ELECTRICAL MEASUREMENTS OF FIRST PULSE
ENERGIES OF EXPLODING WIRES

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ABSTRACT

The capacitatively exploded metal wire is a useful technique for studying high temperature condensation processes. Measurements are reported for first pulse energies delivered to 10 mil Ag, Cu, Al, and Ni and 9,20 and 30mil Fe wires over a stored energy range of 360 to 9000 joules. The vaporization efficiency of Ag, Cu and Al are, at a given stored energy, distinctly higher than for Fe and Ni. The history of the explosion is interpreted as two vaporizations and two condensations, one each following the first pulse and the restrike, respectively. An energy input in the first pulse approximately one-third of the vaporization energy is required to render the wire non-conducting.

Keywords: Exploding Wires, High Temperature Metals.

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INTRODUCTION

The exploding wire phenomenon may prove to be a useful technique for studying high temperature condensation behavior. In this method a quantity of capacitatively stored electrical energy is discharged suddenly through a thin wire. The wire is melted, and in whole or in part converted to vapor in the time frame of a few microseconds. The process is accompanied by a brilliant flash and a prominent shock wave in the surrounding medium.

Our prime interest was in reproducing, if possible, certain of the phenomena associated with the generation of radioactive particles in a nuclear explosion, most particularly the fractionation behavior of trace fission products condensing in foreign matrices (1). This is a problem also of some interest in cosmochemistry and may provide a method of studying vaporization processes of micrometeoritic impact on the lunar surface.

Only a few applications of the exploding wire technique to problems of a chemical nature appear to have been made. Karioris et.al. (2,3) report the preparation of a wide variety of oxide and metal particulates by exploding wires of metals in air and in inert gas atmospheres. Fish and co-workers (4) have measured absorption rates of polar vapors on the surface of aerosols prepared by exploding metal wires and foils. Joncich (5,6) and Siegel (7,8) have used the exploding wire preparatively.

There are, to our knowledge, no studies along the lines reported here, with emphasis on studying metal fractionation when vaporized elements suddenly condense.

Extensive investigation of the exploding wire phenomenon has shown that the explosion is a complex process (9-12)

with the appearance of at least three distinct regimes of energy input, the first pulse, the dark pause and the restrike. During the first pulse the current is carried by the metal wire. The dark pause ensues when sufficient wire material is vaporized to cause a large resistance increase due to cessation of metallic conduction. The current drops to a low, approximately constant value because the particle density is too high to allow gaseous discharge (13). The restrike occurs when the particle density in the region of the wire falls to a value which permits gaseous discharge if a sufficient potential remains on the capacitor bank. The restrike current behaves as a damped harmonic oscillator and continues until most of the electrical energy is dissipated.

Because of the complexity of the exploding wire phenomena it is not possible at the present time to present a comprehensive analytical model such that an equation of the state of the system can be defined at each point in time during and immediately subsequent to the explosion. This renders it difficult to apply the exploding wire technique in a truly fundamental way to the study of vaporization and condensation processes. In the present paper we concern ourselves primarily with the first pulse phase of the explosion, although some consideration will be given to the energetics of the entire discharge which affect the resultant chemical products.

There can be two sources of energy, the electrical energy released through the discharge and the chemical energy released through chemical reaction of the wire with the ambient gas. The energy sinks are the physical changes

in the wire (e.g., melting and vaporization), radiation, shock formation in the environment and thermal and kinetic energies of the explosion products.

As a first step in understanding the energy balance we have measured the first pulse energies for wires of five metals (Cu, Ag, Al, Ni and Fe) at a series of initial voltages. Some measurements of first pulse energies have been reported (14-16), but these are not sufficient for our purposes. We have further measured the time to melt, the time duration of the first pulse and the charge delivered in the first pulse for the five wires, and over a range of stored capacitor energies.

METHODS

The exploding wire system is of conventional design with a total energy storage of 9000 joules (45 μ f at 20 kv maximum). Energy stored is given by $1/2 CV^2$ where C is the capacitance and V the charging voltage. The bank has a ringing frequency of 32 kHz with the wire-holding electrodes installed. The capacitor bank is three 15 μ f capacitors connected in parallel with two copper plates separated by Mylar insulation. The copper plates are connected to the wire holder by copper bus bars through an air spark gap switch. The spark gap is a three element switch after the design of Cullington and Chase (17).

