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ON THE SHOCK WAVE PRODUCED BY UNDERWATER EXPLOSION OF WIRE

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abstract

In the first place, the condition of the optimum wire-explosion under which stored energy of a given circuit is dischardged most rapidly and completely in one pulse, is obtained experimentally and formulated in connection with the length and sectional area of wire of a specified material for various values of capacitance, voltage and ringing frequency of circuit. Next, the propagation patterns of shock waves are studied by means of Schlieren photography using high speed framing camera (500,000 frames /sec), and the peak pressure of shock waves is determined from the measured shock velocities using the Hugoniot's curve for water. Further the amo unt of free forming of diaphragm installed near the wire is measured. The propagation patterns, peak pressure of shock waves and the deformation of diaphragms are compared for several cases containing optimum and non-optimum explosions. Finally, the similarity curve of propagation of peak pressure for various cases of optimum explosions is obtained. The relation between peak pressure and radial distance is found to depend solely on fr_0, where f is the ringing frequency of circuit and r_0 is the radius of wire. There results are confirmed to coincide qualitatively with theoretical conside rations.

1. Introduction.

Many investigations have been reported on the mechanisms of explosion of in gas,[1] and on the structures of generated shock waves. On the explosion of wire in liquid, however, there are reported comparatively less investigations and there still remain many ambiguous points in its fundamental mechanisms,[2][3][4][5][6] though this technique has come to be increasingly utilized as industrial processes such as forming of materials. Therefore, for the development of this technique, it is considered to be necessary to make more clear the fundamental mechanisms of the explosion of wire and the shock wave generation in liquid.

Characteristics of shock waves produced by wire explosion in liquid are known to be influenced by many parameters of the discharge circuit such as the capacitance C, the voltage V and the ringing frequency f together with the dimensions and the material of the wire.

The objective of this study is to investigate the inter-relations of these various quantities with a view of arriving at better understanding about the mechanisms of shock wave generation, particularly, of the phenomena taking place under the optimun condition of wire- explosion in which the stored energy of a given circuit discharges most rapidly and completely in one pulse. In the first place, the measurements are made for such characteristics as the time variation of the voltage across the wire V_R, the current I, and the optimum condition is determined from these results in connection with the length l and sectional area s of wire of a specified material for given values of C, V and f. Next, propagation patterns of shock waves are studied by means of Schlieren photography using the high speed framing camera (500,000 frames/sec), and the size of gas bubbles and the peak pressure of shock waves are thus determined. In these measurements, the peak pressure is calculated from the shock velocity by using the Hugoniot's curve for water. Furthermore, the amount of free forming of diaphragm installed near the wire are measured. The peak pressure of shock waves and the deformation of diaphragms are maximum in the case of optimum condition. Finally discussions about the measured characteristics of the shock pressure are presented on the basis of similarity considerations of the whole processes which include the wire explosion and shock wave generation.

2. Apparatus

2. 1 Discharge system

The exploding wire circuit consists of five condenser banks. Each bank has eight 5 μF capacitors and can be charged up to 30kV. It is discharged by actuating a triggerable vacuum switch which enables to deliver pulses at pre-selectable time delays of 10^{-6} to 10^{-4} sec. The minimum inductance of the discharge circuit is 0.73 μH. In the present experiments, four of the condenser banks are used for the exploding wire and another for light source synchronized with the high speed framing camera.

2. 2 High speed photography

Propagation patterns of shock waves are photographed by means of Schlieren method using the Nikon-Uemura's High Speed Framing Camera (500,000 frames/sec). Wire is exploded in a transparent plastic water tank as shown in Fig. 1(a). Fig. 2 shows the block diagram of the electrical and optical systems. The explosion of wire for light source precedes the wire explosion in water about 10 μsec.

2. 3 Free forming test of diaphragm

The set-up for measuring the deformation of diaphragm is shown in Fig. 3. Polished steel diaphragms of 1 mm thickness are clamped by two steel cylinders of 80 mm interior diameter and installed at the distance of 5 mm from the exploding wire.

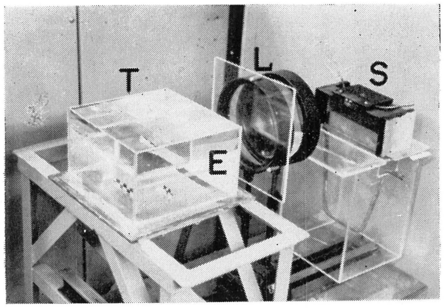


Fig. 1 (a) Water tank in which wire is exploded and optical apparatus. S; light source, L; field lens T; water tank, E; electrode.

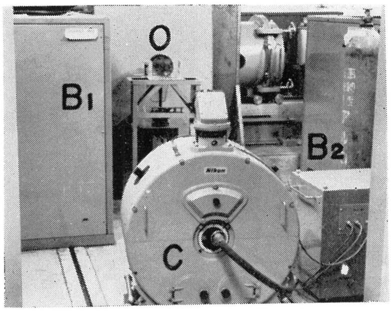


Fig. 1 (b) Exploding wire equipment and high-speed framing camera. B; condenser bank O; water tank and light source C; high speed framing camera.

