POWERFUL WATER–PLASMA EXPLOSIONS

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The experiments described in this letter form a continuation of previously outlined research on electrodynamic explosions in liquids. Current pulse amplitudes have been increased from hundreds of ampere to 25 kA. The most powerful explosion so far observed imparted an impulse of 7 N s to a metallic projectile of 1.6 kg mass. The strengths of the impulses scaled proportionally to the electrodynamic action integral. For an arbitrarily chosen current pulse shape and magnitude, the plasma explosion in saltwater is much more powerful than the action of a railgun.

Underwater electric arcs are known to cause strong explosions. They have been used for metal forming and deep-sea pulse echo sounding. In a previous investigation [1] it was shown that, with pulse current amplitudes of a few hundred ampere, the explosions were driven by electrodynamic forces and not by high-pressure steam. If the electrodynamic mechanism is also operative at large currents, the explosive force should scale with the square of the current.

In a new series of experiments the scaling law was investigated with pulse current amplitudes up to 25 kA. A technique was developed for measuring the mechanical impulse given by the explosion to a metal weight. Of the two electrode configurations previously studied, that is the water cup and the straight-through channel, the latter was chosen for the higher current because it could be made strong without having to face serious materials and mechanical design problems.

Fig. 1 shows the dielectric cartridge with copper electrodes of the straight-through channel arrangement. The body of the cartridge was a block of glass-fiber reinforced epoxy, known as G-10. Fiber-glass mats in the block resulted in a laminated structure which turned out to be a disadvantage. The $\frac{1}{2}$-inch-square copper bars were tightly fitted in a milled groove of the dielectric block and set flush with the upper surface of it. A $\frac{1}{2}$-inch-long butt-gap was left between the copper bars. This cavity was filled with the water in which the arc plasma was formed. Axial motion of the copper bars was prevented by four horizontal bolts passing through the bars and the dielectric block. A small dielectric plate (see fig. 2), of the same material as the cartridge body, was placed on top of the water-filled cavity. The metal weight to be accelerated by the explosion was put on top of the dielectric plate.

When the high-voltage capacitor bank C was discharged through the copper electrodes, as indicated on fig. 2, a bright arc plasma was formed in the water and completely filled the cavity W. This caused the explosion. Provided the cartridge was resting on a solid base, the metal weight would be thrown upward by the explosion. The vertical height through which it ascended was a measure of the impulse it received from the explosion. Fig.

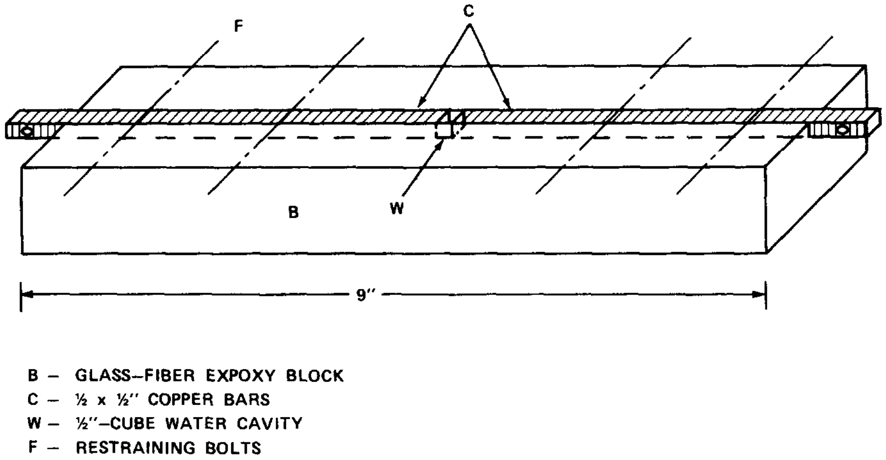

Fig. 1. Dielectric cartridge.

2 illustrates how this height was measured. The cartridge was placed on a sturdy porcelain stand-off insulator. A light wooden rod was attached to the metal weight. The rod passed through a hole in a stationary cross-bar. Two leaf springs were fixed to the top of the cross-bar. The springs permitted the upward motion of the rod, but gripped it firmly as soon as it tried to descend. The springs would actually hold the rod with the metal weight at the apex position for a subsequent measurement of h.

