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Generating High Voltage Pulses by Interrupting Current in an Inductive Circuit

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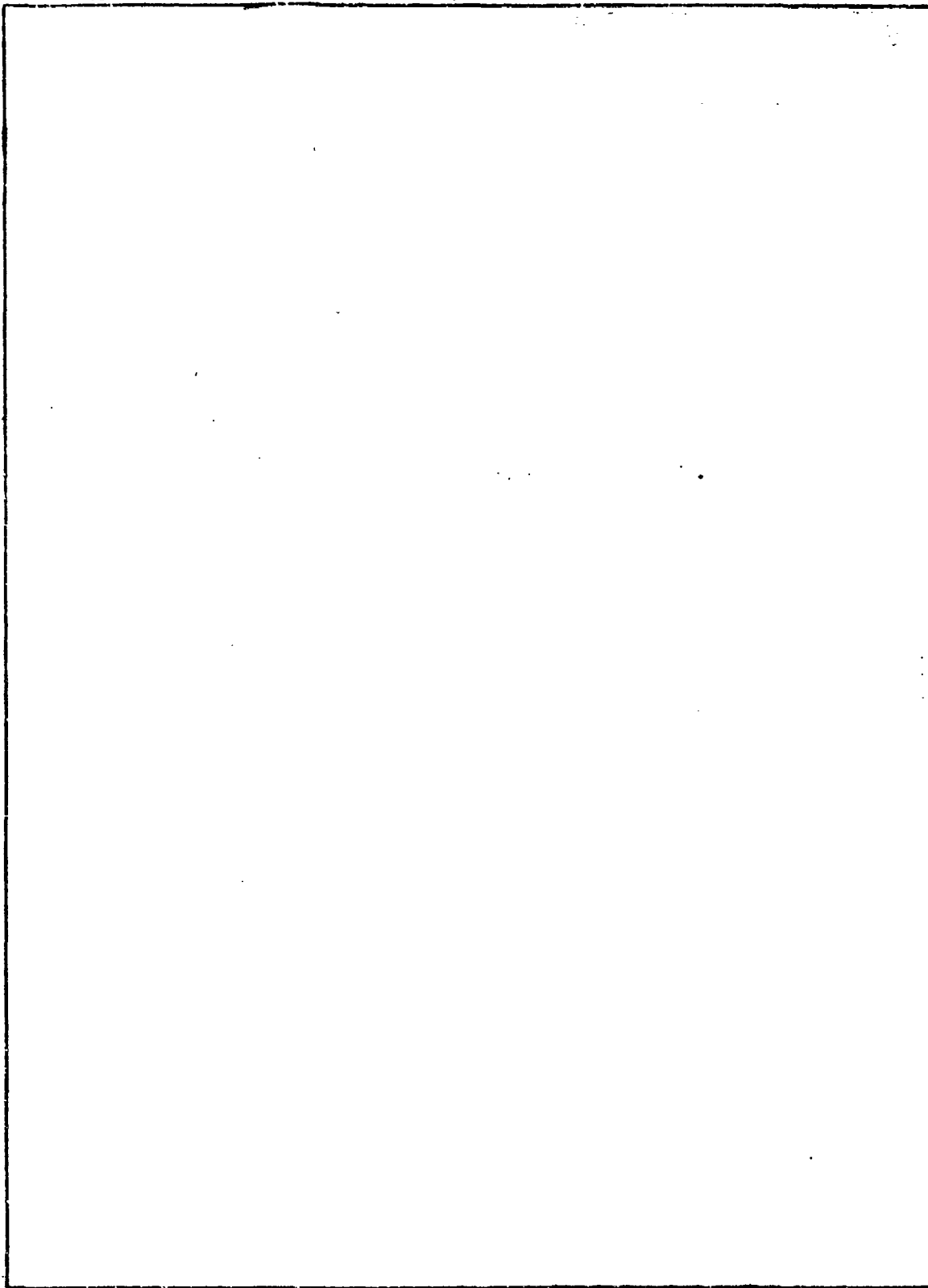
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18. SUPPLEMENTARY NOTES *M. Ury's present address is Fusion Systems Co., Rockville, Maryland.	19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Inductive store Opening switch High power	20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A new approach to the problem of developing an opening switch for inductive systems is described. The switch (fuse) consists of a thin aluminum foil immersed in water. Heat transfer processes and chemical reactions between the Al and water determine switch performance. Six kilojoules of electrical energy was handled by the switch and voltages of up to 100 kV were generated across the switch electrodes.

