- I. Rate and Mechanism of the Hydrolysis of the Hydroxylamine Disulfonate Ion
- II. The Low Voltage Electrically Exploded Wire

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Summary

SUMMARY

I. The rate of hydrolysis of potassium hydroxylamine disulfonate has been measured. This rate may be satisfactorily accounted for by assuming that HON(SO₃)₂H•H₂O[•] is the reaction intermediate whose rate of decomposition into the final products determines the over-all rate of hydrolysis.

II. The study of the low voltage electrically exploded wire was initiated to see if it could be used as a source of metal vapor. The nature of the processes occuring were checked by determining the amount of energy which is dissipated in the filament by the electrical surge and by examining the metal deposit.

For minimum energy explosions, the total energy dissipated in the filament per cm varies a little with filament length, but is unaffected by the substitution of helium for air at atmospheric pressure. The average filament temperature when rupture occurs decreases with increasing filament diameter. As yet no metallic deposits have been found which would indicate that vapor is present during minimum energy explosions.

For moderate energy explosions in vacua, the energy dissipated in the filament is independent of pressure changes from 50 to 760 mm. A second process occurs from 10⁻⁴ to 135 mm. As yet we cannot be sure whether it is a gaseous discharge or whether the filament has vaporized completely. The two processes overlap from 50 to 135 mm. The appearance of the metal deposits in high vacuum indicate that only vapor has been deposited.

For moderate energy explosions in the atmosphere it is found that the energy input into the filament is a simple function of initial condenser voltage and of filament length.

When copper filaments have been exploded in a number of different gases at low pressures no resulting changes in pressure were found Part I

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Rate and Mechanism of the Hydrolysis of Hydroxylamine Disulfonate Ion [Reprinted from the Journal of the American Chemical Society, 63, 2123 (1941).]

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The Rate and Mechanism of the Hydrolysis of Hydroxylamine Disulfonate Ion

By SAM NAIDITCH AND DON M. YOST

Neutral or dilute acid solutions of potassium hydroxylamine disulfonate hydrolyze at a measurable rate at room temperature to give potassium hydroxylamine monosulfonate and potassium bisulfate, the hydrolytic reaction being, in ionic form

$$HON(SO_3)_2^- + H_2O = HONHSO_3^- + H^+ + SO_4^-$$
(1)

The hydroxylamine monosulfonate ion is relatively stable and does not hydrolyze in dilute acid solution except at higher temperatures. Wagner¹ made a single measurement on the rate of hydrolysis of the disulfonate and found it to be proportional to the concentrations of $HON(SO_3)_2^{=}$ and H⁺. The present paper describes the results of a detailed study of the rate and mechanism of this hydrolysis.

Preparation of the Materials. Experimental Procedure

Potassium hydroxylamine disulfonate was prepared according to the method described by Rollefson and Oldershaw² in which an ice-cold, acetate-buffered solution of potassium nitrite is treated with sulfur dioxide. The moist salt obtained was washed with ice-cold water and used directly, or it was washed repeatedly with absolute alcohol, and, after drying by evaporation, it was placed in a vacuum desiccator over concentrated sulfuric acid or phosphorus pentoxide and kept at about 5°. The anhydrous salt thus prepared, K₂HON(SO₃)₂, could be kept for more than a month without decomposition.

In the first 35 runs the freshly prepared, moist salt was washed repeatedly with ice-cold water, and then portions of it were dissolved rapidly in a thermostated volumetric flask nearly filled with a mixture of water and a measured quantity of hydrochloric acid; time was counted from solution of the salt upon shaking after filling the flask to the mark. For the remainder of the measurements the alcohol-washed salt was used, accurately weighed amounts being dissolved in water in a volumetric flask as before. For those experiments in which acid was added initially, hydrochloric acid was used.

The reaction was followed by determining the acid concentration of the reaction mixture at measured intervals. Samples of 25 or 50 ml. were pipetted into an excess of standard sodium hydroxide to stop the reaction, and the excess base was back-titrated with standard hydrochloric acid, using phenolphthalein as an indicator. Consistent results were not obtainable when the back-titration was postponed for more than about fifteen minutes.

All solutions used for the rate runs were carbonate-free, and all flasks were flushed free of carbon dioxide before use. The samples withdrawn from the reaction mixtures were pipetted by means of nitrogen under pressure. During the titration of the mechanically stirred samples, carbon dioxide-free air was passed into the flasks used.

That the alcohol-washed, anhydrous $K_2HON(SO_3)_2$ was pure is shown by the following experiments, in which accurately weighed amounts of the salt were dissolved in pure water and, after several days, the acid formed was determined by the same procedure as that used for the rate determinations.

K2HON(SO3)2 taken, g.	Final acid concn. found, mole/l.	Final acid concn calcd., mole/l.	Diff., %
0.6076	0.00453	0.00451	0.4
.5630	.00417	.00418	.2

It is believed that the present preparations of the pure, anhydrous potassium hydroxylamine disulfonate are the first that have been reported.

