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DUAL VAPORIZATION-CONDENSATION BEHAVIOR
IN THE ELECTRICAL EXPLOSION
OF IRON WIRES

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ABSTRACT

The electrical explosions of iron wires were conducted to investigate the mixing efficiency of surface deposited Fe-59 tracer with the bulk of the wire material. The explosion products, generated in either air or argon, were size graded in situ with cascade impactors. In air a two phase system was produced, a metal phase at the larger particle sizes ($> 1\mu\text{m}$) and an oxide phase (Fe_3O_4) at smaller particle sizes ($< 1\mu\text{m}$). The mixing efficiency is interpreted in light of a dual vaporization-condensation model for these wire explosions.

Keywords: Exploding Wires, Vaporization, Condensation.

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INTRODUCTION

We have been examining the exploding wire phenomenon as a potential tool for studying high temperature condensation phenomena in geochemically interesting systems. In a previous paper (1) we presented the results of electrical measurements which provided estimates of the energies delivered during the first pulse for Ag, Cu, Al, Fe and Ni wires. The efficiency of energy input during the first pulse, before the wire explodes, is a function of the wire material for wires of comparable diameter, and for iron, measured at three diameters, a function of wire diameter. The capacitor system was of conventional design storing a maximum of 9000 joules (45 μ f at 20kV) with a ringing frequency of 32.5 kHz. The experiments were conducted using charging voltages between 4 kV and 20 kV. Low electrical resistance elements such as Ag and Cu received higher first pulse energies than Fe and Ni under the same explosion conditions. Analysis of input energy versus time behavior suggested that a critical energy input is needed to change the wire from a conducting to non-conducting state, i.e., to burst. The critical energy appears to be about one-third the energy required to vaporize the wire at its normal boiling point.

Most of our work to date has used iron wires of 7 cm length and 9 mil diameter. A charging voltage of 18 kV, corresponding to a stored energy of 7280 joules, is required to provide the energy necessary to vaporize the wire in the first pulse. The vaporization energy for the wire is but 144 joules, and the total energy expended in raising the wire from room temperature and vaporizing it is 195 joules. We concluded, therefore, on the basis of energy balance

considerations that the explosions of metal conductors under some conditions must be characterized by a dual vaporization-condensation behavior, i.e., one vaporization-condensation followed by another. This is particularly the case when the first pulse energies are of the same magnitude as the vaporization energy, when energy input rates are not too high, as is the case with banks characterized by significant inductance, and when the low current phase or dark pause follows the disruption of the wire. A dual vaporization-condensation behavior seems to be required because a shock wave develops subsequent to wire disruption after the first pulse (2). Hence, the completely or partially vaporized wire material must lose energy and a portion of the vaporized material must recondense. The time required to vaporize the wire under our conditions is of the order of microseconds, and the first pulse phase can be of the order of a fraction of a microsecond to 10 microseconds (1). When the vapor particle density drops sufficiently (to the order of 10^{18} particles per cubic centimeter in comparable experiments (3)), a new surge of electrical energy passes through the mixture of vapor and metal droplets. The second input of energy may vaporize the material that has previously condensed, and as well that which has never been vaporized. A second shock wave is generated (2). The system expands and eventually achieves ambient pressure. The condensed products now mix with the ambient atmosphere, and in air an oxide product is formed. The overall product is a mixture of oxide and metal particles in air explosions, as will be developed further below.

We will now present some independent evidence for the dual vaporization-condensation mechanism in iron wire explo-

sions, obtained by the use of surface-coated radioactive tracers on iron wires.

Materials and Methods

It is apparent that the applicability of the exploding wire technique to a systematic study of high temperature condensation processes is greatly abetted if an understanding is had of the extent to which trace radioelements deposited on the wire surface mix effectively with the bulk of the wire material in the course of the explosion. Apart from this there are advantages to plating the radioelement on the surface of the wire, since this procedure obviates the need to incorporate trace elements into the wire by diffusion or by special fabrication methods. Such procedure can be reserved for another category of experiment in which one may be interested in the behavior of tracers dispersed throughout the volume of the wire.