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GENERATING HIGH VOLTAGE PULSES BY INTERRUPTING
CURRENT IN AN INDUCTIVE CIRCUIT

Possible needs for high power electrical pulses with energy greater than 10 MJ¹ lead to a re-examination of the concept of inductive storage systems.² In such systems, electrical energy is stored efficiently in an inductor, L, through which current is flowing. The energy is switched into a load by opening a switch in series with the inductor. This causes an interruption in current and therefore a voltage is generated across the switch. A switch must be able to withstand very high inductive voltages to rapidly "discharge" a large inductive energy store. A possible opening switch commonly employed consists of a metallic wire or foil type fuse. When sufficient electrical energy is dissipated in the fuse, it explodes and the resistance can increase by orders of magnitude. This change in the electrical properties of the fuse causes the desired current discontinuity. When a capacitor bank is used to "charge" an inductive store the relative performance of a switch can be measured by a quality factor α which includes the relevant parameters of interest:

$$\alpha = \frac{t_c}{\sqrt{T_{1/2} \left(\frac{L}{R_m} \right)}} \quad (1)$$

Note: Manuscript submitted July 7, 1978.

where t_c is the charging time of the inductor prior to fuse explosion, $T_{1/2}$ is the width of the resultant voltage pulse, and R_m is the resistance of the switch at the maximum voltage. A value of α as high as 10 has been reported, but only at output voltages of 12 kV.³

We report here on an improved opening switch. Values of $\alpha \geq 30$ were obtained and voltages of 100 kV generated across the opened switch. Figure 1 shows the experimental arrangement. A capacitor bank, $C = 300 \mu\text{F}$, was connected to either a 12, 250 or 400 μH inductor, L . A metallic foil or fuse, immersed in a demineralized water bath, completed the electrical circuit. A Rogovsky coil and a resistive divider measured the current flowing in the system and the voltage developed across the foil. Aluminum foils of various length, l , thickness, δ , and width, w , were used. In addition, Mg, Ag, Au, Cu, and Ta foils were also used. Figure 2 shows typical current and voltage traces for a reasonably optimal choice of Al foil.

Since α depends on R_m it is obvious that a greater value of l gives larger values of R_m and α . For example, Fig. 3 shows the dependence of α on l . Figure 4 gives the current, voltage, resistance and power dissipation as a function of time for two values of $L(V_0 \approx 6.6 \text{ kV})$. The performance of different materials used as a switch foil was judged from the value of α and was found to be: Al, Mg, Ag, Au, and Ta (in a descending order).

Four different Al foils with the same cross-sectional area were tested. Each of them had a different width and thickness. Figure 5 shows the voltage developed along each of these fuses. When a very wide

foil was used (Fig. 5a) the fuse never reached high values of resistance and voltage. When the foil resembled a wire (Fig. 5b) the resistance reached initially a high value but immediately dropped (restrike). When foils used were of width which fell between the previous two extremes (Fig. 5c and 5d), resistance and voltage reached and maintained high values.

The switch performance was improved when hydrogen peroxide (H_2O_2) was added to the water immersing the switch. For example an increase in voltage by a factor of two was observed when 70% H_2O_2 was used.

Relationships developed by Maisonnier, et al.⁴ for the condition of foil vaporization at peak current, define a foil cross-sectional area, s , as:

$$s = w\delta = \left(\frac{\left(\frac{1}{2} CV_0^2 \right)^{3/2}}{V_0 L^{1/2} k_1 a} \right)^{1/2}, \quad (2)$$

where a is a constant characteristic of the material of the foil and $1 < k_1 < 3$. Reference (4) does not explain the behavior of the fuse after vaporization, especially the time behavior of the resistance. The experimental results described earlier suggest that mechanisms other than ohmic heating may play an important role when a metallic foil is exploded under water. We speculate that two processes in addition to the ohmic heating have to be considered: (1) a heat loss from the foil to the water and (2) a chemical reaction between the material of the fuse and the water. In that case the internal energy of the foil, e , is governed