The electrical diagnostic equipment consisted of a calibrated inductive pickup coil with a passive RC integrating circuit for current measurement, and a Tektronix P-6015 high voltage probe for voltage measurement. These were connected to a Tektronix Model 551 dual beam oscilloscope equipped with two type L preamplifier units. The

current and voltage traces were recorded photographically.

The time of the first pulse was measured on the current trace from the first inflection to the current minimum (Fig. 1). The time to melt was measured on the voltage trace from the first inflection to the second inflection characteristic of a large resistance increase (Fig. 1). The charge in the first pulse was obtained by graphical integration of the current trace.

The first pulse energy was obtained by graphical integration of the voltage and current traces. The accuracy of the energy measurements was assessed by comparing the energy used to melt a 30 mil diameter iron wire with the literature value. The agreement between the average of five measurements and the literature value was +6.4%. The literature value is 340.4 joules (18) and the average value measured was 362.3 ± 12.9 joules. The quoted error is the standard deviation.

Wires of five metals were used with purity values 99.9% or greater. Wires of aluminum, nickel and silver were 10 mil in diameter (0.0254 cm). The copper wire was 10.4 mil in diameter (0.0264 cm). Three sizes of iron wire were used 9 mil, 20 mil and 30 mil (0.0229 cm, 0.0508 cm and 0.0762 cm respectively). All wires were 7 cm long.

The wires were exploded at a series of voltages from 4 kV to 20 kV in air at 1 atmosphere pressure.

RESULTS

a. First Pulse Energy

The first pulse energy increases as the initial voltage for all wires. The increase is logarithmic over the range of voltages as seen in Figure 2. We have

Figure 1

Figure 3

Figure 2

observed for the three sizes of iron wire the following relation

$$E_1/E_2 = (r_1/r_2)^{0.35} \quad [1]$$

where E is the first pulse energy per unit mass (e.g. kcal/gm atom) and r is the wire radius. The subscripts refer to any pair of iron wires.

Using the observed logarithmic behavior of the first pulse energy vs initial voltage, the following general expression for the energy can be written

$$E = C \exp(aV) \quad [2]$$

where E is the first pulse energy in kcal/gm atom, C and a are constants dependent on the wire material and V is the initial capacitor voltage in kilovolts. Table 1 lists these empirical constants. For the iron wires the value of a is, within experimental error, independent of wire diameter and the constant C may be expressed in the following manner

$$C = C_0 r^{0.35} \quad [3]$$

where r is the wire radius in cm and C_0 is a constant for the three sizes of iron wire. Figure 3 shows the first pulse energy for the iron wires plotted according to equations [2] and [3].

TABLE 1

Empirical Constants for the
Five Metals for Equation [2]

<u>METAL</u>	<u>a (kV⁻¹)</u>	<u>C (kcal/gm atom)</u>
silver	0.0716	60.5
aluminum	0.0600	55.8
copper	0.0726	63.4
nickel	0.0592	41.9
iron 0.0229 cm	0.0534	44.3
iron 0.0508 cm	0.0534	58.5
iron 0.0762 cm	0.0534	67.4

C₀ for equation [3] is 211.5 kcal/gm atom/cm^{0.35}

b. First Pulse Energy Relative to Vaporization Energy

The ratio of the first pulse energy to vaporization energy as a function of initial voltage is shown in Figure 4. The vaporization energy is defined as the energy necessary to bring 1 gram atom of the solid at 25°C to the vapor at the normal boiling point. For the 10 mil nickel wire and the 9 mil iron wire the vaporization energy is not exceeded until the highest initial voltages are approached, approximately 18 kV. The copper, silver and aluminum wires exceed the vaporization energy at relatively low voltages, approximately 6 to 8 kV. This behavior corresponds to the general resistance character of the metals. Copper, silver and aluminum have relatively low resistances compared to the nickel and iron wires of the same approximate diameter at room temperature.

c. Fraction of Stored Energy in the First Pulse

Figure 5 shows the fraction of the total energy stored in the capacitors which appears in the first pulse, as a function of initial voltage. At higher voltages a large amount of energy remains in the capacitor bank for release during the restrike period. The 9 mil iron wire data was adjusted to values corresponding to 10 mil wire using the scaling expression given above (section a). The explosion at 8 kV with the 30 mil iron wire is not considered representative because the total stored energy was about equal to the vaporization energy of the wire. In all other cases the stored energy exceeded the vaporization energy.