The efficiency of mixing of surface-plated Fe^{59} with the stable iron matrix material was investigated by collecting the explosion products with cascade impactor devices of two designs. It was anticipated that imperfect mixing should lead to a variable ratio of radioactive to stable iron in various particle size groups. The Health and Safety Laboratory (HASL) model cascade impactor (4) gives five fractions of size-graded particles in the micrometer (μm) to sub μm diameter size range, four on glass slides and one on a backup filter. The Anderson model impactor (5) separates particles into eight size fractions, including the backup filter. Results given by the two devices are not entirely consistent. The HASL unit appears to yield a superior collection and separation of the larger particles ($>5\mu\text{m}$) and the Anderson achieves a much superior resolution of particles ($<1\mu\text{m}$). Cascade impactor collections are supplemented by

ocular and electron microscopic analysis of particle size distribution, and the composition of the particles is established by X-ray diffraction. A combination of the evidence provided by the two particle separation systems yields a fairly self-consistent picture on which our conclusions will be based.

Some of the test explosions to measure the mixing effect were conducted in a 20 liter stainless steel vessel, in air at one atmosphere pressure. Other air explosions, and those in argon, were carried out in a 78 liter stainless steel chamber; in either case the cascade impactor was placed inside, on the floor of the chamber. In the sets of experiments to be reported on, 7 cm, 9 mil diameter analytical grade iron wires were used. The Fe⁵⁹ tracer was electroplated on the surface of the wires. There is some evidence of a "chamber" effect. The larger particles, in excess of 5 μ m, appear to be less efficiently collected in the 78 liter chamber than in the 20 liter chamber, for reasons not yet understood, since wall loss effects should be expected to be more pronounced in the smaller chamber. However these effects will have little bearing on the interpretation of the results.

The samples from the impactor stages were assayed by gamma ray spectroscopy, using either NaI(Tl) or Ge(Li) detectors. This yielded the Fe⁵⁹ in each cascade impactor stage. Each cascade impactor fraction was measured for its stable iron content by a standard o-phenanthroline procedure on a suitable aliquot of solution by spectrophotometry.

Twelve experiments using surface-plated Fe⁵⁹ and the HASL impactor were conducted in air at ambient pressures and at specific energies ranging from 8.9 to 124 joules per

milligram of iron, at charging voltages of 3 to 12 kilovolts. Four experiments were conducted in argon using the HASL impactor at an energy of 86.2 joules per milligram in the 78 liter chamber, at pressures of 1 and 2 atmospheres. Anderson cascade impactor experiments were performed at 4, 8, 12 and 16 kilovolts in the 78 liter chamber. In a typical experiment the wire was exploded, the current and voltage traces were recorded to provide the first pulse energy, and the impactor was run for one minute at a flow rate of 10 liters per minute in the 20 liter chamber and 28-40 liters per minute in the 78 liter chamber. Between 15 and 25 percent of the total product was collected in a given experiment.

Results

All explosions in air produced a two phase population of spherical particles as revealed by ocular and electron microscopy. The large end of the particle size spectrum ($>1\mu\text{m}$) consisted of metal spheres and the smaller particles ($<1\mu\text{m}$) consisted mainly of iron oxide. An easy distinction between the metal and oxide phases could be made by viewing the product in the ocular microscope under dark field illumination. The X-ray diffraction measurements revealed the oxide component to be mainly magnetite, Fe_3O_4 . The ratio of the two phases is determined by the specific energy of the explosions (joules/mg) with the oxide phase becoming more predominant the higher the specific energy. For example at a stored energy of 8.9 joules/mg it is estimated that about 60% by weight of the product is oxide, whereas at 124 joules/mg about 96% is oxide. These results are similar to those observed by Karioris and Fish (6).

The results for the HASL cascade impaction collections are summarized in Tables 1a and 1b for air and argon explosions, respectively. Table 2 contains the data for the collections with the Anderson cascade impactor.

The tables give the predominant size particle collected on each stage, the mass of iron expressed in terms of the percent of the total collected found on a given stage, and the fractionation or R factor for each stage. R is defined as the percentage of Fe⁵⁹ found on a given stage divided by the percentage of iron mass found on that stage. It is directly a measure of the efficiency of mixing of the radioactive and non-radioactive forms of iron.