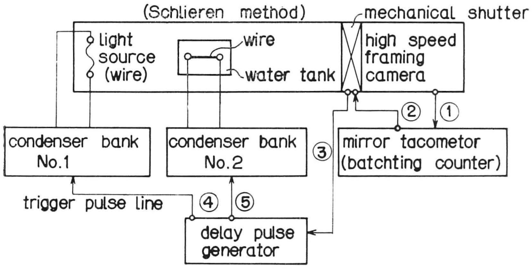


Fig. 2 Block diagram of electrical and optical system of measurement. (1 2 . . . 5, order of generating trigger pulses).

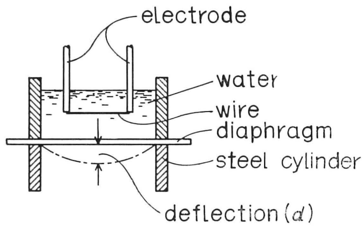
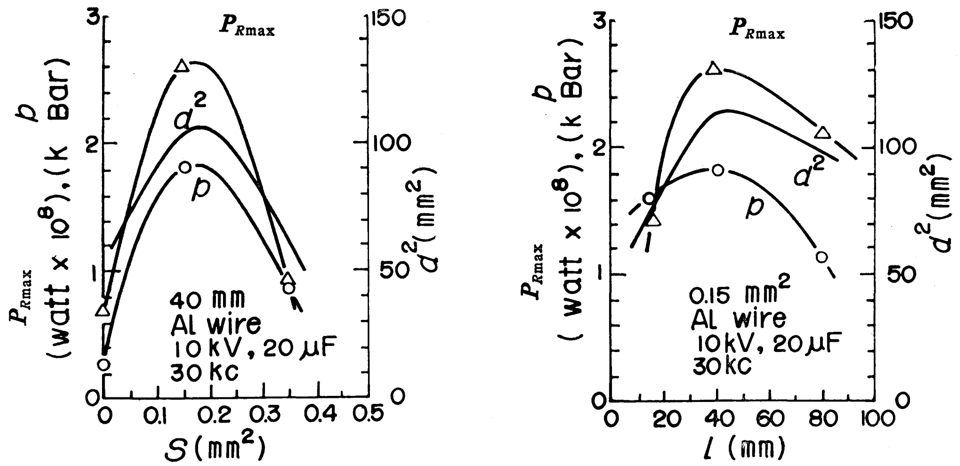


Fig. 3 Free forming of diaphragm in water.

3. Experimental Results

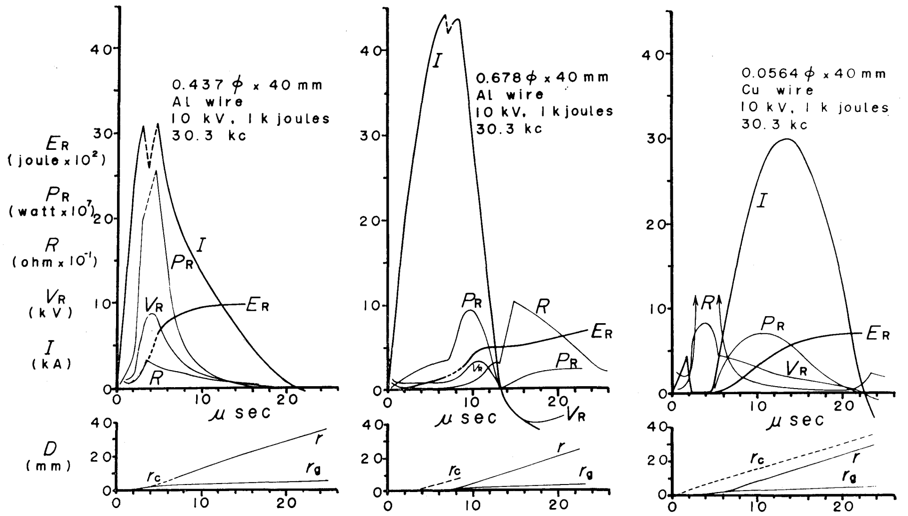
3. 1 Electrical characteristics and optimum condition of explosion

Fig. 4 (a) and 4(b) show the peak of electric power P_{Rmax} across the wire, the peak pressure p of shock waves (measured at the distance of 15 mm from wire), and the squared deformation d^2 of a steel diaphragm as functions of the sectional area s and the length l of wire respectively. The peak pressure p in these figure are calculated from the shock velocity by using the Hugoniot's curve for water. The optimum values of s and l which make the peak power P_{Rmax} maximum, also make p and d^2 maximum at the same time. We define this condition as the optimum condition of explosion. Fig. 5 (a), 5 (b) and 5 (c) show, for comparison, the voltage V_R across the wire, current I, power P_R, energy E_R, radius r_g of exploded gas and radius r of shock wave with respect to the following three cases, (a) s and l take the optimum values, (b) l remains the same but s is too large and (c) remains the same but s is too small. From the results of these experiments, we get the following conclusion on the electrical characteristics of wire explosion in water.