d. Duration of the First Pulse

For all wires the duration of the first pulse decreases with increased initial voltage. Comparison of the

First Pulse Energy Relative to
Vaporization Energy vs. Initial Voltage

First Pulse Energy Relative to
Vaporization Energy vs. Initial Voltage

Fraction of Stored Energy in First Pulse vs. Initial Voltage

Figure 5

values for copper, silver and aluminum shows the following relative order

$$Al < Ag < Cu$$

at all voltages. This is the same order as observed by Nash and Olsen (14). For voltages in excess of 12 kv the following expression holds for the three sizes of iron wire

$$t_1/t_2 = (r_1/r_2)^{0.9} \quad [4]$$

where t is the time of the first pulse, r is the radius of the wire and the subscript refers to any pair of iron wires. Figure 6 shows time of the first pulse as a function of initial voltage.

e. Time to Melt

The time to melt, shown in Figure 7, decreases with increased voltage as does the time of the first pulse for all wires. Considering the five metal wires with diameter of approximately 10 mil, the times to melt at any voltage show an inverse relation to the room temperature resistance. The higher the initial resistance of the wire the greater the fraction of the total circuit resistance it represents and therefore the higher the initial rate of heating. The electrical circuit under short circuit conditions has a resistance of 11.5 mohm most of which is probably contributed by the spark gap switch. The 7.0 cm length of copper wire at room temperature has a resistance of 21.4 mohm which is 65% of the total circuit resistance, while the 9 mil iron wire has a room temperature resistance of 166 mohm or 94% of the total initial circuit resistance. For the other three metals the percent of the total initial circuit resistance represented by the wire is 66%, 76% and 89% for the silver, aluminum and nickel wires respectively.

Time of the First Pulse (Microseconds) vs Initial Capacitor Voltage (Kilovolts)

Figure 6

f. Time to Melt Relative to Calculated Values

Bennett (19) has obtained approximate solutions to equations describing the electrical behavior of the exploding wire process up to the time to melt. The resulting solutions can be used to calculate the time to melt for a wire given the physical parameters of that wire. The resulting expression is

$$t_m (f(t_m))^{1/3} = (\ln(1 + \alpha((T_m - T_o))/A))^{1/3} \quad [5]$$

where A is

$$A = 16\alpha V_o^2 / 3\pi^2 \sigma_o \rho s d^4 (L_c + L_w)^2 \quad [6]$$

and where t_m is the time to melt, $f(t_m)$ is a function of the time to melt which is taken as equal to 1.0, α is the temperature coefficient of resistance of the metal, T_m and T_o are the melting temperature and the initial temperature of the metal, V_o is the initial voltage in volts, σ_o is the room temperature conductivity of the metal, ρ is the density of the metal, s is the specific heat of the metal at the initial temperature, d is the diameter of the wire and L_c and L_w are the inductance of the circuit and the wire respectively.

Using these expressions the times to melt were calculated for the wires and voltages used. Figure 7 shows the results as a function of the initial voltage. Also included in these plots are the experimental values and values calculated using a simple damped oscillator having the same electrical parameters as the exploding wire circuit. The agreement between the experimental data and the calculated values using Bennett's expression is good. The damped oscillator values give a poor fit. This is due to the fact

that no change of resistance with heating is allowed for in the simple equation.

g. First Pulse Charge

The charge delivered through the wire during the first pulse is shown in Figure 8, decreases initially with increased initial voltages for all wires. As the voltage is increased further however the charge is almost constant for all of the wires. Using the values of first pulse charge the total energy dissipated in the electrical circuit during the first pulse can be estimated using the expression

$$E = q(V_0 - (q/2C)) \quad [7]$$

where E is the energy, q is the first pulse charge, V_0 is the initial voltage and C is the capacitance. In every case this corresponds almost exactly to the first pulse energy dissipated in the wire.

