# Electrical Explosion of Metal Wires

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(Submitted to JETP editor Sept. 8, 1954)

J. Exper. Theoret. Phys. USSR 30, 42-53 (January 1956)

Shadow photography and oscillograms of the current and voltage are used to investigate wires exploded by electric current. It is shown that the energy liberated in the wire at the instant of the first current pulse is sometimes less than the energy needed to evaporate the wire fully, and sometimes considerably more. Shadow photographs of the successive stages of wire explosion show a strong dispersion of the wire material after the flow of the first current pulse. A qualitative explanation is given for the basic features of the wire explosion phenomenon, taking into account the high mechanical stresses produced by heating and the radial pressures due to the magnetic field produced by the current.

## 1. INTRODUCTION

THE flow of a large current pulse through a thin wire results in its explosion, owing to its almost instantaneous evaporation. This phenomenon, called electric explosion, is of interest in many respects. Experiments with pulsed currents show that Ohm's law holds at current densities up to approximately $10^8$ a/cm$^2$ [1-6]. Electric explosion of a wire is accompanied by a flash of light of high brightness and very rich in ultraviolet. In many investigations this was used to study the spectra of various metals and to produce pulsed sources of light.[7-11] Within a time interval of the order of a microsecond, enough energy is received to melt and completely evaporate the wire; in view of the short duration of the process, deviations from the ordinary course of melting and evaporation are to be expected[12,13].

Owing to the almost instantaneous heating and corresponding thermal expansion, the wire is subject to very high mechanical stresses during the explosion process. This makes it possible to investigate the properties of the wire under shock compression conditions[14].

Rupture in water or other liquids causes intense dispersion of the wire material. High degrees of dispersion can be obtained, depending on the power of the explosion. Powerful ruptures are accompanied by shock waves, which lead to strong cavitation in the liquid (see below).

Explosion of a wire in vacuum produces supersonic hydrodynamic streams with which it is probably possible to produce molecular beams denser than usual. Such beams can be used to study how one beam interacts with another, or how the beams interact with surfaces of bodies, with beams of charged particles, with electric and magnetic fields, etc. Electric explosion of wire can be used to produce films of certain metals without the use of crucibles or other means of liquefying the metal.

Wire explosion can be used in the laboratory to produce high temperatures at relatively high densities of matter. Ruptures in air and in vacuum do not make it possible to attain a temperature higher than 30,000 °K,[7-8] owing to the so-called discharge-pause phenomenon and to the possible formation of shunting discharges. However, it is possible to obtain a temperature of 100,000 °K and higher if the wire is exploded in a liquid or solid medium (see below).

This phenomenon can also be used to investigate certain properties of explosion under conditions of infinite detonation velocity. The explosion starts simultaneously at all points of the wire. In this case the quantity of exploded matter, explosion time, total explosion energy etc. can all be readily controlled.

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The electric explosion phenomenon is thus related to many interesting problems. Nevertheless, the phenomenon has not yet been thoroughly studied. We approach the investigation of the electric explosion of wires from two points of view; one involving a study of the energy balance of explosions in various surrounding media (air, water, solid insulator) and the other involving a study of the external appearance of the wire at various stages of the explosion. The former uses oscillographs of the explosion made with a two-beam driven-sweep oscillograph capable of recording voltage and current simultaneously. The latter employs shadow photographs made with a spark synchronized with various stages of the explosion.

## 2. MEASUREMENT PROCEDURE

The principal diagram of the setup for simultaneous oscillography of the explosion and shadow photography of the exploding wire is shown in Fig. 1. The setup consists of three interconnected parts: explosion circuit, spark circuit for shadow

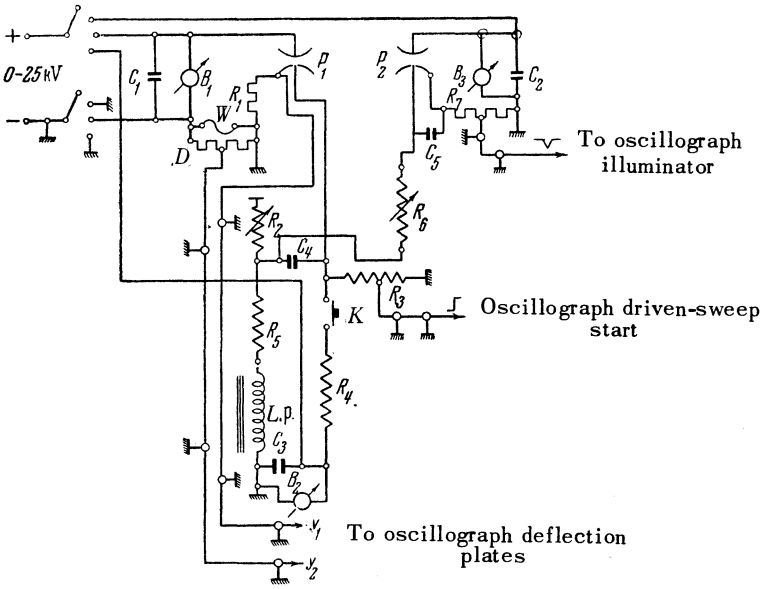


FIG. 1. Principal diagram of installation.

photography, and a circuit to trigger the discharges in the first and second circuits. The explosion circuit consists of capacitor $C_1$, discharge gap $P_1$ with starting electrode, noninductive current-measuring resistor $R$, and wire $W$; $B_i$ is an electroacoustic voltmeter and $D$ a voltage divider. The spark circuit contains capacitor $C_2$, resistor $R_7$, and spark gap $P_2$ with starting electrode; $B_3$ is an electrostatic voltmeter. The trigger circuit consists of capacitors $C_3$ and $C_4$, resistors $R_2$, $R_3$, $R_4$, and $R_5$, choke $L$ and switch $K$; $B_2$ is an electrostatic voltmeter.