(a) (b)

Fig. 4 Peak power across wire P_{Rmax}, peak pressure of shock wave P and squared deflection of diaphragm d^2 as functions of s and l.



(a) Case of optimum dimension of wire (cf, Fig. 8).

(b) Case of too large sectional area of wire (cf, Fig. 9).

(c) Case of too small sectional area of wire (cf. Fig. 10).

Fig. 5 Time variation of resistive voltage V_R, current I, resistance R_R, resistive power P_R, energy discharged E_R, radius of exploded gas r_g and radius of cylindrical shock wave r.

1) Under the optimum condition which makes stored energy discharge most rapidly and completely in one pulse and evidently makes the peak value of electric power maximum, the peak of electric power and that of current are almost in the same phase. However, under non-optimum conditions such that s is too large or too small, there is considerable phase difference between them.

2) Under optimum condition, current dwell is absent. Also in the case of too large s, dwell is not observed, whereas in the case of too small s, there appeared a distinct dwell.

3) In the same manner as in F. D. Bennett's experiment,[7][8] R_{opt} the resistance of wire corresponding to the current peak in the optimum explosion is found to be given by

$$R_{opt} \doteqdot 1.14\sqrt{\frac{L}{C}} \qquad (1)$$

L being the inductance of circuit. Equation (1), however, yields increasing error when f becomes smaller than 20kc.

4) As shown in Fig. 6, when s and l are optimum, nominal energy density E/sl remain constant independently of fr_0, namely

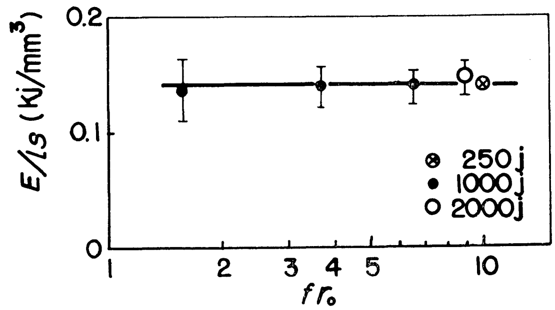


Fig. 6 Nominal energy density versus fr_0.

$$\left(\frac{E}{sl}\right)_{opt} \doteqdot \text{const.} \qquad (2)$$

where $E=\frac{1}{2}CV^2$. This fact can be substantiated also by the theoretical considera tions discussed later.

3. 2 Optimum values of sectional area s and length l of wires

Optimum values of s and l are evaluated from the results of measurements of peak values of electric power, peak pressure of shock waves and deformation of diaphragms. Fig. 7(a) and 7(c) show the relations among C, V and optimum s and l, and Fig. 7(b) and 7(d) those among f and optimum s and l. Curves in Fig. 7 may be approximated fairly well by the equations;

$$s=K_1CVf^{\alpha}, \qquad (3a)$$

$$l=K_2Vf^{-\alpha}, \qquad (3b)$$

where s is measured in mm², l in mm, C in farad, V in volt and f in cycles/sec. K_1 and K_2 are the constants depending only upon the properties of matter of wire as shown in Table 1, and $\alpha \doteqdot \frac{2}{3}$. It will be proved in the theoretical consideration to be stated later that the equations (3a) and (3b) can be derived theoretically together with equations (1) and (2).