DISCUSSION

a. Descriptive Model

Although some initial non-uniform heating or superheating of the wire may occur, thermal equilibrium is probably achieved over the time of the first pulse. Thus the energy to vaporize at the normal boiling point seems a reasonable criterion of the extent of vaporization. During the first pulse the wire begins to expand and to generate a shock in the environment (20). Bennett (21) estimates the shock energy in his system as approximately 50% of the input electrical energy. Although the shock formation process for

Charge in First Pulse (Coulombs/gm Atom) vs.
Initial Capacitor Voltage (Kilovolts)

C = 45 μ f

ALL IRON WIRES 7.0 cm LONG

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C = 45 μ f

ALL WIRES 7.0 cm LONG

the experiments reported here may not be as efficient [Jones and Gallett (22) have shown the shock energy to be dependent on system conditions], a significant fraction of the first pulse energy appears as shock. Müller (23) has shown that a shock wave separates from the vapor front of the wire soon after the first pulse. The energy for this can only be derived from the thermal energy of the heated wire material. Because of shock formation some of the material vaporized in the first pulse must recondense, except perhaps for the highest energy explosions of the aluminum, copper and silver wires.

At the time just before the reinitiation of the discharge the state of the wire material is a mixture of vapor and liquid droplets at or near the normal boiling point. The restrike is a gaseous discharge (24) and transfers more energy to the wire material. During the restrike the electrical circuit has an average resistance of 22 mohms as determined from the decay of the circuit oscillations. Under short circuit conditions the circuit has a resistance of 11.5 mohms. Thus approximately 50% of the restrike energy is deposited in the wire material and 50% in the remainder of the electrical circuit, mainly in the spark gap. The restrike energy is the total bank energy minus the first pulse energy. The energy deposited during the dark pause is considered insignificant. Reithel (25) has shown in an explosion with dark pause that no emission lines of oxygen or nitrogen occur in the optical spectra of the vapor column although these lines do appear in the spectrum of the spark gap. Photographs by Müller (23) and Cheng et.al. (26) show restrike occurs through the center of the wire under explosion

conditions approximating ours. These observations indicate that the majority of the restrike energy deposited in the region of the wire is deposited in the wire and not in the surrounding atmosphere. Under certain conditions, however, a large fraction of the restrike energy can be deposited in the ambient gas (27). With our experimental system we estimate that all of the restrike energy is deposited in the region of the wire and that approximately 50% of the total restrike energy, is deposited directly in the wire materials.

The restrike energy is probably not deposited uniformly in the wire material. The vaporized metal will heat preferentially and the liquid droplets will be heated in turn by the hot gas.

The restrike energy in all but the very lowest energy explosions exceeds the energy to vaporize completely. The vapor is heated strongly during this time; DeSieno and Nash (28) observed temperatures equivalent to 1 ev in the restrike of copper wire explosions under conditions similar to ours. As in the first pulse this new input of energy generates a shock in the environment (23) because of the expansion of the wire vapor. At the conclusion of the restrike the system begins to cool and the vapor condenses.

For understanding the chemistry of the explosion we interpret the electrical portion of the explosion as two vaporizations and two condensations. During the first pulse the metal is either totally or partially vaporized. If partially vaporized the metal remaining as liquid is in the form of small droplets. When the first shock wave forms some of the vapor condenses during the energy transfer from vaporized metal to the ambient gas. The condensing

vapor may deposit on pre-existing liquid droplets, if present, or may form droplets independently. These droplets will begin to coagulate. Calculations by Stewart(29) have indicated that coagulation is the major factor in the growth of particles in a vapor cloud as opposed to direct condensation. During the dark pause the vapor continues to expand and cool with further condensation. During the restrike phase the additional energy vaporizes to some extent the liquid droplets as well as heating the vapor. The efficiency of this vaporization is variable, and depends on the magnitudes of first and second pulse energies. Rough estimates have been made in our laboratory using radioactive tracer techniques and appear to be of the order of 50% (1). Finally after restrike a new shock wave has formed and some energy has been transferred to it from the vapor. The vapor continues to expand and cool, condensing into or onto liquid droplets which then agglomerate to form the final particle distribution.

The problem of chemical reaction between the metal and ambient gas is not considered above and must be the subject of further research.

b. Physical Model

An expression can be derived relating the first pulse energy to the time of the first pulse, using only the physical constants of the wire:

$$E = m(r^2 - r_0^2)/2t^2 + E_0 \quad [8]$$

where E is the first pulse energy in ergs, m is the mass of the wire, r is the radius of the wire at burst, r_0 is the

original wire radius in cm, t is the difference between the time of the first pulse and the time to melt and E_0 is a constant. We have used Newton's second law of motion with the following assumptions to derive equation [8]:

1. the wire expands with cylindrical symmetry,
2. the mass of the wire is in an infinitely thin shell at the leading edge of the expansion,
3. the wire expands against no counter pressure, and
4. the energy is added instantaneously.

