 AN-TNT are approximately 0.3–4 mho/cm[1),2)], 0.1 mho/cm[2)] and 0.04 mho/cm[2)] respectively.

Now, it is the purpose of this study to investigate some electric phenomena accompanied with the detonation of explosives, especially on the electromotive force and the electric conductivity in detonation gases of Sakura dynamite charged in boreholes.

2. Electromotive Force Generated in Detonation Gases

2.1. Experimental procedures

As shown in Fig. 1, a probe for observing the electromotive force was set up on the explosives parallel to their axes keeping its ends open and connected to the input terminals of the synchroscope by means of a coaxial cable. Two enamel-covered copper wires of 1 mm apart (known as an ion-gap) were also inserted near the initiation point of explosive as shown in Fig. 2 and an electric potential difference of about DC 15 V was applied between these two wires.

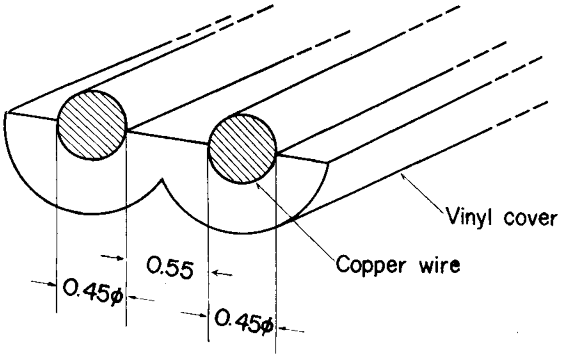


Fig. 1. Probe for measuring the electromotive force.

Triggering the oscilloscope trace was accomplished by utilizing these wires being shorted out by ionized detonation gases, and similar wires were also inserted near the end of the explosive to indicate the finishing point of the detonation on the oscillogram.

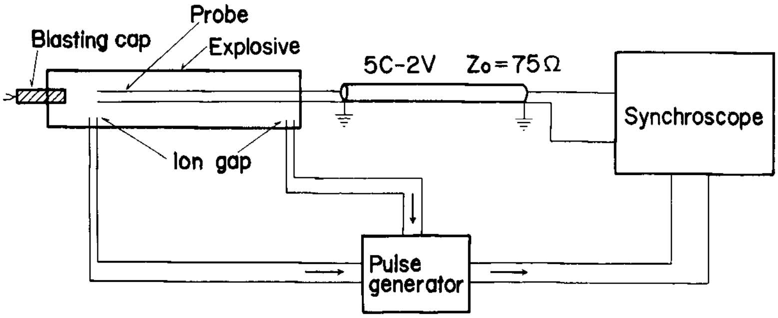


Fig. 2. Schematic diagram of the circuit for measuring the electromotive force.

The measurement of the electromotive force was carried out for the explosives which were detonated in a borehole drilled in the ground.

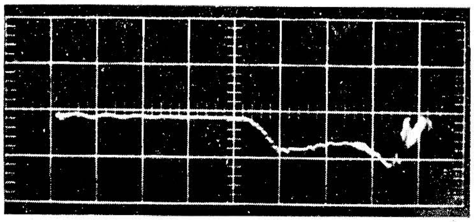
The explosive used in this study is Sakura dynamite of which composition is shown in Table 1.

Table 1. Composition of Sakura dynamite (per cent. by weight)

Nitroglycerine gel	Ammonium nitrate	Other materials
50-54	36-40	8-12

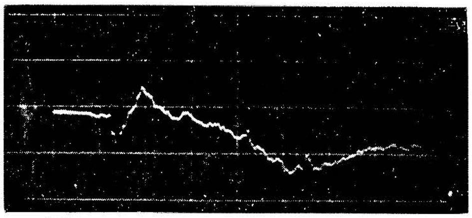
2.2. Results of experiments and considerations

It has been recognized that the detonation gases ionize with the initiation of the detonation and radiate the electromagnetic waves instantaneously because of extremely high temperature (3000−6000°K) and pressure ($10^4-20\times10^4$ atm.) near the detonation wave front[1)-3)]. In observing the electromotive force, at first, the probe shown in Fig. 1 was set up at a certain distance behind the initiation point parallel to the axis of the charge to investigate whether the electromotive force observed was induced by the radiated electromagnetic wave or was caused by the contact of the probe with the detonation gases. Fig. 3 is an example of oscillograms obtained in such an arrangement of the probe, and it shows evidently that the electromotive force is not observed instantaneously after the initiation of the explosive, but it appears just after the time when the detonation wave front arrives at the front end of the probe. From this fact, it may be concluded that the electromotive force is generated by the contact of the probe with the ionized detonation gases after the detonation wave front has reached the probe. Therefore, in further experiments the probe was set up over nearly the total length of the explosive from the initiation point. A typical oscillogram thus



sweep rate : 5 micro-sec./div.
gain : 1V/div.