Results of the Rate Experiments

At ionic strengths from about 0.01 to 0.4 m the rate of hydrolysis in acid solution at 25° is adequately represented by the rate equation

$$- d(\Sigma Ds^{=})/dt = k(\Sigma Ds^{=})(\Sigma H^{+}) = k(a - x)(b + x)$$
(2)

where $(\Sigma Ds^{=})$ is the total concentration of hydroxylamine disulfonate at the time t, and a is its initial concentration in mole/1.; b is the initial normality of acid, and x is the normality produced by the hydrolysis of the disulfonate during the time t. This equation may be integrated to give

$$\log \frac{b+x}{a-x} = \frac{a+b}{2.303}kt + \text{const.}$$
(3)

The specific reaction rate constants, k, were obtained from the slopes of the plots of log (b + x/a - x) against t. Apparently the acids H₃O⁺, HSO₄⁻, HON(SO₃)₂H⁻, and HONHSO₃H, when present in appreciable concentrations, are equally

⁽¹⁾ Wagner, Z. physik. Chem., 19, 678 (1896).

⁽²⁾ Rollefson and Oldershaw, THIS JOURNAL, 54, 977 (1932).





Fig. 1.—Curves for the evaluation of acid rate constants at 25.00° .

effective in catalyzing the reaction in this ionic strength range, since, as may be seen in Fig. 1, the curves show no systematic deviation from linearity.

TABLE I REPRESENTATIVE TIME-CONCENTRATION DATA FOR RATE Measurements at 25.00°. Run 37 Run 10 Run 42 Run 39 a = 0.0473a. = 0.0495a = 0.00448 a = 0.00472mole/l. $b = none^{a}$ b = 0.00640 bb = none^{*a*} N 0.000152 N $\mu = 0.142$ $\mu = 0.155$ $\mu = 0.0136 \quad 0 = 0.0142$ k = 0.262 l k = 0.257k = 0.844k = 0.837mole⁻¹ min.⁻¹ $x \times 10^{3}$, mole/1. $t, x \times 10^2,$ min. mole/l. $\times 10^{4}$, mole/1. $x \times 10^4$, mole/1. x t, min. x min. min. 1.12574.50181 2.0411 18 1,199 241.3442 1.595 132 6.06 230 2.4638 1.67 60 1.885 181 7.14 2722.7058 2.0390 2.4282368.52 318 3.423.78 2.683.44028510.38344 81 148 11.225.76100 3.39 178 3.861324 458 122 4.32208 4.618 376 12.90503 6.90 5.3214.40 559 7.32 144 242 4.912453 164 6.6553217.88 603 8.82 18.60189 8.93 618

256 16.17 ^a When the value *none* is given for the initial acid concentration, it means that no acid was added initially. The initial acid concentration is, therefore, only that obtaining in a solution of the disulfonate.

12.08

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In Table I are presented the time-concentration data for four typical experiments made at moderate and at low ionic strengths; in two of these runs acid was added initially. Table II contains the rate constants found at 25.00° for a number of experiments. The significance of the constants shown in the last four columns of the table will appear later.

In those runs in which no acid was added to the disulfonate, the intercepts of the curves with the ordinate at zero time (see Fig. 1) were larger than expected; for example, the intercept for run 37 corresponds to a value of $b = 1.06 \times 10^{-3}$ mole/l. whereas, since no acid was added initially, b is at most $10^{-6.8}$ (determined by use of a glass electrode about one minute after a test solution was made up). This indicates that the catalytic effect of water must be considered. This effect is included in the rate expression

$$-d(\Sigma Ds^{-})/dt = [k'(\Sigma H^{+}) + k'_{w}(H_{2}O)] (\Sigma Ds)^{-} = [k'(b + x) + k'_{w}](a - x)$$
(4)

where k'_{w} is the rate constant for water catalysis when the activity of water is taken as unity. This equation is readily integrated to give

$$\log\left[\frac{b + \frac{k'_{w}}{k'} + x}{a - x}\right] = \frac{\left[a + b + \frac{k'_{w}}{k'}\right]}{2.303}k't + \log\left[\frac{b + \frac{k'_{w}}{k'}}{a}\right]$$
(5)

When it is assumed, as a first approximation, that the effect of the water catalysis is only important initially, then the rate constants of equation (5) may be obtained graphically from the slopes and intercepts at zero time of curves such as those shown in Fig. 1. This treatment was applied to the results for those runs in which no acid was added initially, and the values of $k'_{\rm w}$ so obtained are shown in Table II.

Because of the approximation involved in the above method for evaluating k'_{w} , the following second method was also used in some cases. The simplified rate equation

$$-\frac{d(\Sigma Ds^{-})}{dt} = k''_{w}(H_{2}O)(\Sigma Ds^{-}) = k''_{w}(a - x) \quad (6)$$

is applicable in the neighborhood of t = 0, providing no acid was added initially. On integration one obtains

$$\log (a - x) = -k''_{\rm w} t/2.30 + \log a \tag{7}$$

and by evaluating the slope of the log (a - x) versus t curve at zero time (when practically all of