b) an equation of the form

$$m \frac{de}{dt} \approx q_1 + q_2 - q_3, \quad (3)$$

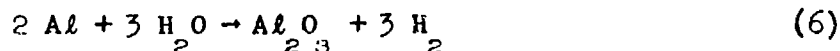
where q_1 is the rate of ohmic heating

$$q_1 = I^2 \frac{\rho(T)l}{w\delta}, \quad (4)$$

$\rho(T)$ is the resistivity of the foil at temperature T , q_2 is the rate of chemical heating and is proportional to

$$q_2 \sim w\ell T^{1/2} \exp(-A/T). \quad (5)$$

This dependence was obtained from kinetic theory. The parameter A depends on the threshold temperature of the reaction. For example the threshold temperature of the reaction



is about $700^\circ C$.⁵ The chemical reaction rate of energy gain, q_2 , depends on the energy released by the chemical reaction. The higher the energy released the larger q_2 is. The interaction described by Eq. (6) gives 15 kJ/gm. Less energy is released when Mg, Cu, Ag, and Au are used (in a descending order). The quantity q_3 (Eq. 4) is the rate of heat loss to water and is given approximately by

$$q_3 \approx \lambda \frac{dm}{dt} \approx \lambda 2 \rho_d w \ell V_s, \quad (7)$$

where λ is the heat of vaporization of water, m_p is the mass of water vaporized, ρ_d is the density of water and V_s is the escape velocity of steam bubbles from the foil. If one assumes that the force which ejects the steam bubbles from the foil depends on gas pressure within the bubble and that only viscous forces oppose the motion of the bubbles in the liquid then $V_s \sim T$ or $q_3 \sim w\lambda T$.

Each of the above processes can be predominant during different times of the current cycle. At the initial stage when R and I both increase with time $q_1 > q_3$ and $q_2 \approx 0$. At a certain time the current does not change very much and the resistance stays constant (although the temperature of the foil increases). Since $q_3 \sim w\lambda T$ it is possible by choosing a large w (and a small δ) to increase q_3 without changing q_1 and to have $q_3 \approx q_1$. This will define an "equilibrium" temperature, T_1 . If T_1 is below the temperature of foil vaporization and $q_2 \approx 0$ no explosion will occur and the energy in the inductive store will dissipate gently into the water (Fig. 5a). If T_1 is above the ignition point of the chemical reaction then $q_2 > 0$. In that case the temperature of the fuse will increase. Since $q_2 \sim w\lambda \sqrt{T}$ and $q_3 \sim w\lambda T$ (for large T) the foil will reach an "equilibrium" temperature T_2 for which $q_1 + q_2 \approx q_3$. If T_2 is below the temperature for which ionization occurs the foil will change its characteristics from a conductor (e.g. Al) to an insulator (e.g. Al_2O_3) and a successful switching will occur (Fig. 5c and 5d). If w is small so that q_3 is always smaller than q_1 the temperature of the fuse will increase to a value for which ionization may start (Fig. 5b).

In order to convert the conductor to an insulator as fast as possible, the chemical reaction has to rapidly supply a lot of energy. The

amount of energy released depends on the material of the fuse. The ranking of such materials (based on the chemical reaction released) is Al, Mg, Cu, Ag and Au (in a descending order). This is exactly the same ranking obtained experimentally based on the switch quality factor α .¹¹ Moreover, by using Al foil immersed in H_2O more chemical energy can be released with an improved switch performance.

In summary, experiments have shown that thin Al foils immersed in water have improved characteristics as fuses in an inductive circuit. The improvement may possibly be due to the process of heat losses through the water bath, and a chemical reaction of the Al foil with water.

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6. The quality factors α for Al, Mg, Cu, Ag, and Au were 40:20:10:8:7
 respectively and were obtained under the same conditions ($V_0 =$
 6.6 kV, $L = 12 \mu\text{H}$, $l = 25 \text{ cm}$).