Fig. 3. An example of the oscillograms showing the electromotive force (1).



sweep rate : 5 micro-sec./div.
gain : 1V/div.

Fig. 4. An example of the oscillograms showing the electromotive force (2).

Table 2. Results of experiments for measuring electromotive force.

Test number	Maximum value (V)	Average value (V)	
		in positive signal	in negative signal
10-18-2	−1.8	0.1	0.5
10-18-5	−2.0	0	0.4
10-18-6	+0.8	0	0.3
11-15-6	−1.1	0.2	0.4
11-15-7	−1.2	0.1	0.5
12- 7-2	−0.5	0.1	0.3

Kind of explosive : Sakura dynamite, Charge weight : 45 g, Charge length : 120 mm, Charge diameter : 20 mm, Initiation : No. 6 electric cap

obtained is shown in Fig. 4, and the results of the electromotive force measurements are summarized in Table 2.

It is shown in Table 2 that the maximum values of the electromotive force range from 1 V to 2 V and the electromotive forces are generally observed in negative signal against the ground. Moreover, the average values in negative sign are always greater than those in positive one, and this may depend upon the fact that the number and density of ions and electrons generated in the ionized gases of different kinds of explosives are considerably affected by the difference in their mobilities.

In these experiments, the electromotive force is generally observed in an oscillatory shape as shown in Fig. 4 and its period shows approximately from 5 micro-seconds to 20 micro-seconds, that is, the frequency of the oscillating electromotive force is nearly from 50 kc/s to 200 kc/s. The reason for the oscillatory nature of the electromotive force may be ascribed to the want of uniformity in the ion and electron densities, but the reason why such frequencies as mentioned above are observed is not obvious at present.

3. Electric Conductivity in Detonation Gases

3.1. Experimental procedures

As in the experimental procedure for measuring the electromotive force, the probe shown in Fig. 1 was arranged to keep its ends open and to be set up on the surface of the charge parallel to its axis. The measurement of the electric conductivity was carried out for the explosives which were detonated in a borehole drilled in the ground, too.

In the present experiments, two electric circuits which were shown in Figs. 5 and 6 respectively were used for measuring the electric conductivity. In the circuit (a) shown in Fig. 5, the current through R_{A_1} is constant (120 mA) regardless of the short circuit resistance of detonation gases appearing

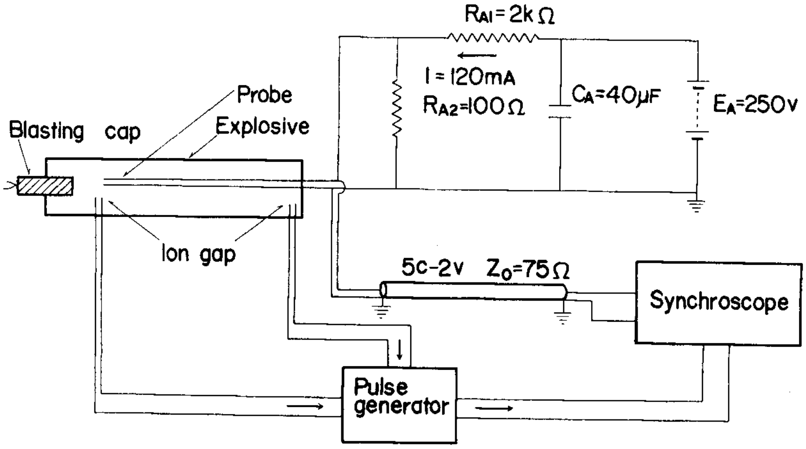


Fig. 5. Schematic diagram of the circuit (a) for measuring the electric conductivity.