REPRESEN?	FATIVE RATE MEA	SUREMENTS ON 7	THE HYDROLYSIS	OF POTASSI	um Hydrox	YLAMINE D	ISULFONATI	E AT 25.00
Expt.	Initial concn. of K2HON(SO3)2, mole/l.	Initial acid concn., mole/1.	Initial ionic strength, µ	$k, \\ 1., mole^{-1} \\ min.^{-1}$	$k'_{W} \times 10^{4}$.	$k_{\mathrm{W}}'' \times 10^4$, min. ⁻¹	k', 1., mole ⁻¹ min. ⁻¹	$k_{\mathrm{B}} \underset{\mathrm{min.}^{-1}}{\times} 10^{2}$
7,8	0.127	0.00640	0.386	0.165			0.163	3.2
9	.0961	None ^a	.288	.202	1.2	2.3	.200	3.0
14	.0846	None	.254	.208	3.8	3.6	.206	2.8
13	.0762	.0104	.239	.229			.227	2.6
15	.0566	None ·	.169	.247	3.1	2.6	.243	2.4
10	.0495	.00640	. 155	.257			.253	2.3
37	.0473	None	.142	.262	2.8	3.0	.258	2.3
29	.0263	None	.0789	.318	1.1	1.5	.310	1.7
38	.0230	None	.0689	.348	2.0	2.1	.339	1.8
30	.0191	None	.0573	.414	1.3	1.2	.403	1.9
40	.00842	None	.0253	.651	1.4	1.1	.626	1.8
39	.00472	None	.0142	.837	0.92		.792	1.7
42	.00448	.000152	.0136	.884			.798	1.5
41	.00273	.000152	.00835	.998			. 926	1.5

^a When the value *none* is given for the initial acid concentration, it means that no acid was added initially; the initial acid concentration is therefore only that resulting from a solution of the disulfonate.

the hydrolysis is caused by water), values of k''_w are found. These compare favorably with the k'_w , as may be seen in Table II. The average value found for k_w was 2.1×10^{-4} min.⁻¹, and it should be practically independent of the ionic strength.

The values of k shown in Table II have been corrected for the catalytic effect of the water as follows. From equation 5, neglecting the effect of k'_w/k' in the logarithm term, the experimental slope, S, is $\left[a + b + \frac{k'_w}{k'}\right]\frac{k'}{2.30}$ hence, $k' = k - k'_w/(a + b)$. The values of k' so calculated are also presented in Table II.

Brönsted's equation as modified by Guggenheim,³ namely

$$\log k = \log k_0 + \frac{Z_1 Z_2 \sqrt{\mu}}{1 + \sqrt{\mu}} + B\mu$$
 (8)

was used to correlate k' with μ for $\mu < 0.1$. On using Fig. 2 and estimating k_0 analytically it was found that

$$\log k' = 0.167 - \frac{2\sqrt{\mu}}{1+\sqrt{\mu}} - 3.4 \mu \qquad (9)$$

The results of the experiments made at 45 and 55° are more difficult to treat than those at 25° because the hydrolytic reaction

 $HONHSO_3^- + H_2O = HONH_3^+ + SO_4^-$ (10)

which may be expected to be catalyzed by acid, can no longer be neglected. A typical log $x/t^2 - x$), t curve at these temperatures is shown in Fig. 3. Features of the reaction to be noted are, (1) the high initial rate, caused by water catalysis; and (2) the upward concavity of the curve at a later time, caused by the hydrolysis of the monosulfonate to hydroxylamine. Since the concentrations of both the monosulfonate and acid increase with time, the hydrolysis of the former becomes important. The effect of water catalysis was estimated as before; the values obtained for k''_w (see Table III) are probably high and therefore the smallest are considered most acceptable.



Fig. 2.—Curve for the determination of Z_1Z_2 and B at 25.00° .

Since no acid was added initially at 45 and 55°, the rate equation for the hydrolysis of the monosulfonate may be assumed to be

 $d(\Sigma HONH_2)/dt = k_2 (\Sigma HONHSO_3^-)(\Sigma H^+) = k_2(x - y)(x + y)$ (11)

where x is the amount of disulfonate hydrolyzed,

TABLE II

⁽³⁾ Guggenheim, Phil. Mag., 19, 588 (1935).

TABLE III

Results of Rate Measurements on the Hydrolysis of Potassium Hydroxylamine Disulfonate at 45 and 55° No acid was added initially in these experiments.

Expt.	Initial concn. of K ₂ HON(SO ₃) ₂ , mole/1.	Initial ionic strength, µ	k, 1. mole ⁻¹ min. ⁻¹	$k_{\rm P}$ l. mole ⁻¹ min. ⁻¹	k'_{w} min. ⁻¹	k''_{w} min1	$k' \\ 1. \text{ mole}^{-1} \\ \min.^{-1}$	k'P 1. mole ⁻¹ min. ⁻¹
				$t = 45^{\circ}$				
50	0.00577	0.0173	5.18	4.59	3.2×10^{-3}	$4.5 imes10^{-3}$	4.83	
51	.04496	.0149	5.66	4.25	4.7	8.3	5.26	
45	.00467	.0141	5.67	5.72	1.8	4.5	5.24	5.29
52	.00342	.0103	6.32	6.22	3.1	4.0	5.74	5.64
47	.00321	.0097	6.33	6.41	2.2	2.7	5.71	5.79
				$t = 55^{\circ}$				
54	.00457	.0137	14.5	14.0	1.9×10^{-2}	$2.1 imes 10^{-2}$	12.5	12.0
55	.00423	.0127	14.8	17.7	3.4	1.5	12.7	
53	.00326	.0098	16.2	16.0	3.5	0.91	13.4	13.2

and y is the amount of hydroxylamine formed, in mole/1. On using this equation in conjunction with (2) there results for x < a

 $d(\Sigma H^+)/dt = k_P(\Sigma H^+)[a - (1 - P)(\Sigma H^+)]$

which integrates to

 $\log\left[\frac{(\Sigma \mathrm{H}^+)}{a - (1 - P)(\Sigma \mathrm{H})}\right] = \frac{ak_{\mathrm{P}}}{2.303}t + \text{const.} \quad (12)$ where $P = k_2/k$.