This expression partitions the input energy into two forms, one a constant the E_0 term and the second variable term which is an hydrodynamic energy. Nash (30) has presented a similar expression to describe the expansion of the wire during the dark pause phase of the explosion.

Figure 9 shows the results of plotting first pulse energies against $1/t^2$ for the seven wires. Plots of the three sizes of iron wires give slopes directly proportional to their masses and intercept the energy axis at the same value of E_0 within experimental error when reduced to energy per unit mass basis. The slope of equation [8] yields radii at burst for all wires between 25 to 40 times that of the original wire. These estimates must be too large because in the derivation of equation [8] it was assumed that all of the hydrodynamic energy was available from the beginning of the expansion. Müller's data (20) reveal that the expanded radius is about 20 times that of the original wire at the end of the first pulse under his conditions.

The constant slope of the plots in Figures 9 and 10 implies that the radius at burst for a given wire is the same irrespective of the energy of the explosion.

Figure 9

Figure 10

c. E_0 Energy

The point on the energy axis where the curves intersect in Figures 9 and 10 is hypothetical and extrapolated from the experimental data. It is interpreted as the energy necessary to place the wire in the "exploded" state at the burst point with no residual energy for expansion. Another view is that it is the energy necessary to produce a nonconducting state from the solid wire. The difference between the E_0 energy and the energy to the liquid boiling point of the five metals, compared to the vaporization energy at the normal boiling point (Table 2) shows that 22 to 40 percent of the vaporization energy is necessary to produce the nonconducting state of the wire.

Whether this E_0 energy has a fundamental significance has yet to be determined. The agreement of E_0 between the three sizes of iron wire suggests that it is a property of the wire material. Further experimental studies using wires of other metals, lengths and diameters must be made to illuminate this point.

TABLE 2

E_o Energy Relative to the Vaporization Energy

<u>Metal</u>	<u>E_o Energy^b</u>	<u>Energy for liquid at boiling point (E_b)^a</u>	<u>Difference $E_o - E_b$</u>
silver	31.0	17.6	13.4
aluminum	44.0	18.5	25.5
copper	50.0	21.5	28.5
iron	57.0	30.1	26.9
nickel	56.0	28.4	27.6

<u>Metal</u>	<u>Latent Heat of Vaporization (ΔH_v)^a</u>	<u>Fraction of Vaporization Energy in E_o i.e. $(E_o - E_b)/\Delta H_v$</u>
silver	60.7	0.222
aluminum	67.9	0.376
copper	72.8	0.391
iron	84.6	0.318
nickel	90.5	0.305

^aValues calculated from ref. (18).

^bAll energy values in kcal/gm atom.

SUMMARY

A detailed examination of the first pulse energetics of the five metal wire materials has revealed systematic behavior based on elemental type. Most of our work to date in studying fractionation systematics have used iron and aluminum wires because of their relevance to the problem of nuclear debris fractionation. Iron and nickel, of the five elements studied show very similar first pulse electrical behavior, and are vaporized with much poorer efficiency than are aluminum, copper or silver. This behavior has a profound effect on the mixing history of the exploding wire products and on the fractionation systematics of trace elements coated on the surface of iron wires (1).

The work reported above reveals that immediately subsequent to the first pulse a two phase system of droplets and vapor must exist even in those instances in which the first pulse energy is adequate to vaporize the wire material completely, because of shock energy losses. Experimental confirmation of this view is provided by tracer experiments on mixing efficiency (1). To further clarify the picture direct measurements of shock energy loss subsequent to both the first pulse and restrike phases are necessary. Also, our bank is currently being redesigned to permit short-circuiting the system after the first pulse has been delivered, using a variation on a technique used by Joncich (31). A series of experiments in which incremental portions of the second pulse are introduced by the shortcircuiting method will lead to a much better understanding of the role of the second pulse in affecting the properties of the final product.

The significance of E_0 , and the observation that typically about 35% of the normal vaporization energy is required to produce a non-conducting state in the wire are worthy of further study.

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