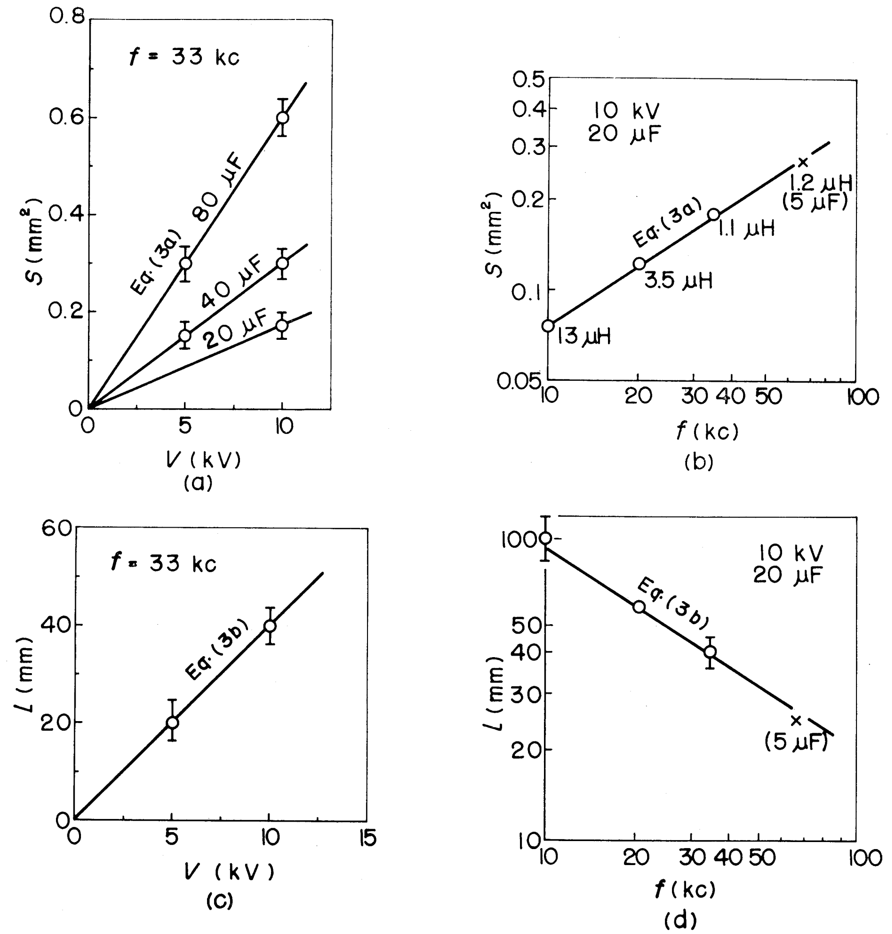


Fig. 7 Relations among optimum sectional area s, optimum length l of Al-wire, initial voltage V, capacitance C and ringing frequency f.

Table 1

wire	Ag	W	Cu	Al	Fe	Mg	fuse	Pb
n	5.1	6.15	7.2	8.2	8.7	10.3	25	31
$K_1=n\times10^{-4}$, $K_2\fallingdotseq4.3$								

3.3 High speed photographs of shock waves in water

Fig. 8(a) and 8(b) are the photographs showing the generation and propagation of the shock wave produced by the optimum explosion of wire. The time variations of the radius r_g of exploded gas and the radius r of shock wave have been given in the lower part of Fig. 5(a). Fig. 9 shows the similar photograph of shock wave produced by the explosion of the wire of the same length but larger diameter than that used in the optimum explosion. Fig. 10 shows also the motion of shock wave corresponding to the wire of same length but smaller diameter. The time variations of r_g and r in these cases are given in the lower part of Fig. 5(b) and 5(c) respectively. All of these photographs are taken under the same value of C, V and f of electric circuit. It should be mentioned here that in every cases shown in Fig. 8 through 10, there can be observed the generation of a comparatively weak wave preceding to the outbreak of shock wave due to explosion of wire. In the case of optimum explosion, however, the time interval between the generation of these two waves, i. e. the weak preceding wave and the dominant shock wave, is so short that they look as if one wave. But in the case when s is too large, the preceding weak wave is clearly observed. The pressure of the preceding wave is low and its velocity is nearly equal to the sound velocity, and it seems to have occurred at the instant when a portion of the wire vaporized. In the case where s is too small, the current dwell is observed and a weak shock wave is generated at the instant of the first peak of current, followed by a shock wave due to the restrike of current, and the propagation of the two different waves are clearly observed. In Fig. 5, r_c represents radius of this preceding wave. The peak pressure of shock wave produced by the optimum explosion is highest. In the case of too large s, explosion is not uniform along the wire and the peak pressure of shock wave is not so high. In the case of too small s, the peak pressures of the two waves are also low.

3. 4 Similarity curve of shock waves in water

The similarity in the propagation of cylindrical shock waves produced by the optimum explosion of wire is shown in Fig. 11 and Table 2. As clearly shown

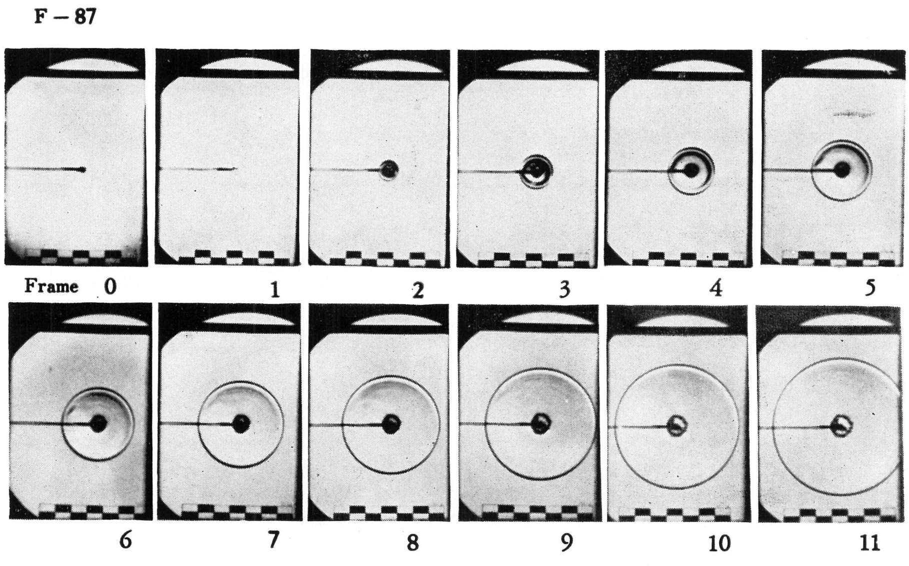


Fig. 8 (a) Framing camera pictures of shock wave produced by wire explosion in water, the case of optimum explosion, axial view, 1/5×. Initia voltage 10 kV, capacity 20 μF, 4×10^5 frames/sec, $0.437\phi\times40$ mm Al-wire.