The operation of the setup is clear from the drawing. The trigger circuit is coupled through the resistor $R_3$ with the starting circuit of the oscillograph driven sweep that is common to both beams. The trigger circuit is also coupled through $R_2$, $R_4$, and $C_4$ with the starting electrode of gap $P_2$. Capacitances $C_7$, $C_2$, and $C_3$ are voltages sources for the respective circuits. They are charged in sequence by a common rectifier. When all capacitors are charged to the proper voltages, closing switch key $K$ starts the oscillograph driven sweep. After a certain time interval, gap $P_1$ is operated and a discharge is produced in the explosion circuit. After still another time interval, operation of the gap $P_2$ energizes the spark circuit and a shadow photograph of the wire is taken through the open camera shutter. Depending on the value of $R_6$, the time interval between the start of the discharge in the explosion circuit and the flash of the spark can be varied from several microseconds to several hundred microseconds. The parameters of the spark circuit were chosen to produce a discharge with a single pulse of light lasting 2 - 3 microseconds. This established the shadow-photography exposure. The

in the wire itself. The pause is longer in water and in organic glass than in air, particularlyat low voltages and for long wires. In the case of short wires and high voltages, there is no pause, and the current decreases after passing through the maximum but does not reach zero. The same occurs with tungsten, molybdenum, and potassium wires under all conditions, i.e., the current never stops in the case of these wires.

From the oscillograms obtained, it is possible to calculate the energy delivered to the wire during any time interval elapsed since the start of the discharge. We are interested here only in the total energy $W$ of the first pulse. This can be calculated from the well-known relationship

$$W = {}^1/_2 C(V_0^2 - V_1^2), \qquad (1)$$

where $C$ is the capacitance in the rupture circuit, $V_0$ the initial voltage across the capacitor, $V_1$ the voltage at the instant of the pause. $V_0$ is measured with an electrostatic voltmeter and $V_1$ is taken from the voltage oscillogram. It is assumed here that all energy delivered by the capacitor during the first pulse is liberated by the wire. The correctness of this assumption was checked by plotting a current-voltage curve for the process to permit direct comparison of the energy liberated by the wire with the energy delivered by the capacitors.

Equation (1) was used to determine from the oscillograms the energy of the first pulse as functions of the amplitude of the initial voltage for copper, silver, and steel wires. The corresponding curves are shown in Figs. 4-6. The abscissas represent initial volts, and the ordinates first-pulse energy in watt-seconds. The dotted parabolas show the dependence of the total capacitor energy on the initial voltage (to the same scale). The wire material and the explosion-circuit parameters are given in the figure captions. Heavy lines $A$ and $B$, drawn parallel to the abscissa in Figs. 4 and 5, indicate the values of energy required for complete evaporation of the corresponding wire, as calculated from tabular data. Line $B$ on Fig. 4 corresponds to a wire 120mm long. From the positions of these lines it is evident that, depending on conditions, the energy of the first pulse can be several times higher or several times lower than the energy required for complete evaporation of the wire. It can be seen that the energy of the first pulse increases rapidly with the initial voltage. This is caused principally by the increase in the overvoltage produced across the wire at the end of the first surge. An especially large amount of energy can be absorbed by the wire at high voltages and when exploded in a dense medium. For

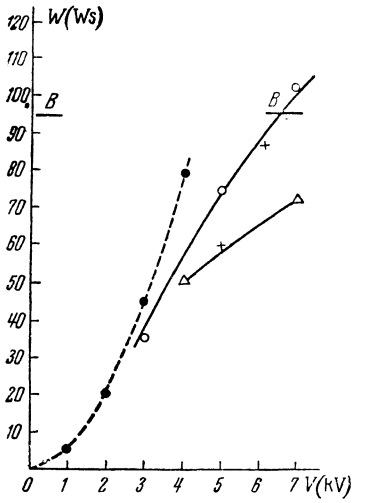


FIG. 4 Curves of $W = f(V_0)$ for copper wire of 0.15 mm cross section diameter. $\Delta$ — $l$ = 120 mm, $C_1$ = 10 $\mu$F, inductance $L = 2.8 \times 10^{-6}$ $H$; x — $l$ = 240 mm, $C_0$ = 10 $\mu$F, $L = 2.8 \times 10^{-6}$ H; o — $l$ = 120 mm, $C_1 = 10^0$ $\mu$F, $L = 3.5 \times 10^{-6}$ H.

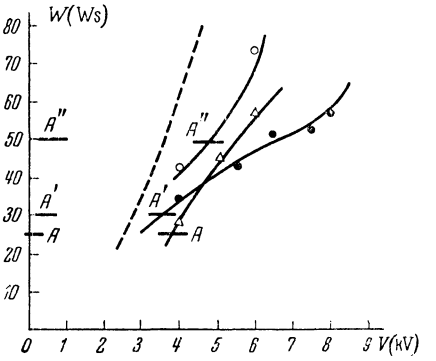


FIG. 5. Curves of $W = f(V_0)$ for silver wire. ○ — $d$=0.15 mm, $l$ = 120 mm $C_1$ = 10 $\mu$F, inductance $L = 3.5 \times 10^{-6}$H; △ — $d$ = 0.25 mm, $l$ = 160 mm, $C_1$ = 10 $\mu$F, $L = 3.5 \times 10^{-6}$H; ● — $d$ = 0.13 mm, $l$ = 100 mm, $C_1$ = 10 $\mu$F, $L = 1.5 \times 10^{-6}$H

example, a silver wire 0.15 mm in diameter and 3 cm in length, embedded in organic glass, absorbs during a first pulse lasting 1.5-2 microseconds enough energy from a 10-microfarad capacitor at 7 kilovolts to heat the wire to 150,000° Kelvin. The temperature is calculated by determining the average energy available for each atom of wire material and subtracting the energy required for complete evaporation of the wire. Here we neglected the radiation losses and disregarded the energy losses involved in ionizing and exciting the atoms

one-microfarad capacitor $C_2$ was charged to 30 kv in all experiments. The shadow-photography optical system is shown in Fig. 2. In many cases, the shadow

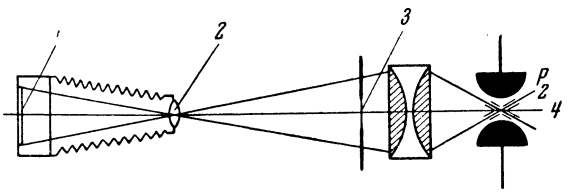


FIG. 2. Shadow photography diagram
*1* - photographic plate, *2* - objective, *3* - wire
*4* - spark.

photographs were paralleled by oscillograms of the wire explosion. The oscillograph recorded simultaneously the voltage across the wire and the voltage across current-measuring resistor $R_1$, proportional to the current in the wire. All of the latter voltage and a fraction of the former (from the voltage divider) were applied through a coaxial cable to the oscillograph deflection plates owing to the special construction of the resistor $R_1$, the resultant oscillograms of the current were quite free of inductive distortion and induced noise. The inductive distortion of the voltage oscillograms was controlled in a special manner*.