Discussion

The HASL collections provide the best definition of the largest particles in the distribution, and the Anderson impactor gives a better separation of the smaller particles. Reference to Tables 1a and 1b reveals that the metal sphere component on stages 1 and 2 in air and argon explosions is always depleted in tracer iron relative to metallic iron. The fractionation factors in stages 1 and 2 appear to be roughly independent of the energy of the explosion in both air and argon, although there may be a tendency for increased fractionation at higher specific energies. The fraction of the mass in the large sizes decreases dramatically when the specific energy is increased from 8.9 to 80.3 joules/mg. At the higher energies the composition of the smallest particle fraction on stage 5 approaches that of the pre-shot wire. This behavior reflects the more efficient vaporization and mixing that occurs at higher specific energies.

TABLE 1a
 Distribution of Fe⁵⁹ Activity and Iron Mass in
 Size Fractions of the HASL Impactor
 (Air, 1 atmosphere, 10 liter/min.)

Spec. Energy (joules/mg)		Stage No. and Size (MMD)				
		1 (>5 μ)	2 (5 μ)	3 (3.3 μ)	4 (1.6 μ)	5 (<1.6 μ)
8.92	% mass	28.4 \pm 1.8	8.3 \pm 0.5	5.8 \pm 1.5	12.4 \pm 1.4	44.9 \pm 3.0
	% Activity	18.1 \pm 3.0	7.6 \pm 0.8	7.3 \pm 1.3	14.9 \pm 0.9	52.0 \pm 4.4
	R	0.64 \pm 0.18	0.92 \pm 0.12	1.26 \pm 0.31	1.20 \pm 0.13	1.16 \pm 0.11
80.3	% mass	2.9 \pm 0.1	5.8 \pm 1.6	11.7 \pm 2.4	9.4 \pm 0.7	70.3 \pm 3.4
	% Activity	2.2 \pm 0.3	4.5 \pm .9	12.0 \pm 2.6	10.0 \pm 0.5	71.4 \pm 3.0
	R	0.76 \pm 0.14	0.76 \pm 0.34	1.02 \pm 0.30	1.06 \pm 0.09	1.01 \pm 0.06
124	% mass	2.6 \pm 0.7	1.9 \pm 0.05	6.0 \pm 0.5	8.4 \pm 0.1	81.2 \pm 1.8
	% Activity	1.1 \pm 0.1	0.88 \pm 0.12	5.1 \pm 0.4	10.6 \pm 1.4	82.4 \pm 2.0
	R	0.42 \pm 0.28	0.46 \pm 0.14	0.84 \pm 0.11	1.26 \pm 0.13	1.01 \pm 0.03

TABLE 1b
 Distribution of Fe⁵⁹ and Iron Mass in Size
 Fractions of the HASL Impactor of Products Collected
 in Argon at 40 liter/min.

Spec. Energy (joules/mg)		Stage No. and Size (MMD)			4 (0.45μ)	5 (<0.45μ)
		1 (>2μ)	2 (2μ)	3 (0.9μ)		
86.2	% mass	4.6 ± 1.4	3.8 ± 0.4	6.5 ± 0.5	10.7 ± 0.5	74.4 ± 1.6
	% Activity	2.9 ± 1.0	2.6 ± 0.3	5.6 ± 0.3	10.8 ± 0.4	78.1 ± 0.3
	R	0.63 ± 0.46	0.68 ± 0.16	.99 ± 0.09	1.01 ± 0.06	1.05 ± 0.02
86.2	% mass	1.6 ± 0.5	2.8 ± 0.3	10.3 ± 0.5	16.2 ± 1.4	69.4 ± 1.1
	% Activity	0.98 ± 0.32	2.1 ± 0.1	10.7 ± 0.4	18.0 ± 1.5	68.3 ± 1.4
	R	0.61 ± 0.45	0.75 ± 0.12	1.03 ± 0.06	1.11 ± 0.12	0.98 ± 0.03

TABLE 2

Distribution of Fe⁵⁹ Activity and Fractionation Factors
in Size Fractions of the Anderson Impactor