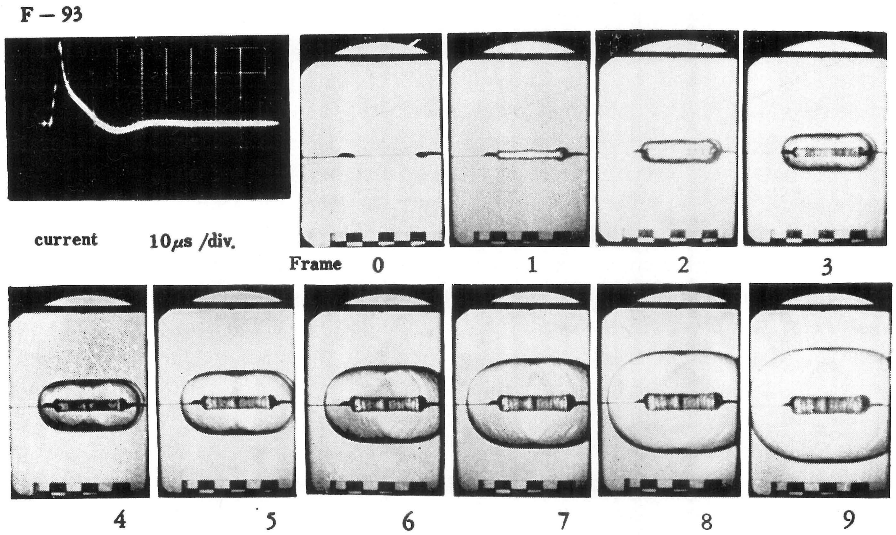


Fig. 8 (b) Framing camera pictures of shock wave produced by wire explosion in water, the case of optimum dimension of wire, side view, 1/5×. Initia voltage 10 kV, capacity 20μF, 4×10^5 frames/sec, 0.437$\phi\times$40 mm Al-wire.

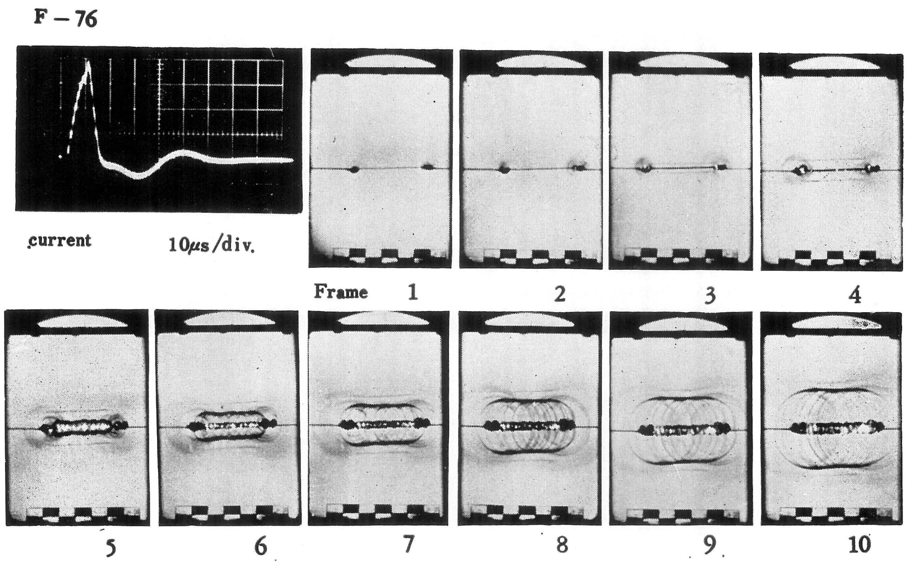


Fig. 9 Framing camera pictures of shock wave produced by wire explosion in water, the case of too large sectional area of wire. Initial voltage 10 kV, capacity 20 μF, 4×10^5 frames/sec, 0.678$\phi\times$40mm Al-wire.