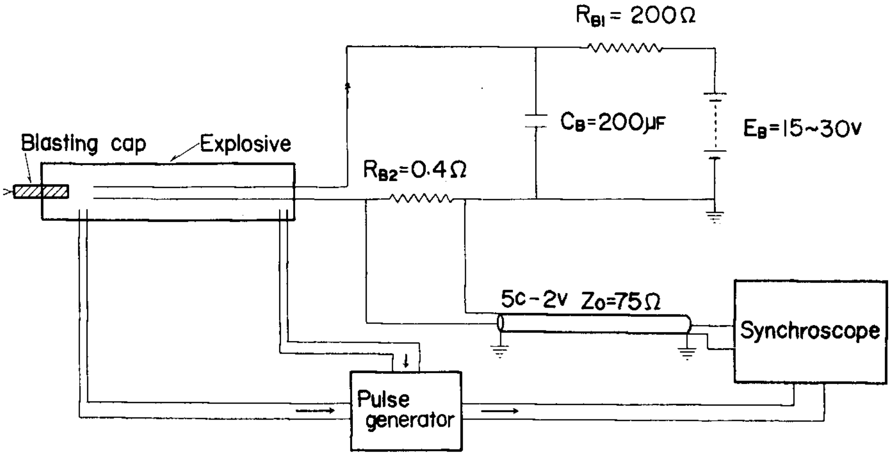


Fig. 6. Schematic diagram of the circuit (b) for measuring the electric conductivity.

across the wires of the probe, because R_{A1} is sufficiently greater than R_{A2}. Now, if we can find the voltage V_A across the probe in this circuit, the equivalent short circuit resistance r_{ex} of the detonation gases will be calculated by the following equation (1)*.

$$r_{ex} = V_A R_{A2}/(R_{A2} I - V_A) \tag{1}$$

The circuit (b) shown in Fig. 6 is that of the constant voltage, that is, in this circuit the voltage applied to the probe is kept always constant, and in this case r_{ex} is given by the following equation (2),

$$r_{ex} = R_{B2}(E_B - V_B)/V_B \tag{2}$$

where V_B is the observed voltage.

3.2. Results of experiments and considerations

The results of experiments for measuring the electric conductivity in detonation gases are shown in Tables 3 and 4. The results (a) and (b) were

Table 3. Results of experiments for measuring electric conductivity (a)

Test number	Detonation velocity (m/sec)	Average equivalent short circuit resistance (ohm)	Length of conduction zone (cm)	Average resistivity (ohm-cm)	Average conductivity (mho/cm)
12-20-1	2210	9.1	2.80	7.4	13.5×10^{-2}
12-20-2	2270	9.1	2.88	7.6	13.2×10^{-2}
12-20-4	2080	7.1	2.64	5.5	18.4×10^{-2}
12-20-5	1880	11.1	2.38	7.7	13.0×10^{-2}
12-20-7	1950	4.4	2.48	3.2	31.5×10^{-2}
Kind of explosive : Sakura dynamite, Charge weight : 90g, Charge length : 240 mm, Charge diameter : 20 mm, Initiation : No. 6 electric cap					

Table 4. Results of experiments for measuring electric conductivity (b)

Test number	Detonation velocity (m/sec)	Average equivalent short circuit resistance (ohm)	Length of conduction zone (cm)	Average resistivity (ohm-cm)	Average conductivity (mho/cm)
4-26-1	1760	19.0	2.23	12.3	8.1×10^{-2}
4-26-3	2000	12.4	2.54	9.1	10.9×10^{-2}
4-26-4	1820	10.0	2.31	6.7	14.9×10^{-2}
4-26-5	1870	13.5	2.37	9.3	10.7×10^{-2}
4-26-6	1770	23.0	2.24	14.9	6.7×10^{-2}
Kind of explosive : Sakura dynamite, Charge weight : 45g, Charge length : 120 mm, Charge diameter : 20 mm, Initiation : No. 6 electric cap					

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* The effect of the input impedance of synchroscope is ignored here, since the conductivity of gas can be estimated to be pretty high.