(Air, 1 atmosphere, 28 liter/minute, 78 liter Chamber)

Stage	D _g	4kV (15.8 joules/mg)		8kV (63.5 joules/mg)		12kV (143. joules/mg)		16kV (254. joules/mg)	
		% Fe	R	% Fe	R	% Fe	R	% Fe	R
1	5.52	3.32	.97	2.44	1.20	2.56	1.11	3.62	.84
2	4.85	3.87	1.01	1.48	1.15	1.78	1.14	0.80	1.26
3	3.38	5.50	1.50	1.48	1.02	.74	1.08	1.25	1.00
4	2.78	6.23	1.90	1.99	1.13	1.18	1.33	0.54	1.28
5	1.21	12.30	1.72	8.37	1.46	4.13	1.33	2.03	2.14
6	.441	9.23	1.00	7.04	1.34	5.51	1.00	3.71	.84
7	.0505	18.58	.66	8.98	.98	7.70	.95	3.26	2.22
8	.0382	40.97	.74	68.22	.89	76.40	.95	84.78	.94

D_g Geometric mean diameter of stage.

% Fe Percentage of iron mass found on stage.

It is probable that the largest particles, the metal spheres larger than a few microns, were never completely vaporized in these experiments. Their fractionation factors lie between 0.4 and 0.7, a composition between that of the initially vaporized material and the inert wire. It is probably safe to assume that all the surface-plated Fe⁵⁹ is vaporized during the first pulse. This is consistent with the view that the surface vaporizes first (7) although it does not necessarily imply that all the vapor generated during the first pulse originates from the surface of the wire.

With this assumption it is possible to treat the composition on each stage of the cascade impactor as a linear combination of two components. The portion of the wire vaporized during the first pulse has an R factor of 1/x, where x is the fraction of the wire vaporized during the first pulse. The R factor of the inert wire material is 0. The ratio of iron which remained unvaporized in the first pulse Fe(liquid), to iron that was vaporized during the first pulse Fe(vapor) in the stage 1 particles of the HASL collector can be shown to be:

$$\frac{\text{Fe(liquid)}}{\text{Fe(vapor)}} = \frac{1/x - R_1}{R_1} \quad [1]$$

R₁ is the fractionation factor found in stage 1. The fraction of the wire initially volatilized during the first pulse is deduced from the first pulse electrical measurements (1). In the 8.9 joule/mg explosion x = 0.33, and it follows that the ratio of iron vaporized in the first pulse to total iron on stage 1 particles is 0.21. Thus 79 percent of the mass found on this stage did not experience vaporization during the first pulse. It is improbable that all particles on

stage 1, which covers a range of sizes, are of the same specific activity. This stage undoubtedly contains particles consisting of coalesced high and low specific activity spheres which suffered encounters while still molten.

A variant on equation [1] is of general applicability for calculating the fraction of iron found on each stage of the cascade impactor which originated from the first pulse vaporization phase. The fraction of iron vaporized in the first pulse which is found on a given stage of the cascade impactor is xR_i where R_i is the fractionation factor for Fe^{59}/Fe on that stage. In the HASL collections, typically 40-50% of the total mass of iron found on stages 3 through 5 was the result of first pulse vaporization processes, indicating the balance, or 50-60% of the iron on these stages resulted from second stage heating and dispersion of iron that escaped vaporization in the first pulse.

Reference to Table 2 reveals a persistent tendency for a maximum in the fractionation factor of Fe^{59}/Fe to occur in the vicinity of stage 5 (1.2 μm) in the Anderson collections between 4 and 16 kilovolts. The 16 kV explosion is more erratic for reasons to be discussed below.