Fig. 3.-Curves showing the effect of the hydrolysis of hydroxylmonosulfonate ion: $P = 0, \oplus; P = 0.1, O.$

The value of P is not known, but the assumption that an upper limit is P = 0.1 leads, except for the initial period in which water catalysis is important, to the straight line shown in Fig. 3. Since P = 0.10 is probably too large, and since the P's are different for different ionic strengths, the resulting curves, although more nearly linear than those obtained previously, will yield only approximate values of $k_{\rm P}$. The values of the acid rate constant $k_{\rm P}$ obtained using P = 0.10 are tabulated in Table III. The water catalysis corrections to the rate constants were made as before.

The Arrhenius equations for the acid and water catalyzed hydrolysis of hydroxylamine disulfonate were derived for solutions of zero ionic strength and are shown in Table IV which also contains the limiting values of k' and k_w .

TABLE IV The Limiting Values of k' and k_w for Solutions of ZERO IONIC STRENGTH k'_0 1. mole⁻¹ min.⁻¹ k_{w}^{0} min.⁻¹ Temp., °C. 25.001.47 2.1×10^{-4} 2.0×10^{-3} 45.0010.4 55.0022.0 0.9×10^{-2}

 $k_0' = 10^{13.1} e^{-17,600/RT}$ l. mole⁻¹ min.⁻¹

 $k_{\rm w}^0 = 10^{13} e^{-23,000/RT} \min^{-1}$

The Reaction Mechanism

The simplest mechanism suggested by the results for the hydrolysis catalyzed by acid assumes that the ion $HON(SO_3)_2H^-$ forms a reactive complex with water. The over-all rate is determined by the rate at which the complex is converted into the hydrolytic products. It is evident that the concentration of HON(SO₃)₂H⁻ will be determined by that of H⁺.

 $\begin{array}{l} H^+ + HON(SO_3)_2^- \rightleftarrows HON(SO_3)_2 H^- \\ HON(SO_3)_2 H^- + H_2 O \rightleftarrows HON(SO_3)_2 H_3 O^- \\ HON(SO_3)_2 H_3 O^- \longrightarrow HONHSO_3 H + HSO_4^- \end{array}$

The rate equation for the hydrolysis will be $- d(\Sigma HON(SO_3)_2^{-})/dt = k_B(H_2O)(HON(SO_3)_2H^{-})$

(13)

and this may be integrated readily on the assumption that the ionization constants of the acids HSO_4^- , $HONHSO_3H$ and $HON(SO_3)_2H^$ are all equal. After lumping several very insensitive terms (terms which vary little with time) into the integration constant, the following integral is obtained for equation (13) for the cases in which no acid was added initially

$$\log \frac{x}{a-x} + C \log (a-x) = \frac{k_{\rm B}a}{2.303 (a+K)} t + \text{const}$$
(14)

where K is the acid ionization constant for HSO_4^- , $HON(SO_3)_2H^-$ and $HONHSO_3H$; C is a constant, less than unity in most cases, and affects the linearity of the log x/a - x, t curves only slightly. Equation (14) differs little from equation (3), and it is for this reason that straight lines were obtained in Fig. 1.

As a first approximation

 $k_{\rm B}(a + b)/(a - b + K) = k'(a + b)$ (15)

and therefore, $k_{\rm B} = k'(a + K)$ for those runs in which no acid was added initially. In order to obtain values of $k_{\rm B}$ which may be subjected to inspection, the values of K for HSO₄⁻ calculated by Pedersen⁴ were used, those for the other acids not being known.

The values obtained for $k_{\rm B}$ are tabulated in the last column of Table II; for zero ionic strength $k_{\rm B} = 1.5 \times 10^{-2}$ min.⁻¹ at 25°, and should be nearly independent of μ . When $\mu < 0.1$, $k_{\rm B}$ is effectively constant as may be seen in the table.

(4) Pedersen, J. Phys. Chem., 38, 601 (1934).

That the mechanism assumed provides a satisfactory explanation for the experimental results is shown by their accord with the experimentally found rate equation and by the fact that the rate constant $k_{\rm B}$ varies but little with the ionic strength.

Summary

Anhydrous potassium hydroxylamine disulfonate, $K_2HON(SO_3)_2$, has been prepared and kept more than a month without appreciable decomposition.

The rate of the hydrolysis

 $HON(SO_3)_2^- + H_2O = HONHSO_3^- + H^+SO_4^-$

has been measured. For acid solutions the rate equation was found to be

 $-d(\Sigma HON(SO_3)_2^{-})/dt = k(\Sigma H^+)(\Sigma HON(SO_3)_2^{-})$

where the sigmas refer to the total concentration of all ions containing the group indicated. Water also catalyzes the hydrolysis, but its effect is much less than that of acid. The effect of temperature on k corresponds to an energy of activation of 17,600 cal./mole.

A mechanism which explains the observations satisfactorily assumes that $HON(SO_3)_2H\cdot H_2O^-$ is the intermediate whose rate of decomposition into the final products determines the over-all rate of the hydrolysis.