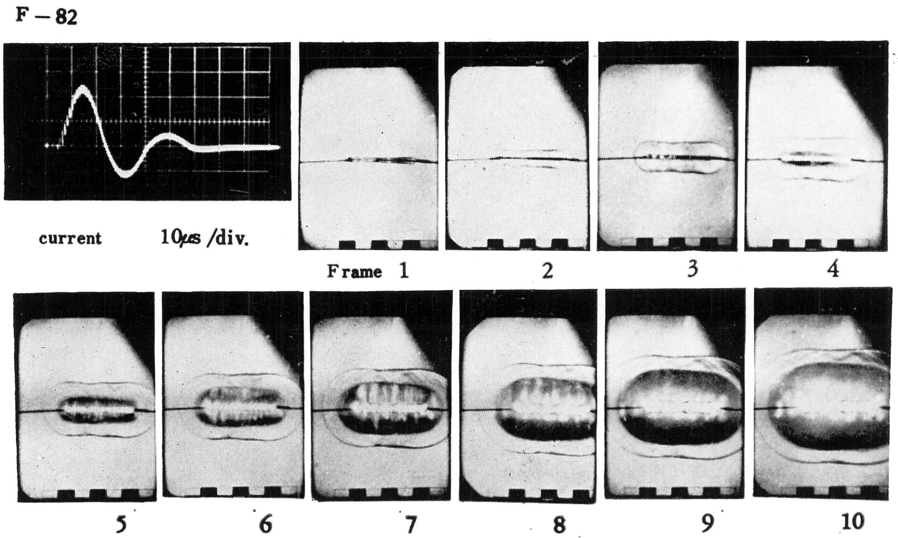


Fig. 10 Framing camera pictures of shock waves produced by wire explosion in water, the case of too small sectional area of wire. Initial voltage 10 kV, capacity 20 μF, 4×10^5 frames/sec, 0.0564$\phi \times$40 mm Cu-wire.

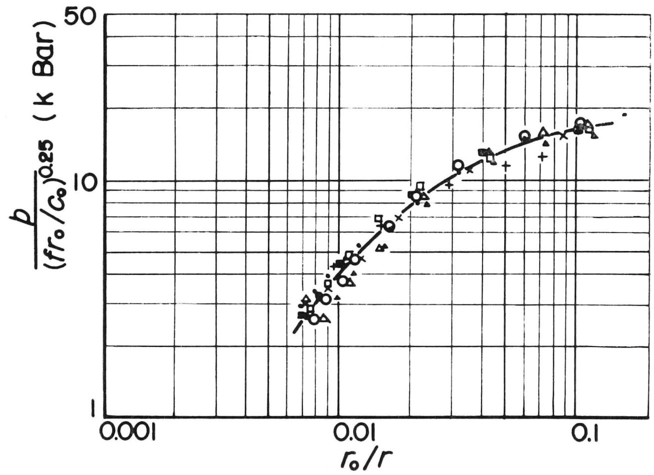


Fig. 11 Similarity curve of peak pressure.
r_0 ; initial radius of wire
r ; distance from center line of wire
C_0 ; sound velocity in water.

in Fig. 11, the relation between the peak pressure and the radial distance is found to depend solely on fr_0, where r_0 is radius of wire. In connection with this problem, theoretical considerations will be made in the next section.

Table 2

	No	E(kj)	V(kV)	C(μF)	f(kc)	r_0(mm)	fr_0
○	F-104	4.00	20	20	33.0	0.309	10.197
•	81	2.00	10	40	29.0	0.309	8.961
△	105	1.00	20	5	62.5	0.212	13.25
▲	102	1.00	14.1	10	46.0	0.226	10.396
□	93	1.00	10	20	30.3	0.219	6.6357
■	97	1.00	10	20	18.5	0.200	3.70
×	72	1.00	10	20	14.7	0.179	2.6313
+	100	0.25	10	5	62.5	0.149	9.3125

4. Theoretical Consideration

With a view of analyzing the wire explosion in dense medium, especially optimum explosion, several theoretical considerations are made. Since the details of them are reported in the other report,[6] only an outline of the theory will be presented here.

First of all, to simplify the theoretical treatment, the following idealizations will be introduced by taking the characteristics of explosion in such a medium of high density as water into consideration:

a) Electric current flows mainly through wire and ionized gas evaporated from the wire, and the short current passing through the surrounding medium is negligible.

b) The ionized gas is almost in a thermal equilibrium and the degree of ionization is low because of very high density of the gas.

c) The energy in the electric circuit is almost consumed in the stage of main discharge (restrike) and "dwell" of the current is absent in the optimum and nearly optimum explosion as is verified in our experiment.

Under these idealizations, we can derive the following equations which describe the process of explosion.

1) Circuit equation,

$$R_R I + \frac{1}{C}\int I dt + L\frac{dI}{dt} = 0, \qquad (4)$$

where R_R; electric resistance of wire,

I; electric current, C; condenser capacity,

L; inductance of circuit, t; time.

2) Equation of conservation of energy,

$$\int_0^t R_R I^2 dt = M(Q + C_v T) + \int_{r_0}^{r} p 2\pi r l dr + \int_0^t 2\pi r l \sigma T^4 dt, \qquad (5)$$

where M; mass of wire,

Q; factor including heat of fusion, heat of vaporization and energy of ionization,

C_v ; factor including various kinds of specific heat,

T ; Temperature of ionized gas, p ; pressure of ionized gas,

r, l ; radius and length of ionized gas, r_0 ; radius of wire,

σ ; constant of heat radiation from surface of gas.

3) Equilibrium equation of ionization (Saha's equation),

$$\frac{x_i^2}{1-x_i^2}p=2.4\times10^{-4}T^{\frac{5}{2}}\exp\left(-\frac{H_i}{kT}\right), \tag{6}$$

where x_i ; degree of ionization, H_i ; ionization energy,

k ; Boltzmann's constant.

4) Equation of state (Equation for ideal gas),

$$pv=R(1+x_i)T, \tag{7}$$

where v ; volume of gas per mol, R ; gas constant.