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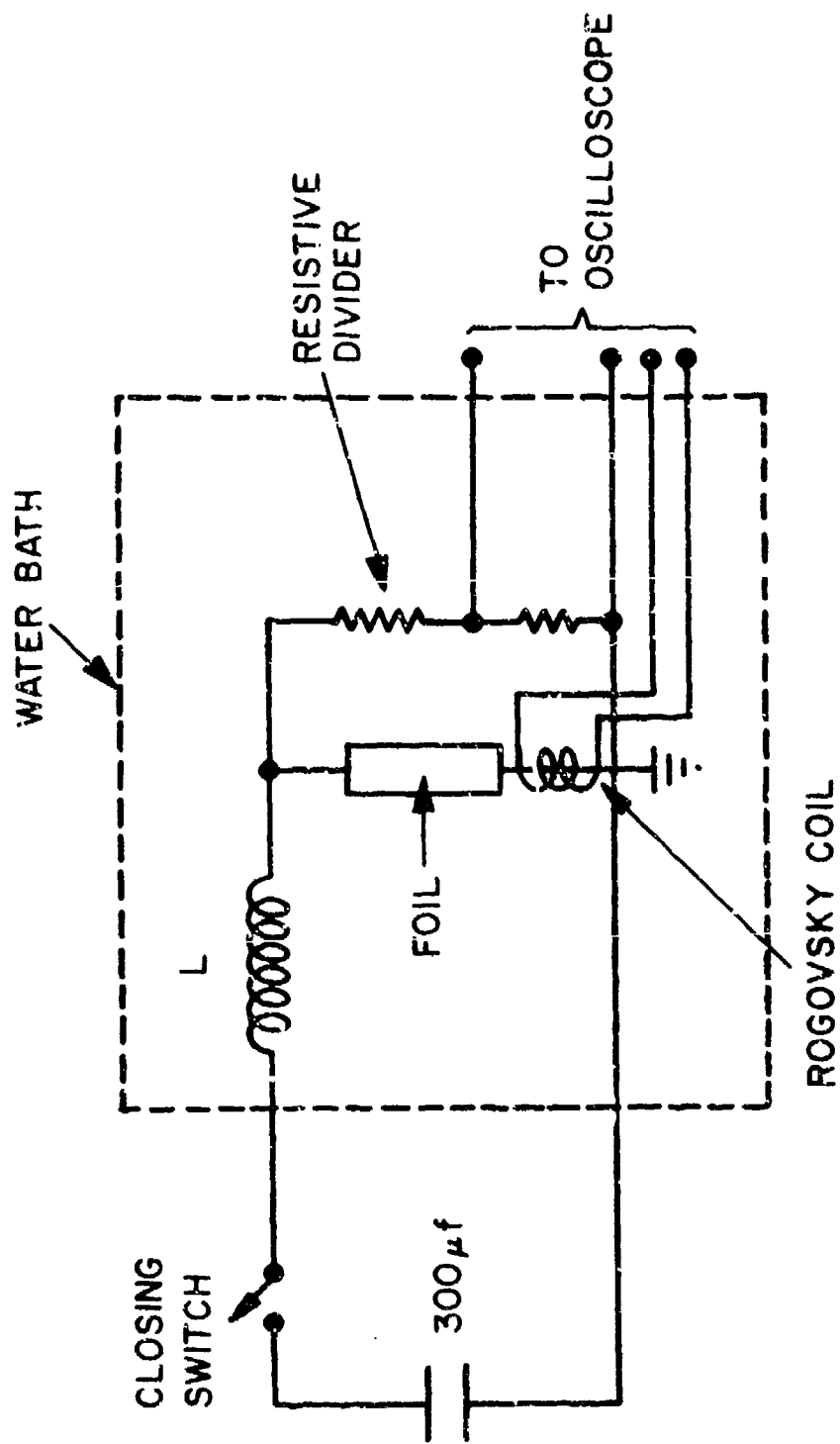