PASADENA, CALIFORNIA RECH

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Part II

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The Low Voltage Electrically Exploded Wire

A. Introduction

Several high temperature phenomena have been studied by the electrically exploded wire method, which consists in discharging a large condenser through a fine metallic filament. Anderson¹ pointed out that the rate of energy input into a filament may be made very large by use of electrical conductivity and Joule heat dissipation, The rate of heat dissipation in his experiments was about 10⁹ joules per gram per second. Temperatures above 9,000°K and pressures of the order of 30 atmospheres are attained momentarily when large energies are used^{1,2} Anderson also demonstrated the absence of several heat loss effects. Anderson and Smith³ state that after an explosion the vapor first occupies a volume not much larger than the filament and is at high temperature and pressure, then expands with diminishing speed. After 20 or 30 microseconds its volume becomes nearly constant at the pressure of the surrounding atmosphere, its diameter being Smith⁴ found that the mass of the exploding 2 to 3 cm. filament had little effect on the maximum voltage across the The maximum voltages below were obtained with a vapor. 0.6 microfarad condenser initially charged to 55 kilovolts for 5 centimeter lengths of filaments.

Metal Cu Ni Fe Al Pb Ag W Zn Sn Li Maximum Potentials 81 79 72 39 58 58 51 49 51 42 Across Explosion. kilovolts

1. Anderson: Astrophysical Journal, 51, 37 (1920).

Futagami: Inst. Phys. Chem. Res. Tokio Sci. Papers, <u>31</u>, 1 (1937).
 Anderson and Smith: Astrophysical Journal, <u>64</u>, 295 (1926).
 Smith: Ibid, <u>61</u>, 186 (1925).

Using a rotating-mirror spectrograph, Anderson and Smith³ found that throughout the first 6 microseconds the spectrum of the explosion is continuous. After about 10 microseconds the continuous spectrum weakens rapidly and is replaced by a spectrum of bright lines similar to that of an arc. The spectrum of an iron wire exploded in a confined volume and photographed end-on by Anderson¹ gave the following results:

Pressure, mm	wave J range,	, A	Spectral characteristics				
20	3600-4	1200	Emission spectrum				
50-130	77	11	Continuous background increasing in intensity. Reversal becoming prominent.				
150-200	29	Ħ	Continuous background. Only absorption lines obtained.				
760	2250-5700		Continuous background. Only absorption lines obtained.				

Nagaoka and Futagami⁵ studied incomplete (low energy) explosions. They found that locally the density of luminosity fluctuated greatly. In the case of an incomplete explosion of an aluminum ribbon, the positive end appeared to explode immediately, followed by a minor explosion in the center region, finally by a still smaller explosion at the negative end. Portions of the ribbon apparently did not explode.

A few effects which depend on the nature of the filament have been found. Anderson¹ stated that it is not possible (with the condenser and voltages he used) to obtain good effects with wires larger than 5 mils or longer than 8 cm. Anderson and Smith³ found that parallel spark gaps discharged the current when vaporization had been completed for all metab except

5. Nagaoka and Futagami:Phys Chem. Res. Tokio Sci. Papers, 8, 269 (1928) Nagaoka and Futagami: Imp. Acad. Tokio Proc., 2, 387 (1926) Nagaoka, Futagami, and Machida: Ibid, 2, 328 (1926)

tungsten. The behavior of tungsten was ascribed to the innization of the vapor of tungsten at its high boiling point.

Anderson ⁶ found that "copper, silver, and gold are anomalous in that the pure wires of these metals will not explode properly when placed in a slot in a block of wood, the main discharge always seeking a path around the outside of the wooden block. By very slightly amalgamating the surface of the wires they explode normally, giving fine continuous spectra crossed by their own absorption lines, the lines due to Hg not having been obtained." He also found that "iron vapor as here used is perfectly opaque ... the absorption coefficient has been shown to be fairly large but has not been measured."

Sawyer and Becker⁷ conclude that "the ionization produced in the exploded (aqueous) solution compares with that in the sun and stars of class B". Similarly, Anderson¹ found that "it requires 200 times the exposure to the sun to produce the same (photographic) density as that given by the explosions".

A variety of other studies have been carried out by exploding both metals and aqueous solutions of salts. References to these studies will be found in Appendix E. 6. Anderson: Proc. Nat. Acad. of Sci., <u>8</u>, 231 (1922) 7. Sawyer and Becker: Astrophysical Journal, <u>57</u>, 98 (1923)

The rapid heat input of the exploded wire method enables one to investigate metals at high temperatures in an atmosphere at room temperature. Our original aim was to use the exploded wire as a source of metallic vapor. After attempting to study reactions of exploded copper filaments with a number of gases, we concluded the low voltage explosions were not behaving as anticipated, it being obvious that the filaments were only partially exploded. The voltages we used, 50 to 350 volts, were easier to handle with inexpensive equipment than voltages from 20,000 to 70,000 as used in much of the spectral studies. We studied the effects of the various variables involved to see how much of the condenser energy went into the filaments. From this we hoped to find conditions under which the filaments would vaporize completely.

One way of characterizing the explosion involved the measurement of the initial and final condenser energies. A second way was to collect and examine the exploded metal. The filament is clamped against a glass microscope slide, metal being deposited thereon after the explosion. The appearances of these deposits are similar to the photographs taken by Anderson and Smith³ of exploding wires.

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B. Apparatus and Experimental Procedure

1. The surge generator

In most of the experiments eight 25-microfarad Dubilinier condensers were connected in parallel. Across the condensers a semi-infinite resistance electronic voltmeter was placed. The readings on this meter were calibrated against a Weston precision voltmeter at the end of each experiment. The system was wired with coaxial cable (resistance = 0.01 ohm/ft., inductance = 0.09 microhenries/ft.). The condensers were connected to the central terminals of a number 3294 Leeds and Northrup pinch type double-pole, double-throw switch, the lower terminals of which were connected to the power supply and to the Weston voltmeter. The upper terminals of the switch were connected to the filament explosion unit. A three microhenry inductance was placed in series with the explosion unit in most of the experiments.