5) Equation for electric resistance,

$$R_R=\frac{V}{I}=\frac{l}{\pi r^2}\frac{q_e}{e^2}\frac{\sqrt{8mkT/\pi}}{x_i}, \tag{8}$$

where $q_e \doteqdot 1.157\times10^{-4}/T$ cm^2, e ; charge of electron,

m ; atomic weight of the material of wire.

6) Equation of the expansion of ionized gas,

$$r-r_0=\int_0^t u\ dt, \tag{9}$$

where u ; expansion velocity of surface of gas which is assumed to be equal to the particle velocity of shock waves determined from Hugoniot's curve for water.

By replacing variables, t, r and R_R in the foregoing equations (4) through (9) with the following normalized variables, τ, ξ and Ω,

$$\tau=\frac{t}{t_c}, \qquad (t_c=\pi\sqrt{LC}),$$

$$\xi=\frac{r}{r_0},$$

$$\Omega=\frac{R_R}{R_c}, \qquad \left(R_c=2\sqrt{\frac{L}{C}}\right),$$

we can readily see that the two parameters, i.e., nominal energy density $\rho(E)=\frac{1}{2}CV^2/\pi r_0^2 l$ and $\frac{t_c}{r_0}$, give parameters of similar solution of these equations. Namely various kinds of discharges in which these parameters take the same values can be described by the same solution expressed in the above-mentioned normarized variables.

Now we consider the condition under which the electric energy stored in the condenser is converted into the kinetic energy associated with the shock wave with maximum efficiency. This condition can be obtained as the extremum case by solving the system of equations (4)~(9). However we introduce here an approximate calculation, that is, we take mean values of the quantities I, R, T, p, x_i and r in the process of explosion instead of pursuing the time change of them, and denote the time duration of explosion by t_m. Then we assume here

$$t_m \simeq \frac{1}{2} t_c, \text{ and } R_{opt} \simeq R_c, \tag{10}$$

in the case of maximum efficiency from the reasoning stated below. At first, it is considered that all of the stored energy has to be discharged during one pulse of discharging current and the duration of the pulse to be short as far as possible in order to obtain maximum efficiency, and such condition is considered, from the circuit equation (4), to be realized when the state of circuit is nearly under the condition of critical damping. Then solving the system of equations (5) through (9) under the above assumption (10) instead of using (4), we obtain the following results. That is, the condition that makes the efficiency of transformation of electrical energy to the shock wave energy maximum is obtained by

$$\text{nominal energy density of wire: } \rho(\mathrm{E})_{max} = \frac{1}{2}\frac{CV^2}{sl} = F\left(\frac{t_c}{r_0}\right), \tag{11}$$

$$\text{nominal specific resistance of wire: } \sigma_{max} = R_{opt}\left(\frac{s}{l}\right) = G\left(\frac{t_c}{r_0}\right). \tag{12}$$

Here, F and G are the functions depending solely on $\left(\frac{t_c}{r_0}\right)$. Namely, the condition of maximum efficiency can be determined uniquely by the variable t_c/r_0. An example of numerical results is shown in Fig. 12 and Table 3. The results of calculation are no more than qualitative ones because of its approximate character, but we shall here compare them with our experimental results. At first, the condition of maximum efficiency deduced from the deformation of diaphragm is coincided with the measured optimum condition in I, $P_R \sim t$ curves, i. e., all of the electric energy is con sumed during one pulse of discharge within the range of our experimental conditions. The results seem to substantiate partially the assumption (10) in the above theory. However we may point out that the measured R_{opt} is proportional to but rather smaller than R_c as shown in (1), but the time of occuring of peak of electric power, which is close to

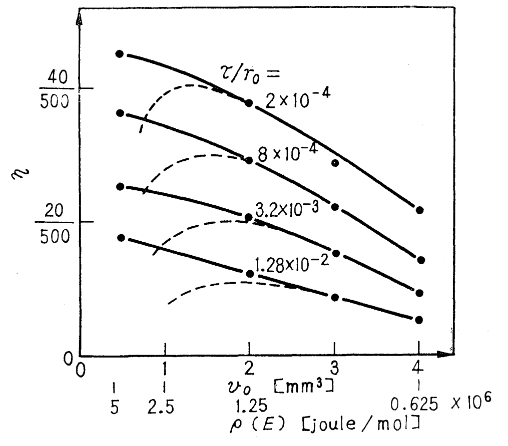


Fig. 12. An example of calculation on the relation between the efficiency η and the nominal energy density ρ (E). Material of the wire is Al. Solid lines are the calculated values when the radiation loss is not taken into account. Dotted lines are the cases where the radiation loss is approximately taken into account. V_0 is the volume of wire when the charged energy is 250 joule.

Table 3. Calculated values of the quantities in the case of ρ (E)=1.25×10⁶ joule/mol.