Fig. 1 — Experimental schematic

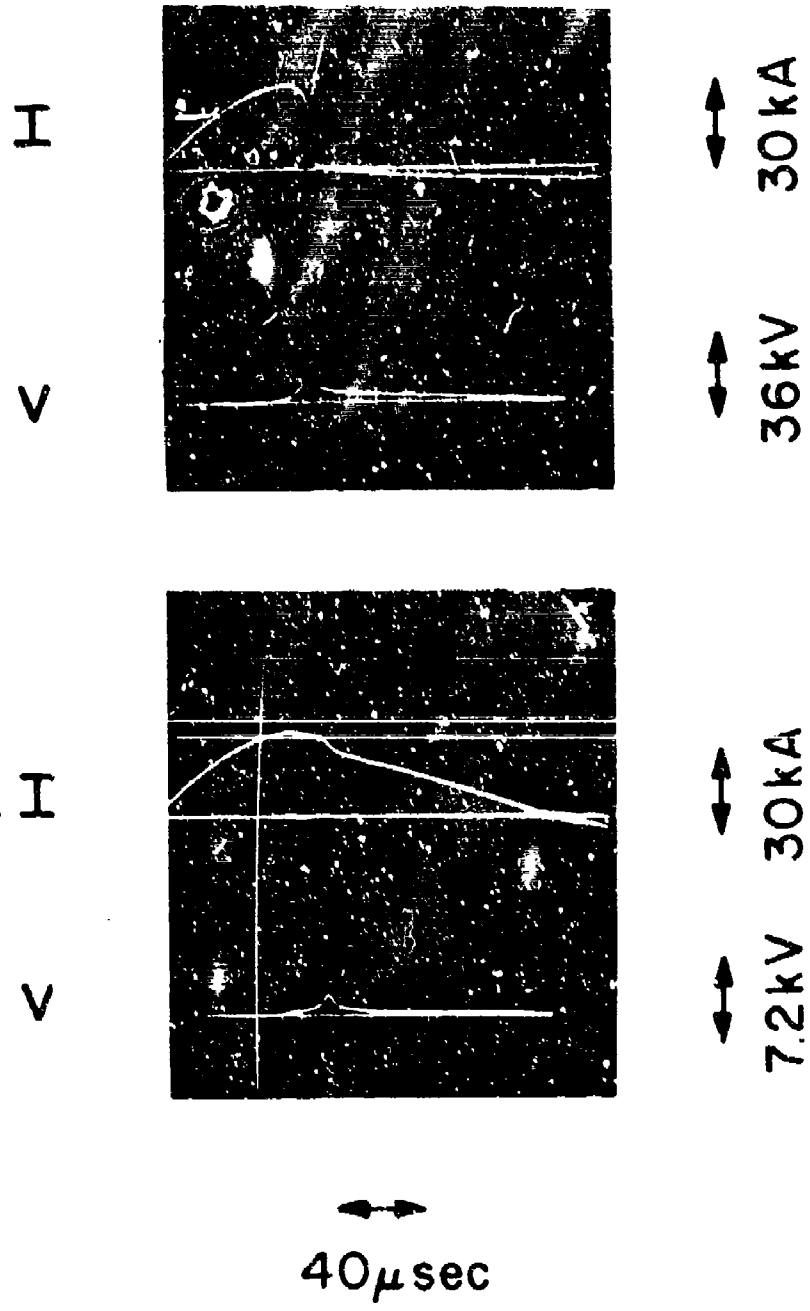


Fig. 2 — Traces of the current flowing through the system and the voltage developed along the switch for Al foil in water (top) and in air (bottom) [$l = 25$ cm, $\delta = 2.5 \times 10^{-3}$ and $w = 2.5$ cm]. The inductance L was 12 μ H and the voltage on the capacitor bank, V_0 , was 6.6 kV.