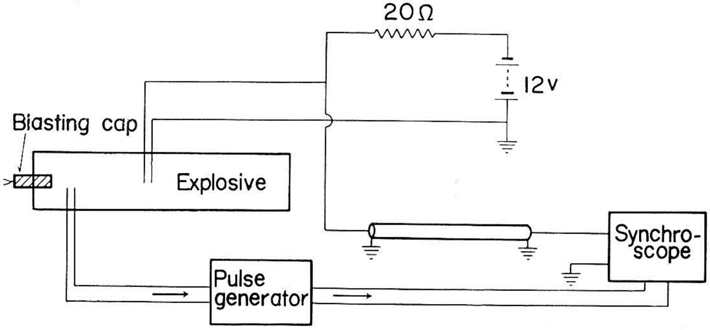
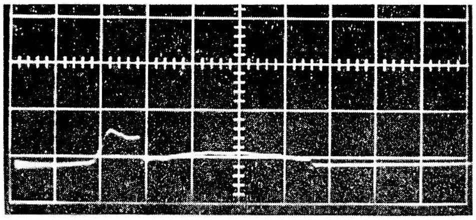


Fig. 7. Schematic diagram of the circuit for measuring the duration of the conductive phenomena.

obtained by employing the circuits (a) and (b) respectively. The length of the conduction zone, the average resistivity and the average conductivity shown in Tables 3 and 4 were calculated from the values of the average duration of the conductive phenomena (approximately 14 micro-seconds) obtained by using the circuit shown in Fig. 7, the detonation velocities, the diameter of the probe and the spacing of the probe wires.

A typical oscillogram showing the duration of the conductive phenomena is shown in Fig. 8.

As shown in Tables 3 and 4, the average electric conductivities range from 5×10^{-2} mho/cm to 30×10^{-2} mho/cm, and these values are generally smaller than those which have been presented by the former investigators. This may depend chiefly upon the kinds of explosives and the differences in the measuring conditions (mainly those in the confining conditions of explosives).



sweep rate : 10 micro-sec./div.
gain : 5V/div.

Fig. 8. A typical oscillogram showing the duration of the conductive phenomena.

According to the hydrodynamic theory of detonation, it is said that the detonation wave is composed of the shock zone, the reaction zone and the zone of detonation products. The shock zone with extremely high pressure exists in front of the detonation wave, and the width of this zone is very thin, nearly 10^{-5} cm, for most explosives. The explosive constituents may begin to react against each other by being fired in this zone, and this reaction ceases at the C–J plane. It has been generally recognized[4)] that the electric conductivity observed in detonation gases depends upon the thermal ionization due to the heat of reaction. Now, we have the Saha's equation[5] which represents the degree of ionization for gases in high temperature and in the state of thermal equilibrium. Furthermore, according to Chapmann and Cowling[6] the electric conductivity relates to the degree of ionization through equation (4).

$$\log\{\alpha^2 p/(1-\alpha^2)\} = -5040\ V_i/T + 2.5\log T - 3.62 \tag{3}$$

$$\sigma = 0.532(\alpha e^2/\sqrt{m_e \cdot k \cdot T}) \cdot (1/Q) \tag{4}$$

In equation (3), α, p, T and V_i denote the degree of ionization, the pressure, the temperature, and the ionization potential respectively, and in equation (4), σ, e, m_e, k and Q denote the electric conductivity, the electric charge of an electron, the mass of an electron, the Boltzmann's constant and the collision cross section respectively.

Then, assuming $T=3000°\mathrm{K}$, $V_i=10\mathrm{V}$, $Q=10^{-16}\mathrm{cm}^2$[7] and $p=1.7\times10^4\ \mathrm{kg/cm^2}$ which is calculated by applying the detonation velocity of Sakura dynamite, 2000 m/sec, to the H. Jones' equation, and substituting these values into equations (3) and (4), we can obtain $\sigma \fallingdotseq 8.6\times10^{-9}$ mho/cm. This calculated value of the electric conductivity is extremely smaller than those measured in the present experiments, and therefore it may be concluded that the electric conductivity in detonation gases depends not only upon the thermal ionization, but also upon the other phenomena. Other than the thermal ionization, the photo-ionization which is originated in the luminosity radiated from the detonation wave front may contribute to the electric conductivity in the ionized gases.

It is well known that whether detonation gases can be photo-ionized or not depends not only upon the magnitude of energy $h\nu$ which photons possess (h: the Planck's constant, ν: the frequency), but also upon the energy required in ionization eV_i (e: the charge of an electron, V_i: the ionization potential). That is to say, the photo-ionization can be generated if equation (5) holds true.