Applying suitable corrections, oscillograms obtained in this manner permit calculation of the explosion energy at any instant of time with an accuracy to 5-7%. Shadow photographs were taken of explosions in air and water. A container made of organic glass and having plane parallel walls was used for the latter.

## 3. EXPERIMENTAL RESULTS

### a) WIRE EXPLOSION OSCILLOGRAMS. EXPLOSION ENERGY

Figure 3 shows oscillograms obtained with different wires under varying experimental conditions. The upper and lower curves show respectively current and voltage vs. time. Oscillograms obtained with copper, silver and platinum wires were described by us in Ref. 6 and are not repeated here.

Oscillogram I was taken with a potassium wire in a glass capillary tube. Oscillograms II (copper wire) and III (tungsten wire) are given as examples to illustrate the entire wire-explosion process, starting with the first pulse and ending with the complete discharge of the capacitor in the second pulse. The oscillograms were made at high voltages. Oscillogram III shows only the current curve.

The oscillograms show that during the initial stage of the discharge, lasting from a few up to several dozens of microseconds the wire first receives a fraction of the energy in the form of a pulse. This first pulse is followed in most cases by the so-called current pause, when the current drops to zero[8,12,15,16].

The voltage across the wire first rises and reaches at the point of maximum current a value that is somewhat less than the initial voltage across the capacitor.** Next, in view of the fact that the current starts decreasing, $\partial I/\partial T < 0$, and an overvoltage occurs across the wire. At the end of the first pulse both current and $\partial I/\partial T$ approach zero, and the voltage, which passes through its maximum at the instant $I = 0$, assumes a constant value, which nevertheless represents a considerable fraction of the initial voltage. Once the pause starts, no more energy is liberated in the wire. The duration of the pause, depending on experimental conditions may usually range from zero to several hundred microseconds. The pause is followed by a second discharge pulse, characterized by higher currents and lower voltages than the first pulse. This means that in the second pulse an arc strikes across the gap formerly short circuited by the wire and the following full capacitor discharge is accompanied in this case by the usual damped oscillations. The length of the pause depends both on the processes occurring during the wire explosion and on the de-ionization time of the discharge gap. If the pause is longer than the gap de-ionization time, the second pulse cannot occur at all.

The oscillograms of aluminum, silver, and gold wires are similar to the copper-wire oscillogram. The oscillograms of tungsten, molybdenum, iron, nickel, and nichrome wires are similar to that of platinum wire, and are characterized by a first-pulse region in which the current and voltage vary little with time. A similar region, although less clearly pronounced, occurs in the case of long copper, silver, and aluminum wires.

Oscillograms were also taken of exploding wires placed in water or embedded in organic glass. These oscillograms showed that the waveform and

* A detailed description of the oscillography, an evaluation of the fidelity of the oscillograms, and the construction of current-measuring resistor $R_1$ are given in Ref. 6.

** Because only a small fraction of the energy can be liberated by the wire in the form of heat and in the form of magnetic energy of the current within that time. Furthermore, the voltage drops across the resistances in the explosion circuit are low.

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amplitude of the first pulse depend little on the character of the surrounding medium, and are consequently determined by the processes occurr