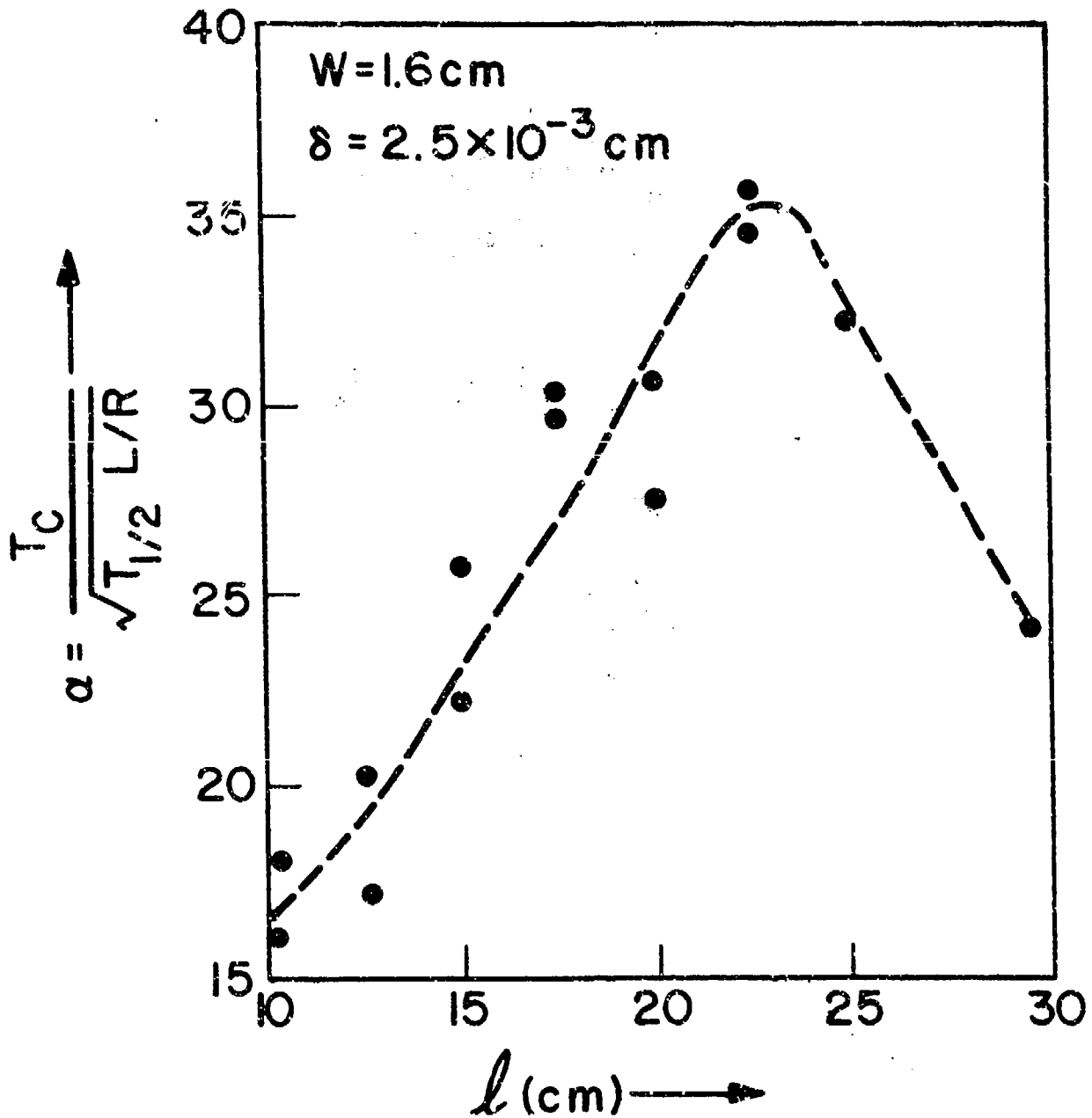


Fig. 3 - The dependence of α on the length of the Al foil