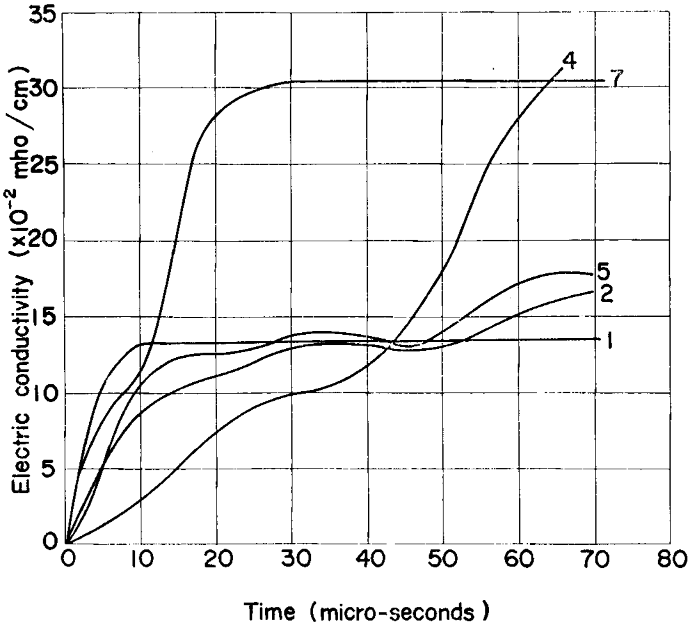
$$h\nu > eV_i \tag{5}$$

Now, substituting the values of constants into equation (5), equation (5) can be transformed as

$$\lambda < (12400/V_i)\ (\text{Å}) \tag{6}$$

where λ denotes the wave length of light. If $V_i=10\ \mathrm{V}$, equation (6) gives $\lambda<1240$Å, but it will be reasonable to consider that the value V_i is smaller than 10V because each molecule may be excited by the heat of reaction. Referring to this fact, the photo-ionization can occur when the wave length λ ranges from 2000Å to 3000Å which corresponds to the range of ultraviolet rays. Since we have not yet learned as to the wave length of the light radiated from the detonation wave front, we cannot discuss the phenomenon of the photo-ionization further.

The values of the electric conductivities obtained in the present experiments employing both the circuits (a) and (b) are approximately identical in spite of the difference in the values of currents and applied voltages across the probe. This may explain the following fact; that is, the "negative resistance" and the "discharge potential" phenomena which are generally accompanied with the ordinary electric discharge in gases do not appear in the detonation gases and the electric conductivity in the detonation gases can mostly be determined according to the state of the detonation. In Fig. 9 which illustrates the values of the electric conductivities as a function of time, we can observe that it takes from 10 micro-seconds to 20 micro-seconds after the initiation of the explosive for each electric conductivity to reach its average value. This time is supposed to correspond to the time



Note: Numbers set down on the curves correspond to the last figures of the test number in Table 3

Fig. 9. Electric conductivity versus time curve.

which Sakura dynamite requires to attain to the steady state detonation.

The values of the electric conductivities shown in Table 4 are appreciably smaller than those shown in Table 3, and this may be due to the fact that Sakura dynamite in the former case would be too short to attain completely to the steady state detonation. This can also be explained from the values of the detonation velocities shown in each Table. Moreover, because the reproducibility in the strict sense cannot be expected in the detonation phenomenon, and the experiments for measuring both the electromotive force and the electric conductivity have not been carried out simultaneously, the relationship betweem the electromotive force and the electric conductivity is not obvious at present. But from the results of the present experiments, it has been clarified that when we try to measure continuously the detonation velocity in a borehole along the detonated explosive by using the resistive electrode set up on the explosive, the electric disturbances such as mentioned above may be generated around the electrodes by the detonation gases.

4. Conclusions

The results obtained in this study can be summarized as follows.

Firstly, when such a probe as shown in Fig. 1 is employed, the electromotive force observed in the detonation gases produced by the detonation of Sakura dynamite is not induced by the electromagentic wave emitted from the detonation gases, but results from the contact of the probe with the detonation gases. These electromotive forces are generally observed in an oscillatory shape, their frequencies being from 50 kc/s to 200 kc/s, their maximum values ranging from 1 V to 2 V, and they generally appear in the negative signal against the ground.

Secondly, the values of the electric conductivities in detonation gases produced by the detonation of Sakura dynamite are in the range of 5×10^{-2} mho/cm to 30×10^{-2} mho/cm, and they may depend not only upon the heat of reaction but also closely upon the luminosity radiated from the shock zone. Moreover, it takes about from 10 micro-seconds to 20 micro-seconds for the electric conductivity attains to these values, and these times may correspond to the time which Sakura dynamite requires to accomplish its steady state detonation.

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