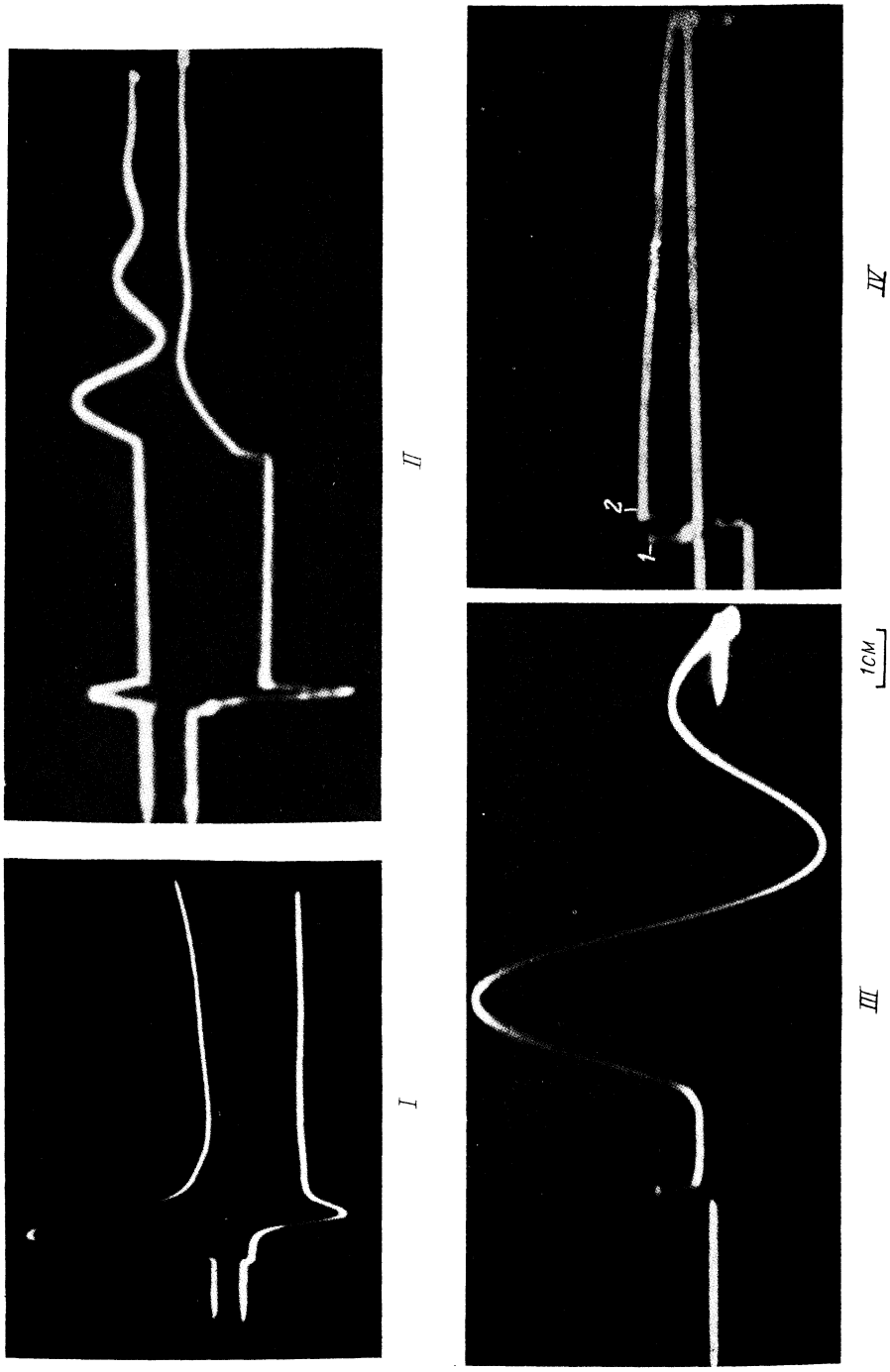


FIG. 3. Samples of current and voltage oscillograms (current--upper curves, voltage--lower curves, horizontal axis--time axis). *I* -- K, $d$= 0.14 mm, $l$ = 140 mm, $V_0$ = 7 kv, $C_1$ = 8 $\mu$F, current scale $m$ = 100 A/mm, voltage scale $n$ = 550 V/mm, time scale $\tau$= $2 \times 10^{-7}$ sec/mm. II--Cu, $d$ = 0.05 mm, $l$ = 60 mm, $V_0$ = 5 kv, $C_1$ = 8$\mu$F, $m$ = 150 A/mm, $n$ =.600 V/mm, $\tau$= $2.5 \times 10^{-7}$ sec/mm. III--W, $d$ = 0.08 mm, $l$ = 100 mm, $V_0$ = 10 kv, $C_1$ = 0.5 $\mu$F, $m$ = 60 A/mm, $\tau$= 8 $\times 10^{-8}$ sec/mm. IV -- Cu, $d$ = 0.05 mm, $l$ = 150 mm, $V_0$ = 3.5 kv, $C_1$ = 8$\mu$F, $m$ = 120 A/mm, $\tau$= $1.1 \times 10^{-6}$ sec/mm.

of the wire material.

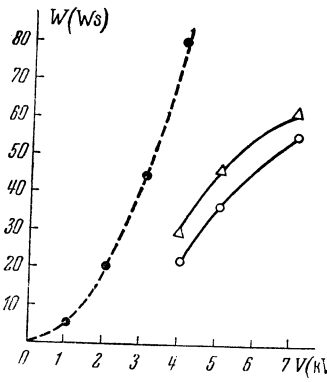


FIG. 6. Curves of $W = f(V_0)$ for steel wire of 0.15 mm cross-section diameter. $\Delta - l = 60$ mm, $C_1 = 8.4$ $\mu F$, inductance $L = 3.5 \times 10^{-6}$ H; O – $l = 120$ mm, $C_1 = 8.4$ $\mu F$, inductance $L = 3.5 \times 10^{-6}$ H.

### b) SHADOW PHOTOGRAPHY

Many wire-explosion oscillograms were paralleled by shadow photographs showing various stages of explosion in air and water. To prevent doubly exposing the film by the light of the second pulse, most photographs were made of copper wires at conditions under which no second pulse occurs. The photographs were taken at time intervals ranging from several microseconds to several hundreds of microseconds after the start of the discharge. The state of the wire at a given instant was established for each explosion with an exposure of 2-3 microseconds. To obtain shadow photographs of successive states of the wire, the explosions were repeated under identical conditions and the photography was carried out at various time intervals measured from the start of the process. The reproducibility of the shadow photographs was quite satisfactory in these experiments.

Figure 7 shows shadow photographs of an enamel-insulated copper wire of diameter $d = 0.10$ mm and length $l = 15$ cm taken at an initial voltage $V_0 = 3.5$ kv. Photographs V, VI, VII, and VIII, correspond to an elapsed time of 5, 10, 15, and 50 microseconds from the start of the discharge. The magnification of the photographs is approximately 15 diameters. It is evident from these photographs that during the first five microseconds after the start of the discharge (photograph V) there is no external change in the wire, except for a few short incandescent wire segments still seen in photograph VI that follows. After 10 microseconds (photograph VI) the layer of enamel peels off the wire noticeably and continues to peel off the wire, as shown in the subsequent photographs. Noticeable evaporation of the wire, becoming progressively stronger, begins at 15 microseconds (photograph VII). At 50 microseconds (photograph VIII) a considerable portion of the wire is still unevaporated, and the wire splits into individual longitudinally-elongated "beads". A photograph taken at 150 microseconds after the start of the discharge (not reproduced here) shows that the evaporation is almost complete by that time, and the unevaporated remnants of the wire, in the form of small particles, are scattered in space in disorderly manner. What calls attention in these photographs is the uneven explosion of the wire.