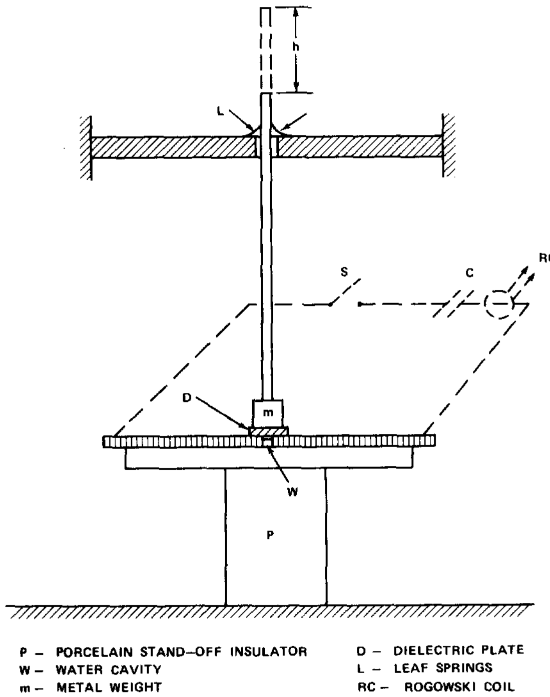

Fig. 2. Impulse measuring stand.

If the mass of the metal weight with rod and plate is m, the initial vertical velocity of the assembly is v_0, and the instantaneous lift force of the explosion is F, we have

$$\int_0^\infty F\,\mathrm{d}t = mv_0 = m\sqrt{2gh}\,, \tag{1}$$

where g is the acceleration due to gravity. Also shown on fig. 2 is the switch S, with which the previously charged capacitor bank was discharged, and a Rogowski coil RC for monitoring the current pulse.

Successive capacitor discharge shots at the same charging voltage, and therefore with nominally the same pulse current, did not lift the weight to the same height h. Time-constant variations recorded on the current oscillograms and the loud clap generated by the explosion left no doubt that a substantial fraction of the arc current was shunted from the water to surface flash-over in air. The air portion of the arc contributed little to the lift of the weight. This difficulty was largely overcome by machining a 1 mm deep, $\frac{1}{2}$-half-inch square plunger on the underside of the dielectric plate D of fig. 2. This plunger fitted in the water cavity and displaced much of the air which had caused the external flash-over. It was also found helpful to spread a layer of grease on top of the cartridge where it touched the dielectric plate.

The strength of any explosion was found to depend on the salinity of the water. The early experiments [1] were performed with NaCl-saturated water. It was also discovered in these low-current experiments that, in the absence of an arc plasma, quite strong electrolytic convection currents through the saltwater created no explosion at all. Some electrolytic conduction is likely to take place right at the start of any discharge current pulse before arc formation. It will subtract from the strength of the explosion. This offers an explanation for the fact that explosions in tap-water were nearly twice as strong as those in saturated saltwater. Distilled water seemed to escalate the explosion even further, but it was difficult to break it down with voltages up to 30 kV. A reduction in the strength of underwater arc explosions due to electrolytic current flow was also reported by Gilchrist and Crossland [2]. In spite of the loss in explosive strength, it was finally decided to carry out the main series of experiments with a saturated salt solution because this led to immediate breakdown when the switch S was closed and thereby minimized the risk of external flash-over.

A number of the experimental shots damaged the cartridge assembly. At the very high pressure generated in the explosion cavity, water would be driven between the copper bars and the cartridge material. In some cases this caused the bars to bend upward. More serious was de-lamination damage of the cartridge body. On one occasion a complete layer of the laminated structure was pushed sideways out of the block. Sooner or later the laminations would part and permit water to leak out of the cavity. This made frequent repair and even replacement of the cartridge necessary. The damage suffered by the cartridge testified to the fact that a significant part of the energy of the explosion was given up to destruction rather than the acceleration of the projectile.

Assuming the explosion to be driven by electrodynamic forces, the mechanical impulse imparted to the projectile should obey an equation of the form

$$\int_0^\infty F\,\mathrm{d}t = \frac{\mu_0}{4\pi} k \int_0^\infty i^2\,\mathrm{d}t, \tag{2}$$

where i is the instantaneous value of the pulse current, t is time, μ_0 the permeability of free space, and k is a dimensionless shape constant depending only on the layout of the circuit. If the force law governing the explosion is known, k may be calculated with the macroscopic current element analysis [3].