2. Preparation of the filaments

It was felt that soldering filaments to leads is unsatisfactory because 1) solder does not wet tungsten, 2) solder frequently flows beyond the point where filament and lead meet, making the effective filament length and diameter uncertain, and 3) the filament may become fouled with rosin. The following procedure was adopted since it a) yielded satisfactory reproducibility of data, b) eliminated the above difficulties, and 6) furnished quantitative agreement for data obtained using carefully prepared soldered joints and for capillary joints. Each end of the filament is inserted into a short piece of monel capillary, which is then crushed onto the filament using a flat-jawed vice or long noseppliers. The joint is tested for mechanical contact by pulling the filament away from the monel ends; the assumption is made that good mechanical contact is a satisfactory test for good electrical contact.

That this procedure gives reproducible results may be seen from the results for 3.1 mils constantan filaments for 50 μ F and 1 μ H. For minimum energy explosions the total energy dissipated in the filaments is 0.240 and 0.242 joules per centimeter for soldered and capillary joints respectively.

The filaments used were the best grade metal wires which we could obtain. These were manufactured by Sigmund Cohn, Driver-Harris, and Callite.

3. The filament explosion unit

The filament explosion unit used in most of the experiments is shown in fig. 1. It was constructed so that 1) it could be directly connected to a high vacuum system, 2) the filament would be supported vertically, clamped against a glass slide, and 3) the electrical circuit around the filament would be a continuation of the coaxial leads.

A large brass standard taper joint was constructed which gave a vacuum-tight seal with a glass standard taper joint. The glass was sealed to a mercury manometer and an oblique bore stopcock, beyond which were a series of standard taper and ball joints by means of which the system was connected to the high vacuum apparatus.

also ind

Fig. 1 Filament explosion apparatus



The outside lead of the coaxial cable was soldered to the brass joint. The inner lead went through a hole in the center of the brass joint, being insulated both for vacuum and electricity, and was then soldered to a clamp. The jaws of this clamp were clinched about a glass slide (kept in place by two ways soldered to the brass joint), pressing the monel ends on the filament against the glass and establishing electrical contact with the filament by strong clamping action. A two-ended clamp was secured on the other monel end of the filament from the upper end of the slide. A heavy brass tube. the upper part of which was soldered onto flexible dome-shaped. copper mesh, slipped over the clamps, filament and glass slide and into a deep groove in the upper face of the brass standard taper joint, establishing electrical contact therewith. The upper end of the two ended clamp was then clamped onto a heavy copper wire soldered to the center of the dome.

When experiments were performed in atmospheres other than air, the glass standard taper was slipped over this assembly and connected to the vacuum apparatus. Commercial gases were used without further purification. The glass slides were the ordinary microscope slides. C. List of symbols

Explosion	Process of blowing out filament with electrical surge.
Filament	The fine wire blown out by the electrical surge.
l	Length of filament (cm)
D	Filament diameter (mils, i.e. 0.001 inches)
M	Microgram atoms in one cm of filament
E	Total energy dissipated in filament per cm (joules/cm)
. 🖲	" " (kcal/g.atom)
E(analytical)	E calculated by eq. 1 and Appendix A5.
E(graphical)	E obtained by solving eq. 1 graphically.
E _o , E _l	Terms in the series, $E = E_0 + E_1 l$
K	The total energy dissipated in the apparatus (excluding the filament) (joules), K = EF.
0	Filament resistance per cm (ohms/cm)
	Mean filament resistance per cm when there is no gaseous discharge (ohms/cm) defined by $ \int_{-\infty}^{+\infty} \frac{\int_{-\infty}^{+\infty} i^{2} dt}{\int_{-\infty}^{+\infty} i^{2} dt} $
(E/2)	ρ when E/2 joules/cm has been added to the filament.
°0, °1	Terms in the series, $\rho = \rho + \rho l$
L.	The apparatus resistance (ohms), (excluding filament) This is taken as the values obtained in Appendix A5.
ro, r1	Terms in the series, $r = r_0 + r_1 f$
R	Total resistance of system, apparatus plus filament (ohms)
F	r/~, cm
Fo, Fl	Terms in the series, $F = F_0 + F_1 l$
Vo	Initial condenser voltage before the surge (volts)
Vr	Residual condenser voltage after explosion (volts)

L	Inductance of the system (microhenries)
C	Capacity of the condensers (microfarads)
$\Delta \frac{v^2 c}{2}$	Total energy dissipated (joules), i.e. the initial minus the final condenser energies.
i	Current (amperes)
t	Time after effective initiation of surge (microseconds)
texp	t at which explosion occurs when there is no gaseous discharge (microseconds)
A1, A2	Constants in eq. 4.
G ₁ , G ₂	Constants in eq. 8.
Y ₁ , y ₂	Constants in eq. 11.
z ₀ ,z ₁ ,z ₂	zo, z1, z2 are defined in eq. 6.
₩o, ₩1, ₩-1	These are defined in eq. 10.

D. Experimental results

The mechanism of the explosion that occurs when an electrical surge is passed through a metallic filament is complicated. In order to study some of the effects of the surge, four series of experiments were devised in which only one initial condition was varied throughout the series. Each series was repeated with a number of different metals and diameters.