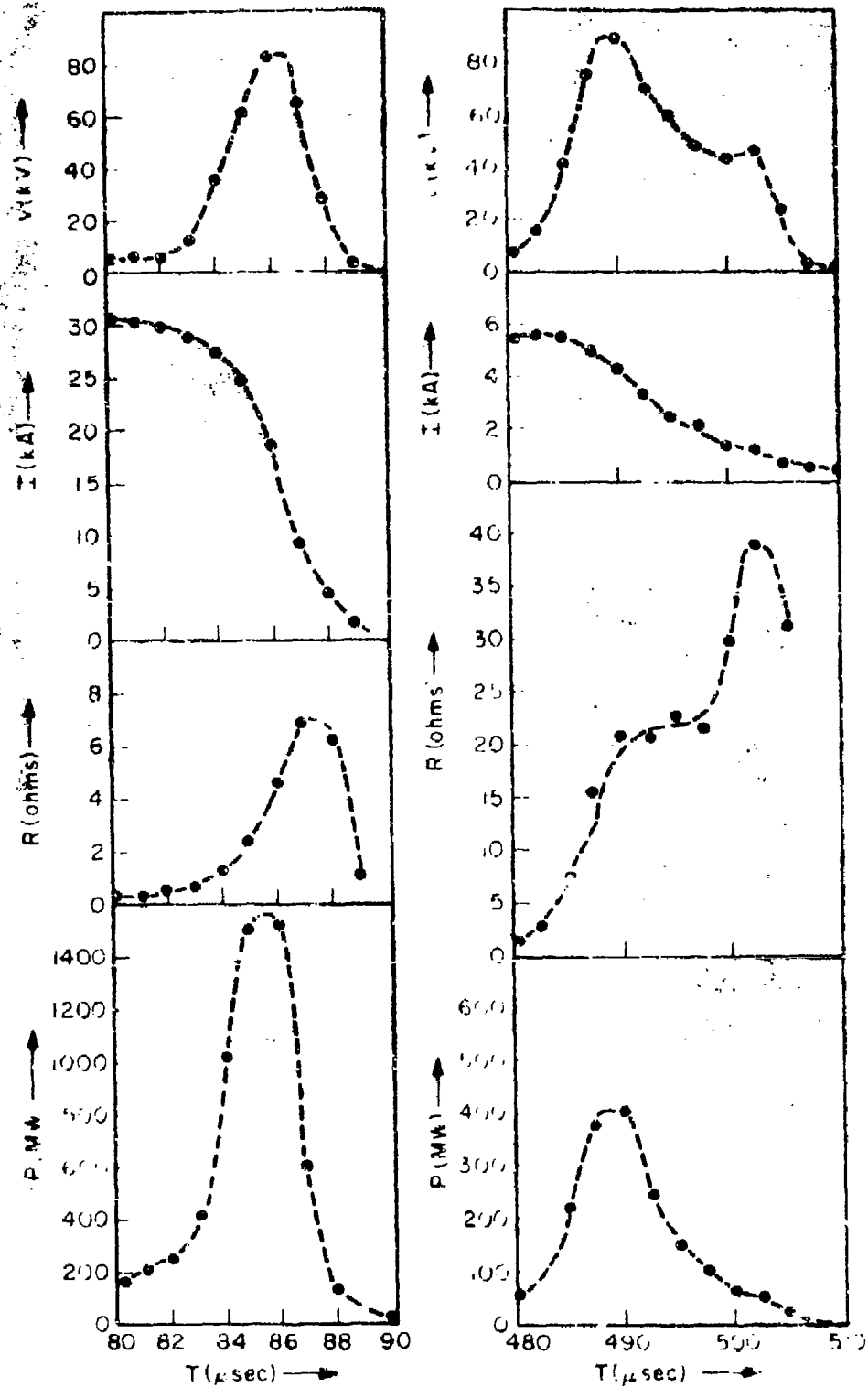
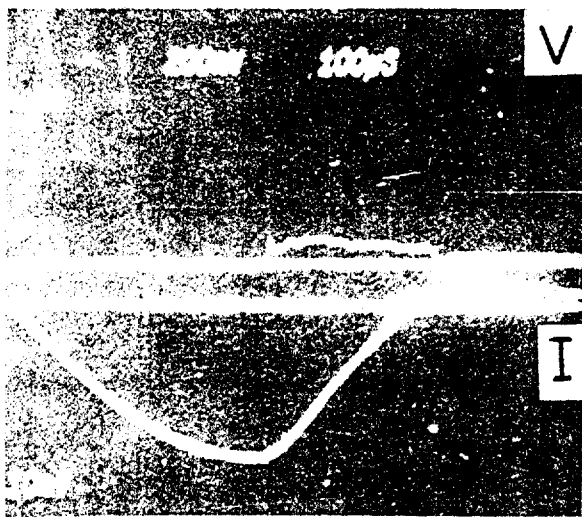
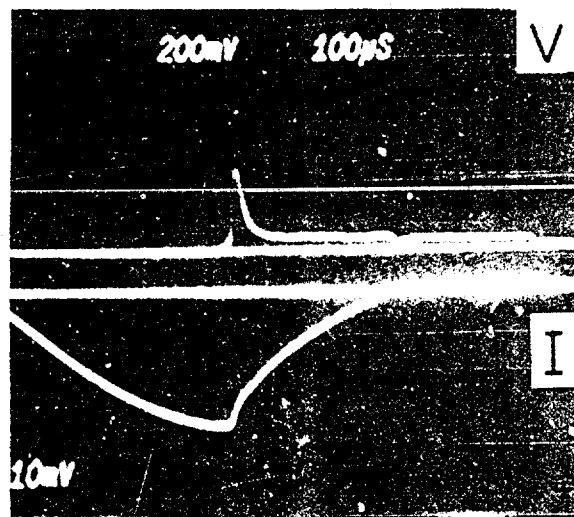