The oscillogram belonging to the above series of shadow photographs shows that the first discharge pulse lasts not more than 3-5 microseconds. The energy of this pulse is sufficient to evaporate completely 60% of the entire mass of the wire. It must therefore be assumed that the wire is in a superheated liquid state for some time after the first pulse. In view of the high surface tension of metals, the formation of incipient gas state is difficult, and therefore there is a short period of time (on the order of microseconds) when evaporation cannot begin over the entire volume. The evaporation occurs only on the surface of the wire. Since the wire liberates energy very rapidly (the power is $10^8$ watts) it should become considerably superheated. Our shadow photographs confirm such an assumption. To obtain a more convincing proof of a superheated state, simultaneous oscillograms were taken of the current in the explosion circuit and of the photoelectric current excited in a photocell multiplier by a strongly collimated beam of light coming from a narrow portion of the surface of the wire. The corresponding curves are shown in Fig. 3 (oscillogram IV). A much longer sweep time was used to cover the entire evaporation process. The current curve (upper beam) shows the presence of the very narrow first pulse (arrow 1) in the initial portion of the oscillogram. This is followed by a current pause. The photocell-current curve (lower beam) has a maximum (arrow 2) at the start of the oscillogram, followed by a gradual decrease. This indicates that the wire, having its maximum temperature at the end of the first pulse, is consequently in a superheated state. Later on, the temperature of the wire should decrease as the energy of the superheated state is consumed by the evaporation. However, the shadow

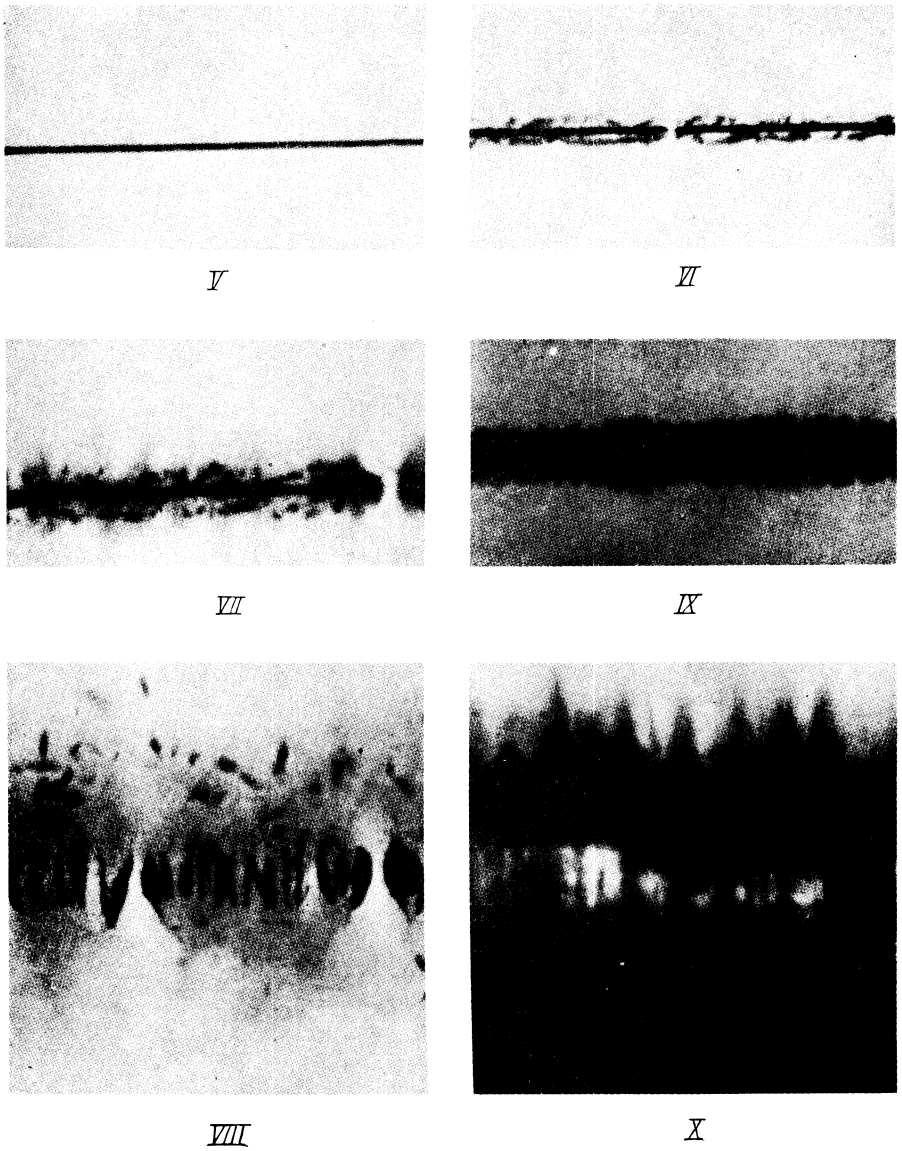


FIG. 7. Shadow photographs of wire explosion. Photos V, VI, VII, and VIII show successive explosion stages for enameled copper wire 0.1 mm dia. and 15 cm long (weak explosion); IX and X show the scattering of explosion products at relatively high voltages (strong explosion).

photographs show that the evaporation gains intensity with time. This must be explained by the fact that the wire becomes gradually broken up into individual "beads" and the evaporation surface increases greatly.

Photograph IX (Fig. 7) shows the condition of an uninsulated wire with $l$= 15 cm, $d$ = 0.05 mm, exploding in air at $V_0$ = 5.2 kv. There is no second pulse. The photograph was taken 28 microseconds after the start of the discharge, and the magnification is 1.5-2 diameters. It is evident from this photograph that the evaporation proceeds in layers that run perpendicular to the axis of the wire. The stratified nature of the evaporation is shown even more clearly in photograph X, taken 28 microseconds after the start of the discharge with $l$=15 cm, $d$=0.15 mm, and $V_0$=5kv.

$V_0 = 5$ kv. One sees clearly here two streams of explosion products, one with a small quantity of matter, low velocity, and deeper penetration into the air; the other with a larger quantity of matter lower velocity, and shallower penetration in the air. Both streams are radially stratified.