1. Minimum energy explosions

It appeared desireable to study experiments in which the states of the filaments at the times of explosion would be known. Although this was not feasible with the available equipment, a more modest aim appeared to be experimentally acheivable. By using only the minimum energies necessary to blow out filaments it seemed reasonable to assume that the states of the filaments at the times of explosion might not differ much from each other as filament length is varied. a. Experimental procedure and precautions

In order to find the minimum energy required to blow out filaments, repeated surges were sent through the system, each with more energy than the preceding surge (V_0 being increased by 5 volts) until the filament blew out. Quantitative agreement was obtained in experiments to see if six surges gave the same results as a single surge explosion. In some experiments, especially with 1.0 mil tungsten filaments, $V_0^2 - V_T^2$ was less than ($V_0 - 5$)², indicating that the filaments should have blown out on previous surges. These data were discarded. The difficulty may have arisen from changes in shape of metal filaments as a result of repeated meltings. Helium was used in the cases of several metals which reacted with oxygen.

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b. Appearances of filaments and glass slides

Generally the filaments blew out at one to three points. There were a few globules of metal deposited on the glass slides in the enighborhoods of blowing out points (cf. Plate 1 below). There were no metallic mirrors deposited. <u>Plate 1</u>. 632x. Microphotograph of glass slide for minimum energy explosion; gold filament, l = 0.62 cm, $V_0 = 70$ volts.

The dark balls are globules of gold. The cloud-like white region apparently is a chip in the glass since it focuses below the slide surface. Unlike the plates at higher energies, the background is dark on account of the absence of metallic vapor, a metallurgical microscope having been used. A 4.7x photograph has not been taken since nothing was visible.



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c. Results

When the total energy dissipated, $\Delta v^2 C/2$, is plotted against filament length, \mathcal{L} , a straight line fit is valid within experimental error, as may be seen in fig. 2. The scatter at 50 µF and 1 µH is seen to be appreciably less than at 200 µF and 4 µH. These graphical results may be represented by equations of the form; $\frac{\Delta v^2 C}{2} = E (\mathcal{L} + F) = E\mathcal{L} + K$ (1) E. F. and K are listed in Table I.

The derivation in Appendix Al shows that if we assume that the surge energy is dissipated uniformly along the filament (and "hot points" are also well distributed), we may interpret E, F, and K rather simply. E is then the total energy dissipated in the filament per cm, F the ratio of the mean effective apparatus resistance to that of the mean filament resistance per cm of filament, and K the total energy dissipated in the apparatus (excluding the filament). This interpetation is strictly applicable to the quantities in Table I only if E, F, and K are independent of filament length.

The effects of inductance and capacity are summarized in Table II. More experiments are obviously needed to clarify the situation. Since we have been unable to correct the results at 50 μ F for variation with filament length, we may not conclude that the blowing out temperatures for minimum energy explosions are higher at 200 μ F and 4 μ H than at 50 μ F and 1 μ H.



Fig. 2

TABLE I. Graphical results of the experiments at atmospheric pressure in which the minimum energies for rupture have been used. Experiments with constantan filaments are given in Appendix D.

F Meta	ilament 1 D, mils	Gas	E, joules cm	kcal g.atom	F, cm	K, joules	t _{exp} /R, microse ohm	conds
C s	50 pF, L	= 1 µH,	texp/R	calcul	ated f	rom grapl	nical re	sults.
Ag	3.0	Air	0.138	7.41	1,50	0.207	105	
Au	2,9	Air	0.157	8.96	0.92	0.144	155	
Cu	3.1	Air	0.212	7.40	1,50	0.318	130	Ň
Ni	3.0	Air	0.334	11,5	0.60	0,200	157	
Pt	3.0	Air	0,283	13,5	0,62	0,175	139	
C =	200 pF,	$L = 4 \mu H$	I, t _{exp} /	R calcu	lated	from ana	lytical	results.
Ag	3.0	Air	0.147	7.88	2,60	0,382	256	
Au	2,9	Air	0.173	9.88	1.68	0.291	313	
Cu	3.1	Air	0,285	9.95	2.02	0,575	305	
Fe	3,1	Helium	(0.60)(21.1)	0.06	(0,036)	278	
Ni	1.2	Air	0,092	20.0	(0,35)	(0.032)	288	
	2.0	Air &	0.247	19.1	0.25	0.062	324	
	3.0	Air &	0,472	16.2	0.41	0,193	285	
	4.0	Air	0.857	16,6	0,20	0,171	390	
	5.0	Air	0,98	12.1	1.00	0,98	495	
	6.0	Air	1.46	12.6	0,85	1,24	371	
Pt	3.0	Air	(0,38)(18.1)	0,46	0.175	311	
W	1.0	Helium	0.140	63.0	(0.06)	(0.0084)	292	
	2.3	Helium	0.487	41.5	0.36	0.175	270	
	3.0	Helium	0,690	34.5	0,59	0.41	351	
	4.0	Helium	(1.30)(36,5)	(0.47)	(0,61)	424	

TABLE II. Comparison of graphical results of Table I to show the differences between the results at 200 μ F and 4 μ H and those at 50 μ F and 1 μ H.