The underdamped discharge current pulse may be written

$$i = I_0\,\mathrm{e}^{-t/T} \sin \omega t, \tag{3}$$

where I_0 is the initial current amplitude, T the damping time constant, and $\omega = 2\pi f$ is the ringing frequency. In the previous letter [1] it has been shown that the action integral of (2) with eq. (3) is given by

$$\int_0^\infty i^2\,\mathrm{d}t = I_0^2\left(T/4 - \frac{1/T}{(2/T)^2 + (2\omega)^2}\right) \approx I_0^2 T/4. \tag{4}$$

I_0 and T may be read off the discharge oscillograms obtained with the Rogowski coil RC of fig. 2. With eq. (2) the shape constant K may be expressed as

$$k = \frac{4\pi}{\mu_0}\int_0^\infty F\,\mathrm{d}t\left(\int_0^\infty i^2\,\mathrm{d}t\right)^{-1}. \tag{5}$$

This is to say that k is an index, or figure of merit, of the strength of the explosion per unit action integral of the current pulse. For constant pulse shape and circuit layout, the figure of merit k should be constant. If for any given shot, in a series of identical shots, the measured value of k falls below this constant magnitude, it indicates that some inefficiency was at work. Inefficiencies of this nature do arise from air flashover, salinity differences, and water leaks.

Out of a series of 27 capacitor discharges, the results of the four most important shots are listed in table 1 and plotted on fig. 3. All four shots involved the full 8 μF capacitance of the bank. The charging voltage V was increased in steps of 5

Table 1
Experimental results.

Shot	C (μF)	V (kV)	I_0 (kA)	T (μs)	m (kg)	h (m)	$\int F\,dt$ (N s)	$I_0^2 T/4$ (A^2 s)	k	Remarks
20	8	15	12.7	65	0.977	0.123	1.52	2621	5799	old cartridge
25	8	20	16.9	65	0.977	0.508	3.08	4641	6637	new cartridge
26	8	25	21.2	65	0.977	0.950	4.21	7303	5765	new cartridge
27	8	30	25.4	65	1.597	0.975	6.98	10484	6658	new cartridge

kV from 15 to 30 kV. Shot 20 was the last reliable shot obtained with the first G-10 cartridge. Cumulative damage made subsequent shots with this cartridge unreliable. A new G-10 cartridge was then built, with the fiber-glass laminations vertical rather than horizontal. Shots 25 to 27 were the first three shots fired with the new cartridge. Shot 27 caused major water leaks, terminating the series of experiments.

As the nominal resistance of the water arcs was in the milliohm range, the initial current I_0 was determined by the surge impedance of the discharge circuit, or

$$I_0 = V/\sqrt{L/C}\,. \qquad (6)$$

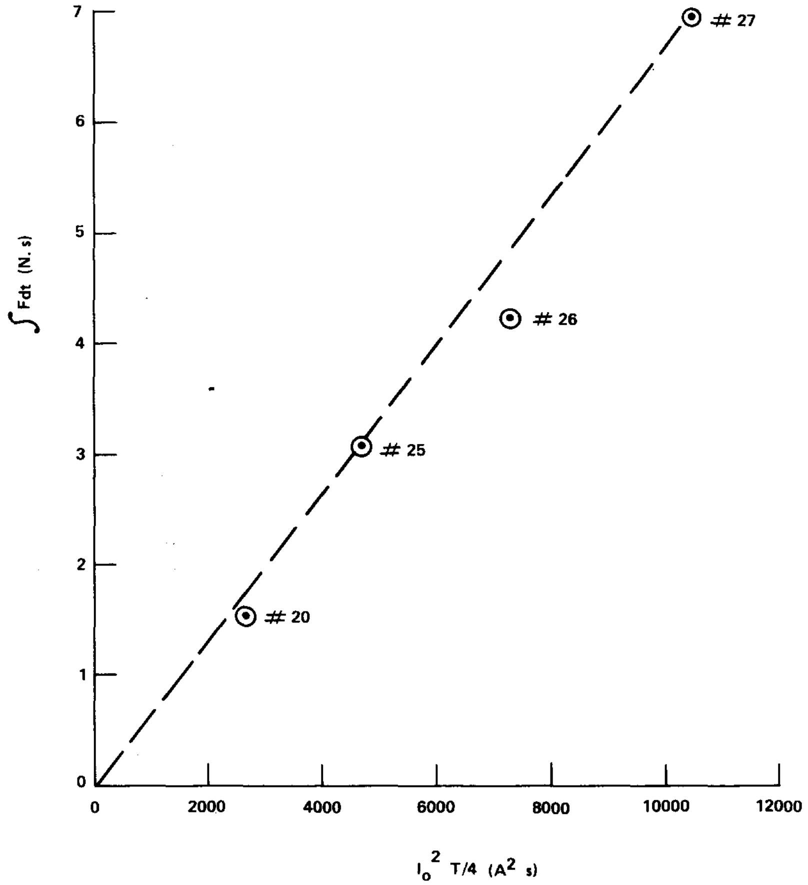

Fig. 3. Experimental results.