The accompanying shadow photographs thus disclose certain interesting details of the explosion process. However, the corresponding experiments were carried out at relatively low initial voltages (3.5 kv) to slow down the process and to make it possible to distinguish the individual explosion stages. At higher voltages the explosion is much faster and the pictures all merge. To obtain a better understanding of the explosion phenomenon in general and of the mechanism of current interuption in particular, it is necessary to investigate the behavior of the wire at higher values of $V_0$, i.e., at higher rates of energy influx in the first pulse. The method employed for this purpose was to shunt a segment of the wire with a discharge gap[8] connected in series with a resistor. Since considerable overvoltage occurs across the wire before the end of the first pulse (see rupture oscillograms), it is possible to produce breakdown of the shunt at the required instant of time by adjusting the length of the gap. If the resistance of the shunt is nearly zero, almost all of the current flows through the shunt once the gap breaks down and no more energy is liberated by the wire. If the shunt resistance is not zero, the voltage drop across this resistance continues to feed energy to the wire. By varying the breakdown voltage of the shunt and its resistance it is possible to change the energy of the first pulse and its delivery rate over a wide range. The results obtained in this manner are not sufficiently quantitative, for we know that the starting time and development of a discharge in a gap has a certain statistical dispersion. However, the results are well founded qualitatively. Figure 8 shows three photographs of a copper wire having $d = 0.05$ mm. Photograph XI was taken 28 microseconds after the start of the discharge at $V_0 = 4$ kv and $l = 65$ cm. The breakdown voltage of the shunt was 2.5 kv. Photographs XII and XIII were taken 15 microseconds after the start of the discharge at $l = 12$ cm and at 5 and 6 kv respectively. The approximate breakdown voltage of the shunt was 5 kv and its resistance was approximately 0.2 ohm. The magnification of the photographs is 10 diameters. It is evident from these photographs that the current interruption is preceeded by states characterized by an intense movement of the matter in the wire. At low pulse energies (photograph XI) the wire remains solid and after several tens of microseconds it manages to assume a well-developed wave-like shape. At higher energies (photograph XII) individual highly-superheated sections evaporated completely. The remaining portions did not have a chance to curve noticeably and enter into a dispersed state with a large number of breaks along the entire wire, probably under the influence of shock wave occuring when the material is ejected at the superheated locations. It can be seen from photograph XIII that the distribution of the superheated sections becomes almost periodic in the more uniform sections of the wire and at larger pulse energies. Careful examination of photograph VII, corresponding to a low-energy first pulse also discloses the beginning of dispersion.

The next photograph (XIV) illustrates the explosion of copper wire in water at $l = 12$ cm, $d = 0.05$ mm, and $V_0 = 1.5$ kv. The photograph was taken 150 microseconds after the start of the discharge and the magnification is 3-4x. The shadow spots on these photographs indicate the formation of gas bubbles around short glowing sections of the wire. Some of these bubbles have a regular spherical shape, indicating that individual overheated sections are small in size. Where several superheated sections have accumulated, the bubbles are drawn out in the direction of the wire axis. The presence of illuminated sections in the middle regions of the spots is due to the radiation of the overheated sections of the wire.

The last photograph XV shows the explosion of a copper wire with $l = 12$ cm, $d = 0.05$ mm, and $V_0 = 6$ kv. The photograph was taken 50 microseconds after the start of the discharge. The pause is less than 15 microseconds. What is remarkable in this photograph is the water cavitation resulting from the wire explosion. The bubbles formed are illuminated by light from the arc of the second discharge pulse. It is probable that the cavitation of the water is related to the shock waves propagated in the water as the result of the second current pulse.

Several experiments were performed to clarify the role of the superheated short sections, appearing in the wire at the initial stage of the discharge. They are assumed to be very short arcs produced where the wire has slight inhomogeneities due to rapid evaporation or occurring where the wire breaks. Shallow and very narrow equidistant transverse notches were made in a uniform copper wire with a knife. Shadow photographs of the explosion of such wires showed that short arcs actually occur at such notches and that these arcs were further developed than the short arcs on homogeneous