In Table 3 are summarized some data for the 4, 8, 12 and 16 kilovolt explosions based upon the Anderson collections which suggest that the high specific activity of the iron found in the vicinity of stage 5 (1.2 μm) is related to the nature of the product formed during the first pulse phase of the explosion. In the table the values for the fraction of iron vaporized during the first pulse are taken from the first pulse electrical measurements (1). The fifth column gives the ratio of the $[Fe^{59}/Fe]_{max}$ to $1/x$, the fractionation factor of the originally vaporized material. The

TABLE 3

Fraction of Vaporized Iron,
Maximum Specific Activity vs
Initial Capacitor Voltage

<u>Voltage (kV)</u>	<u>χ</u>	<u>1/χ</u>	<u>(Fe⁵⁹/Fe)_{max}</u>	<u>(Fe⁵⁹/Fe)_{max}/1/χ</u>	<u>% Fe</u>
4	0.33	3.04	1.90	0.63	6.23
8	0.44	2.27	1.46	0.65	8.37
12	0.58	1.72	1.33	0.77	4.13
16	0.83	1.21	2.14	1.76	2.03

χ - Fraction of iron vaporized in the first pulse

sixth column gives the percentage of stable iron found on the stage.

From 4 kilovolts through 12 kilovolts we find a ratio of $\{Fe^{59}/Fe\}_{max}$ to $1/x$ of about 0.7 the values expected if the particles on this stage represented a portion of those formed during the first pulse recondensation, and no further mixing with other lower specific activity material ensued. In fact, a portion of the material found on the intermediate stages has particle sizes similar to the very small particles found on stages 7 and 8. This small size component is present as satellites on the larger spheres characteristic of the stage. Any addition of particles of the composition characterizing stage 7 or 8 will, of course, tend to reduce the Fe^{59}/Fe value found on stages 4 or 5.

The absolute quantity of Fe found on this most highly fractionated stage decreases with increasing energy of the explosion. This may be interpreted as due to destruction of this component in part in the great surge of energy during the restrike. Available restrike energies at 4, 8, 12 and 16 volts are estimated to be, respectively, 132, 613, 1560 and 2795 joules (1).

As before, xR_i is assumed to represent the fraction of the iron found on a given stage that experienced vaporization during the first pulse, all or a part of which recondensed subsequent to the first pulse. The percentage of such iron found on each stage of the cascade impactor is shown by the open circle datum points in figure 1a through 1d for each of the four explosions. The solid circles represent iron that escaped vaporization during the first pulse but which was vaporized or dispersed during the second pulse.

Discussion will be confined initially to the 4, 8, and 12 kilovolt behavior. Iron which experienced vaporization in the first pulse is found preferentially in the vicinity of 1.2 μm and in the smallest sizes. As the second pulse energy increases a larger fraction of the iron which condensed prior to the second pulse revaporizes and appears in the 0.04 - 0.05 μm sizes.

The 16 kV data do not fit a pattern consistent with a fraction vaporized of 0.83. In Table 3 the Fe^{59}/Fe value is anomalous. This behavior is most probably due to poor mixing of vaporized material subsequent to the first pulse. The dwell time at 16 kV is about 0.85 μs compared to 4.5 μs at 12 kV. Thus, the second surge of energy occurred directly on the heels of the first pulse. Further, as we approach complete vaporization of the wire during the first pulse the radially directed velocities must be larger, and localized pockets of high and low concentration may be formed which poorly mix. The apparently erratic behavior of the Fe^{59}/Fe ratio in the 16 kilovolt experiment was observed to be reproduced almost perfectly by such dissimilar surface-coated tracers as In, Sn, Sb, Te and I in the same experiment.

Summary

The explosion of 9 mil iron wires on which Fe^{59} was surface-coated provides confirmation of a two step vaporization-condensation process at explosion energies below 12 kV. The Fe^{59}/Fe ratios in the size-graded particle fractions indicate that a particle size group in the vicinity of 1.2 μm is formed subsequent to the first pulse and is not