The circuit selfinductance L was derived from the ringing frequency recorded on the current pulse oscillograms. I_0 calculated with eq. (6) agreed well with measurements of the Rogowski coil. The time constant T did not vary with V so long as the capacitance C was kept constant. The oscillograms indicated a time constant of 65 μs. The k-values calculated for the four shots vary from 5765 to 6658. This nearly constant performance index suggested the apparatus was working close to maximum effectiveness as a projectile accelerator. It also provided evidence for the scaling of the force of the explosion with the action integral of the current pulse, as required for electrodynamic explosions.

To obtain an idea of the amount of energy that was supplied to the water arc of the most powerful shot 27, the cartridge was replaced by a solid copper bar of the length and cross section shown in fig. 1. When discharging 8 μF at 30 kV through the short circuit, a time constant $T_{sc} = 255$ μs was obtained. If R_{sc} is the short-circuit resistance of the capacitor discharge circuit, this may be equated to

$$R_{sc} = 2L/T_{sc}. \tag{7}$$

As before, $L = 11.1$ μH, because the selfinductance depends only on the geometry of the discharge circuit which was not changed by the short circuit. In this way it was found that $R_{sc} = 87$ mΩ. If we assign an "effective" resistance R_a to the water arc, which must allow for the back emf in the arc, then the total resistance in shot 27 must have been $R_a + R_{sc}$ which , with a time constant of 65 μs, comes to 342 mΩ. Hence by the difference, the effective water resistance was found to be 255 mΩ. The total energy stored in the capacitors and then dissipated in the circuit was

$$E = \tfrac{1}{2}CV^2. \tag{8}$$

For shot 27 this came to 3600 J. The fraction of this energy consumed in the water arc therefore should have been

$$\frac{R_a}{R_a + R_{sc}} E = 2684 \text{ J} = 642 \text{ cal}.$$

The $\frac{1}{2}$-inch-cube water volume is equal to 2 cm^3. The latent heat of evaporation of water is 529 cal/cm^3. Hence the energy deposited in the water was insufficient to evaporate it all, let alone superheat it to the required pressure.

The pressure accelerating the projectile may be estimated with eq. (2) and (4). Let us define an average acceleration force F_{av} for electrodynamic explosions as follows

$$\int_0^\infty F \, dt = \frac{\mu_0}{4\pi} \frac{kI_0^2 T}{4} = \frac{F_{av} T}{4}. \tag{9}$$

Therefore

$$F_{av} = (\mu_0/4\pi) k I_0^2. \tag{10}$$

In the case of shot 27 this average force was found to be no less than

$$F_{av} = 4.3 \times 10^5 \text{ N}.$$

When converting this figure to a pressure on the underside of the projectile it comes to 27000 atm. This explains why the cartridge was split.

Regardless of the force law governing the explosion [3,4], the water plasma cartridge may be treated as an electromagnetic accelerator with a high performance index k. Another – and perhaps the best known – electromagnetic accelerator is the railgun. Deis et al. [5] described experiments with one of the most powerful railguns so far built. It obeys eq. (5) and was found to have a performance index of $k = 5.85$. Coaxial accelerators [6] are known to be more effective than railguns. The induction accelerator is a special form of coaxial accelerator. It was first described by Bondaletov [7] who achieved with it a record performance index of $k = 2000$. The series of water plasma explosions described in this letter betters this by a factor of three.

References

[1] P. Graneau and P.N. Graneau, Appl. Phys. Lett. 46 (1985) 470.
[2] I. Gilchrist and B. Crossland, I.E.E. Conf. Publ. No. 38 (London, December 1967) p. 92.
[3] P. Graneau, Ampère–Neumann electrodynamics of metals (Hadronic Press, Nonantum, 1985).
[4] H. Aspden, Phys. Lett. A 111 (1986) 22.
[5] D.W. Deis, D,W. Schertbarth and G.L. Ferrentino, IEEE Trans. Magn. MAG-20 (1984) 245.
[6] H. Kolm and P. Mongeau, IEEE Trans. Magn. MAG-20 (1984) 227.
[7] V.N. Bondaletov, Sov. Phys. Technol. 12 (1967) No. 2.