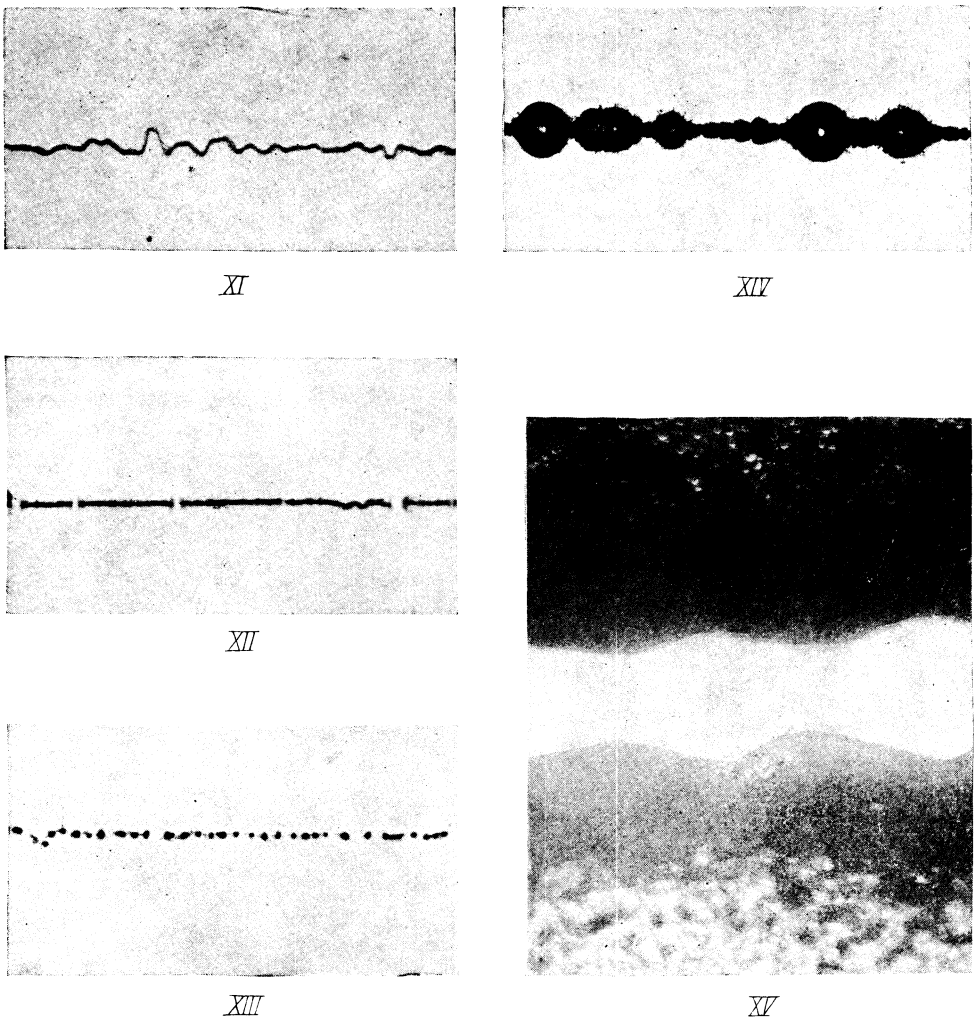


FIG. 8. Shadow photographs of wire explosion. Photos XI, XII, and XIII show explosion of shunted wire; XIV and XV show explosion of wire in water.

wires. This is probably related to the magnitude of the inhomogeneity. Comparison of current oscillograms of a notches and a homogeneous wire shows that in the former current diminishes faster after the maximum of the first pulse is steeper. This indicates a faster rise in the resistance of the wire due to the presence of stronger short arcs. From this it follows that in the case of a strong explosion, when the evaporation has a clearly pronounced stratified character, the simultaneous occurrence of a large number of short arcs over the entire length of the wire may contribute to the interruption of the current.

## 4. EVALUATION OF RESULTS

The now prevalent ideas concerning the mechanism of electric wire explosion cannot explain the basic features of the phenomenon. For example, the almost-instantaneous interruption (within several tenths of a microsecond) of such large currents (several thousands of amperes) has been attributed to the transformation of the wire from metal into non-conducting--very dense--gas[12,15,16]. This hypothesis, on first glance quite natural, is contradicted by experimental data. Actually, the oscillographic data above show that, depending on experimental conditions, the energy of the first

pulse of the discharge can be several times greater or smaller than the energy needed for total evaporation of the wire. Consequently, not all the wire need evaporate before the current is interrupted. Furthermore, the shadow photographs show that if the explosion is delayed, the current is interrupted even before the wire starts evaporating noticeably. In cases where the energy of the first pulse exceeds by many times the energy required for total evaporation of the wire, there is every reason for assuming that this wire is fully evaporated even within the first pulse . Nevertheless, in those cases the current is frequently not fully interrupted.

There is no explanation, particularly in the case of strong explosion, for the clearly pronounced stratified character of the evaporation and for the tendency of the wire to break up into minute "beads" when the explosion is delayed. Attempts to explain the stratified nature of the evaporation by attributing it only to the action of the surface-tension forces in the molten metal[17] must be considered groundless because these forces are too small. In fact, as was already noted, the wire in the explosion process may even reach critical temperature, and therefore the surface tension tends to zero.

It is equally incorrect to attribute the discharge pause to the reaction of the metal vapors with the oxygen in the air and to the accompanying further heating of the vapor (thermal breakdown). Such a point of view is disproved by wire-explosion experiments in inert gases (nitrogen, argon) and dense insulators (water, organic glass, glass, etc.) in which a reaction with the vapors of the metal is impossible, and the character of the pause remains unchanged. References 8, 12, and 16 correctly relate the appearance of the pause with the radial expansion of the vapor during the explosion. However, they do not take into account the cylindrical symmetry of the explosion,[18] and cannot give a convincing explanation of the phenomenon.

Nor are explanations given for the large dispersion of the energy of the first pulse, for the dependence of the waveform of the first pulse on the wire material, for the role of superheated short segments produced in the wire in the initial stage of the discharge, etc.

Analysis of the experimental material given above permits forming a definite concept of the mechanism of electric wire explosion, giving at least a qualitative explanation for the basic features of the phenomenon. We start with the fact that in the first pulse, even before noticeable evaporation begins, the wire material is already in state of intense motion. For correct understanding of the explosion mechanism, it is first necessary to evaluate the forces causing this motion and their action, taking into account the gradual transition of the wire from solid into liquid and from liquid into gas. In the initial stage of the explosion the wire heats rapidly, while still in a solid state; not having enough time to expand in an axial direction (owing to inertia), it becomes subject to a strong axial compression. The magnitude of the compression can be approximately calculated from the following equation:

$$f = \alpha TES, \tag{2}$$

where $\alpha$ is the average coefficient of linear expansion, $E$ the modulus of elasticity of the wire material, $T$ the temperature rise, and $S$ the transverse cross section area of the wire. Since the volume of the wire does not have time to change noticeably while it is being heated in a solid state, we can roughly assume $E$ to be constant. Then Eq. (2) for copper wire, say, at temperature $T = 1{,}000°$ gives an axial stress of approximately 20,000 atmospheres.

According to Euler, an axially-stressed homogeneous wire should assume a sinusoidal form. The connection between the wave length $\lambda$ of the deformation and the critical axial compression stress $f_n$ is given by the following expression

$$(\lambda/2)^2 = \pi^2 EM/f_n, \tag{3}$$

where $E$ has the same meaning as before, and $M$ is the moment of inertia of the transverse cross section of the wire ($M = \pi d^4/64$, where $d$ is the diameter of the wire). Since an actual wire has a certain inhomogeniety, one cannot expect a strict periodicity . A detailed theoretical study of this problem and an experimental check on the results of the theory in the case of a platinum wire is found in Ref. 14. That such a phenomenon actually occurs in the initial stage of wire explosion is confirmed by the shadow photograph (Figure 7). Even though the wire remains only briefly in the solid state (less than 1 microsecond) it manages during that time to assume the shape of a wave of certain small amplitude. As a result, the compression along the wire distributes itself with the same periodicity. Since the melting point depends on the pressure, and the compression is periodic, the distribution of the regions where the melting begins will also have a

[17] W. Kleen, Ann. Physik **11**, 579 (1931).