τ/r_0 [sec/cm]	T[°K]	p[Kbar]	x_1	r/r_0	u[m/sec]	σ_{opt}	$\eta\times500$
1.56×10^{-4}	40000	198	0.29	1.5	3200	18.9×10^{-4}	46.0
5.0×10^{-4}	34700	102	0.30	2	2000	11.1×10^{-4}	32.0
37.5×10^{-4}	29200	23.5	0.40	4	800	2.25×10^{-4}	20.4
$292.\times10^{-4}$	25200	5.8	0.53	8	240	0.46×10^{-4}	7.7

the time of outbreak of shock wave, is proportional to $\frac{1}{2}t_c$. Using equations (1), (11) and (12), we can obtain equations which are to be satisfied by the optimum values of l and r_0 under given C, V and f. From the numerical calculations as seen in Fig. 12, $F\left(\frac{t_c}{r_0}\right)$ is found to take a nearly constant value and to be almost independent for $\left(\frac{t_c}{r_0}\right)$. Hence the experimental results already mentioned in equation (2) is proved theoretically. Moreover the results of numerical calculation of $G\left(\frac{t_c}{r_0}\right)$ is found to coincide qualitatively with the experimental results, i. e., the equations (3a) and (3b) can be obtained from the equations (1) and (2) by approximating as $G\left(\frac{t_c}{r_0}\right)\propto\left(\frac{t_c}{r_0}\right)^{1-2\alpha}$.

5. Discussion

The relation between the conditions of discharge and the characteristics of shock waves has been evaluated by measuring the electric characteristics in the course of discharge as well as by carrying the optical measurements of generation and propagation of shock waves in water and measurements of deformation of diaphragms installed in the neighborhood of exploding wire. Furthermore, the results of experiments made on the optimum explosions have been submitted to theoretical considerations. In the case of optimum explosion where the stored energy is discharged most rapidly and completely in one pulse, both the peak pressure of shock wave and the deformation of the diaphragm show nearly the maximum values. However, it is not strictly correct to infer from our experiments that the efficiency of transformation of the electrical energy to mechanical energy is maximum in the case of optimum explosion. In other words, in order to evaluate a strict correspondence of the maximum deformation of diaphragm with the maximum conversion efficiency, we have to clarify first of all the structure of shock wave and then the mechanism of energy transfer by the collision of shock wave with the diaphragm and finally the interaction between the diaphragm and the slower fluid motion following to the collision of shock wave. Nevertheless, it seems justifiable to consider the two approximately equivalent for our present objectives aiming to obtain an outline knowledge on the process of underwater explosion of wire.

Next, in the theoretical considerations in the present report, the authors have attempted bold idealizations and assumptions on some phenomena. Although these seem to leave many problems to be considered in future, the experimental result that nominal energy density $\left(\frac{E}{sl}\right)_{opt}$ in the case of optimum explosion is almost constant, independently of ringing frequency f within the range of $f=10\sim80$kc, has been confirmed by the theoretical considerations. Moreover, a qualitative agreement between the theory and experiment has been obtained concerning the interrelations of optimum sectional area s and length l of wire and C, V and f as well as the similarity law on the propagation of shock waves produced by the optimum explosions. In these respects, the results obtained in this study can be said to clarify the functional relation of various factors participating in the optimum explosion of wire and generation and propagation of shock wave in water, and to give an outline of the whole process as a first approximation.

6. Summary

a) Under the optimum condition of explosion which makes stored energy discharge most rapidly and completely in one pulse and the peak value of electric power in the course of discharge maximum, the peak of electric power and that of current are in almost the same phase and current dwell is absent.

b) In the case of optimum explosion, nominal energy density of wire, i. e., stored energy per unit volume of wire, possesses almost constant value independently of ringing frequency f within the range $10\sim80$ kc. The optimum sectional area s and the length l of the wire can be determined by the following equations,

$$s=K_1\ CVf^{\alpha},\quad l=K_2Vf^{-\alpha},$$

where, K_1, K_2 are the constants determined from the material of wire and α is an experimental constant and is equal approximately to $\frac{2}{3}$. These relations agree qualitatively with the theoretical results.

c) In the case of optimum explosion, the peak pressure of shock wave shows the maximum value at a given distance (about half of wire length l) from the wire, and the deformation by free forming of diaphragm installed near the wire becomes maximum. The relation between peak pressure of shock wave and radial distance of prpagation depends only on a single parameter fr_0.

d) These experimental findings are explained theoretically based on the considerations of similarity of discharges, in which the similarity is predicted to depend on the two parameters, i.e., $\rho(\mathrm{E})=\frac{1}{2}\ CV^2/\pi r_0^2\ l$ and t_c/r_0 in general and particularly on the single parameter t_c/r_0 in the case of the optimum explosion.

e) In the case of too large sectional area of wire compared with that in the optimum case, the explosion dose not take place uniformly along the wire and the peak pressure of shock wave is low. In this case, a weak wave is generated in the instant when a portion of the wire vaporizes, followed by the outbreak of shock wave due to explosion. On the contrally, in the case of too small sectional area, the current dwell is observed and a weak shock wave is generated in the instant of first current peak and then the second shock wave due to restrike of current blows up. In both cases, the peak pressure is lower than that in the optimum explosion.

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