DISTRIBUTION OF IRON WITH PARTICLE SIZE

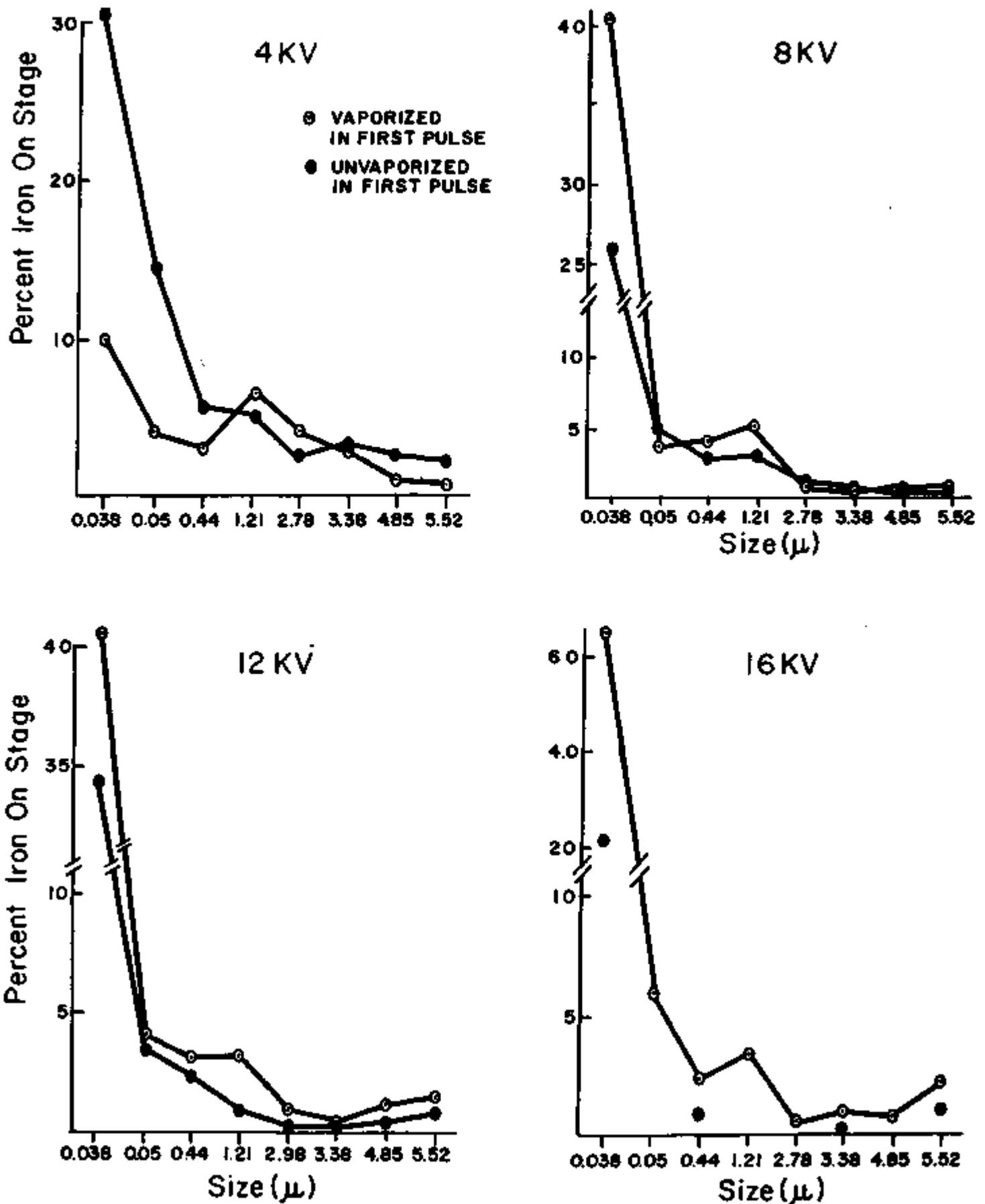


Figure 1

completely destroyed when the second pulse ensues.

These mixing experiments also suggest that there is an intermediate range of explosion energies in which mixing is optimum. In these experiments it probably occurred in the vicinity of 12 kV.

If other radioactive tracers are introduced onto the wire surface, one may determine the manner in which these trace elements fractionate relative to each other and to the matrix wire material in various particle size groups. For many wires a suitable isotopic tracer can be found which serves to define the mixing history of the surface-coated tracers with respect to the wire material. For example Cu^{64} could be used with copper wire.

Examination of the size fraction in which the wire isotopic tracer is enriched to a maximum degree relative to the nonradioactive form of the element constituting the wire, serves to identify the material which condensed during the first pulse and escaped vaporization during the second pulse.

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