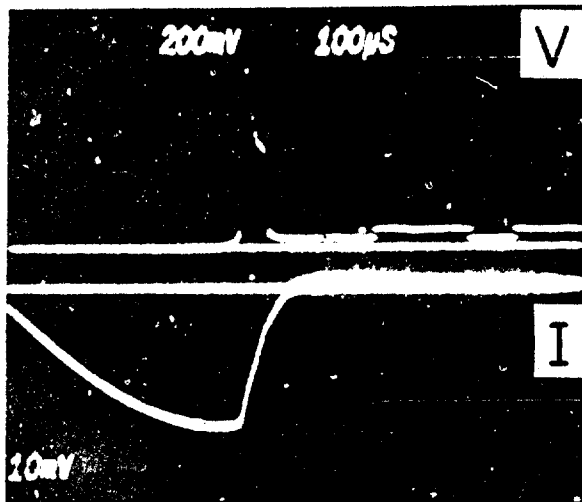
Fig. 4 - Voltage, current, resistance and power vs time for [these results were obtained using A₂] (1) (left) $L = 12 \mu\text{H}$; $V_0 = 6.6 \text{ kV}$; $w = 2.5 \text{ cm}$; $\delta = 2.5 \times 10^{-3} \text{ cm}$; $l = 22.5 \text{ cm}$ and (2) (right) $L = 400 \mu\text{H}$; $V_0 = 6.6 \text{ kV}$; $w = 1.6 \text{ cm}$; $\delta = 0.5 \times 10^{-3} \text{ cm}$; $l = 83 \text{ cm}$



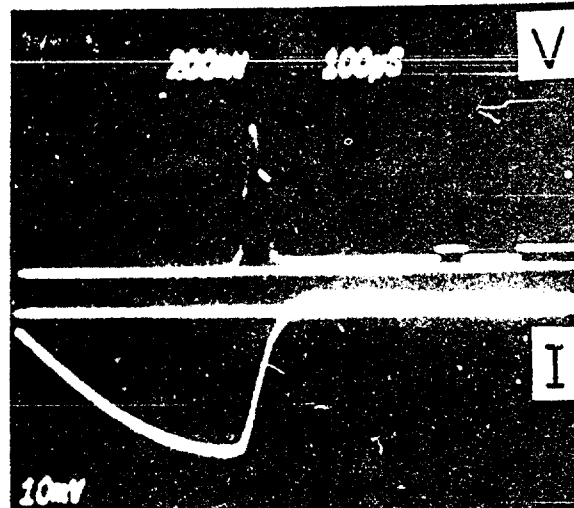
(a)



(b)



(c)



(d)



 500 μsec

Fig. 5 — Traces of the current flowing through the system and the voltage that developed along the Al foil in water

(a) $l = 37$ cm, $w = 7.8$ cm, $\delta \approx 0.5 \times 10^{-3}$ cm

(b) $l = 37$ cm, $w = 0.4$ cm, $\delta \approx 9.4 \times 10^{-3}$ cm

(c) $l = 37$ cm, $w = 1.5$ cm, $\delta \approx 2.5 \times 10^{-3}$ cm

(d) $l = 37$ cm, $w = 2.1$ cm, $\delta \approx 1.8 \times 10^{-3}$ cm.

The traces were obtained for $L \approx 250$ μ H and $V_0 = 6.6$ kV.