[18] L. I. Sedov, Metody podobiia i razmernosti v mekhanike (Analogue and Scale-Model Methods in Mechanics), Moscow-Leningrad, 1952.

periodical character. Where the compression is high, the mass should immediately begin to shift so as to reduce the compression. Thus there are dynamic reasons for a periodic variation in the transverse cross section along the wire as the wire changes to the liquid state. It is also necessary to take into account the action of the forces due to the magnetic field of the current, tending to compress the wire in a radial direction (the so-called "pinch effect"). This compression can be characterized by a force $F$ acting on a unit of wire perimeter surface and directed toward its center. The magnitude of this force is given by the equation

$$F = \sigma j^2, \tag{4}$$

where $\sigma$ is the perimeter of the wire and $j$ is the current density.*** [20] Under the conditions of our experiments, with a wire of approximately 0.1 mm the current density reaches values of $10^6 - 10^7$ electromagnetic current units. According to Eq. (4) the corresponding forces will be on the order of $10^{10} - 10^{12}$ dynes. These forces reach a maximum in the region of the current maximum, where according to oscillographic data the wire begins its transformation to the liquid state. Under the influence of these forces, the masses begin to shift where the liquid wire becomes narrower, the shift being in a direction perpendicular to the axis of the wire. Conversely the masses are pushed out in the opposite direction where the liquid wire becomes wider. The acceleration of the motion will increase with the difference in the radii in the compression and expansion locations ($F$ is inversely proportional to the third power of the radius). Under the influence of the large currents flowing through them, the compressed sections will start to evaporate much sooner than the neighboring sections, and this will accelerate the compression. The compression accelerates both because of the evaporation of the material, and also because of the forces produced in this evaporation.

Since the transverse periodicity along the entire wire occurs simultaneously, the compression of the narrow portions begins simultaneously everywhere. Consequently a set of short superheated sections is produced simultaneously over the entire wire and for a very short time (considerably shorter than the duration of the first pulse) the matter appears to be expelled from this set beyond the limits of the charge. It is evident that intense shock waves will propagate along the wire from the superheated sections, and these shock waves are capable of causing a considerable disturbance and result in the dispersion of the remaining sections of the wire (a phenomenon similar to the initial stage of cavitation in liquid without vapor bubbles developing). As a result of such dispersion, these sections apparently lose their conductivity, and this in turn also contributes to the interruption of the current. According to Eq. (4), the compression forces of the magnetic field of the current rise very rapidly with the current density, and it is therefore possible that this generally limits the maximum current density that can be reached in metals. The picture drawn here for the processes occurring in the first pulse makes it also possible to explain other facts that characterize the electric wire explosion. For example, it follows naturally from this picture that the evaporation of the wire should be characterized by strata perpendicular to the axis of the wire.

Taking into account the uneven rate at which energy is liberated along the wire and the possibility that in short wires the isolating sections can be broken down by the large initial voltages, the high limit of energy absorbed by the wire during the first pulse becomes now understandable.

Also understandable now is the tendency of the wire to break down into individual "beads" if the explosion is slowed down. In fact, while processes contributing to the dispersion of the wire predominate before the current is interrupted, once the current is interrupted, the reverse processes start predominating and lead at least to a partial rejoining of the small liquid particles into larger droplets. In view of the intense evaporation, these droplets which interact with each other flatten out in an axial direction and stretch out in a radial direction. The random character of the rejoining of the particle leads to a certain statistical distribution of the droplet dimensions along the wire.

The role played by the compression forces of the magnetic field due to the current is further corroborated in the fact that in wires having a high specific resistivity, and consequently carrying low current, such as tungsten, molybdenum, platinum, iron, nichrome, nickel, and the like, the first pulse is characterized by a slight step in which the current in the voltage changes little in time, i.e., the wires have a negligible thermal coefficient of resistivity within the confines of this step. The reason is that in view of the low current the compression effect is weakly pronounced and the liquid wire maintains its cylindrical shape for a certain time. In the liquid state

*** We neglect the skin effect [19] and the inverse skin effect as being too small.

[19] Z. Lubin, Zhur. Prikl Fiz 4, 2, 45 (1927).

[20] E. Fr. Russ, Z. techn. Phys. 11, 529, (1930).

the metals, as is well known, have a low coefficient of resistivity. An analogous phenomenon occurs also for copper, silver, and aluminum in the case of long wires and relatively low voltages. Under these conditions the currents in these materials during the first pulse are also low.

As was shown above, potassium, tungsten, and molybdenum cannot produce a complete interruption of the current under any condition. This is explained by the thermal ionization of the vapors and by the intense thermal electron emission of tungsten and molybdenum. Not one of the materials can lead to a complete interruption of the current regardless of the vapor pressure and meet the conditions required for sufficient thermal ionization of the vapor. This holds for all materials in the case of short wires and high voltages.

The duration of the pause is determined principally by the energy of the first pulse, which in the final analysis determines the radial velocity of the vapor. The higher the energy of the first pulse, the higher the velocity of the vapor. In particular, it was shown in Ref. 18 that, depending on the initial energy, the pressure on the axis and near the axis can drop to any value down to a vacuum in the case of a radial scattering of particles in the explosion of a wire with cylindrical symmetry. Under this condition, and in the presence of a certain residual voltage, it is quite natural for a finite pause to exist, that is, for a second pulse to form as a result of the breakdown that occurs within a finite time after the beginning of the pause. As to the possibility of the existence of an infinite pause, this can be basically explained by two causes.

An infinite pause is characteristic of a delayed explosion with low energy in the first pulse. In view of this, the radial velocity of the vapor is insufficient to reduce the pressure enough to permit a breakdown to occur. Furthermore, under those conditions when the duration of the pause exceeds the de-ionization time of the gas in the discharge gap of the rupture, the pause becomes practically infinite, since the residual voltage is insufficient to produce breakdown.

It thus becomes possible to explain qualitatively the principal outlines of the phenomenon of electric explosion of wires.

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Translated by J. G. Adashko
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