Fi: Metal	lament D, mils	E(200 µF) E(50 µF)	F(200 µF) F(50 µF)	$\frac{K(200 \mu F)}{K(50 \mu F)}$	t _{exp} /R (200 µF) t _{exp} /R (50 µF)
Ag	3.0	1.06	1.73	1,84	2,44
Au	2,9	1,10	1,83	2.02	2.02
Cu	3.1	1.34	1.35	1.81	2,35
Ni	3.0	1.41	0,68	0,97	1,82
Pt	3.0	(1.34)	0.74	1.00	2.24

 t_{exp}/R has been calculated by means of the equation in Appendix A3. The differences between the explosion times per ohm at 200 µF and at 50 µF are mainly due to two factors. The ratios of the capacities, 200/50, contribute a factor of 4. Since the initial voltages at 50 µF are about double those at 200 µF for comparable conditions, the ratios of the logs of V_0/V_r contribute a factor less than unity. It is seen in Table II that the combination of these two factors results in a series of ratios of the order of 2.

So far eq. (1) has been solved graphically. In order to correct E, F, and K for the effects of variation with filament length, an analytical method has been developed to solve eq. (1). The whole procedure of using eq. (1) is an indirect method of obtaining our desired results. If more equipment were available we would be able to measure the voltage and current as functions of time, thereby obtaining the energy input into the filaments more directly.

In the analytical method we solve eq. (1) by assuming a) that $\rho = \rho(E/2)$, i.e. that the mean filament resistance may be adequately represented by the filament resistance when E/2joules/cm has been dissipated in the filament per cm, and b) r is proportional to the square root of the frequency (skin effect relationship), and that for cur overdamped systems the time at which the current reached its maximum value is an adequate relative measure of the frequency, being inversely proportional to the frequency, and the correct order of magnitude of r is obtainable from the graphical results (i.e. the curve is passed through an experimental point, cf. fig. 7 in Appendix A5). Calculations are made by successive approximations until E, r, and ρ are self-consistent.

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The analytical calculations have been limited to the data at 200 µF and 4 µH. The uncertainty in the inductance for the data at 50 µF and 1 µH makes the skin effect corrections unreliable. The individual experiments at 50 µF are given in Table III, and those for 200 µF in Table IV. The analytical averages for 200 µF are given in Table V and compared with the graphical values of Table I in Table VI. These analytical averages have been made by neglecting experiments with very Quantitative correlation is obtained short filaments. between e(graphical) and e(analytical) when e(graphical) is corrected for variation of E and F with filament length (cf. Appendix A4) for the six nickel filaments, gold and silver. but not for one tungsten filament, iron, and copper. For the latter experiments these discrepancies may be due to lack of sufficient data to evaluate all the quantities involved accurately or to the failure of the mean resistance hypothesis. For the case of an alloy like constantan, the mean resistance hypothesis sould obviously be inadequate for large E ranges. Now that the data may be satisfactorily interpreted we will consider some of the results of the analytical calculations. (1) Total energy input into filament per centimeter.

For minimum energy explosions, E is seen to vary with D, ℓ , and filament metal. We have already discussed the effects of C and L. Nickel filaments showed no differences in behavior when exploded in air and in helium at atmospheric pressure.

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TABLE III. Minimum energy explosion data for 50 μ F, 1 μ H, and air at atmospheric pressure. t_{exp} and t_{exp}/R have been calculated with graphical values of R.

Fila Metal	D, mils	l, cm	V _o , volts	V _r , volts	$\frac{\Delta v^2 c}{2}$, joules	t usec.	t _{exp} /R, usec/ohm
Ag	3.0	0,50	105	5	0.275		8
		1,55	130	15	0.417	38	104
		2.00	140	2.0	0,480	40	96
		6,85	215	10	1.15	115	116
Au	2.9	0,25	85	0	0.181	5×P	extit
		0.87	105	5	0,275	45	136
		4.00	175	5	0,76	160	174
Cu	3,1	0,65	135	5	0.455	=	\$
		1.70	165	33	0,65	33	82
		3,25	200	5	1.00	107	178
		5.20	243	35	1.44	81	96
		8.10	285	10	2.03	199	165
Ni	3.0	0.75	130	10	0.420	139	127
		1.35	165	7	0,68	249	157
		3,10	220	7	1.21	448	172
		6.80	315	10	2,48	1038	172
Pt	3.0	0.83 .	125	5	0,390	221	160
		1,45	155	5	0,60	238	121
		7.06	295	20	2.17	985	135

TABLE	IV.	Results	s of n	ninimum	energy	explos	ions at	l atmos	sphere,	200 NF	, and 4μ E	i .
Filame Metal	ent D, mils	Gas	l, cm	V võlts	V _r , volts	$\frac{\Delta v^2 c}{2}$, joules	E, joules cm	e, kcal g.atom	K, joules	t _{exp} , jusec	t _{exp} /R, µsec/ohm	Regions of constant e,"x"
Ag	3.0	Air	0.51 1.62 2.80 3.95	70 80 90 105	10 20 3 39	0.48 0.60 0.81 0.95	0.235 0.149 0.150 0.139	12.6 8.0 8.0 7.5	0.36 0.36 0.39 0.40	145 144 161	387 300 211	X X X
Au	2,9	Air	0.62 1.22 2.28 2.92 4.68	70 75 85 90 105	20 24 21 10 2	0.45 0.50 0.68 0.80 1.10	0.44 0.181 0.169 0.170 0.165	25. 10.2 9.6 9.7 9.4	0.18 0.29 0.30 0.30 0.33	215 131 217 392	250 234 278 427	x x x x
Cu	3,1	Air	0.68 2.28 3.23 4.79	90 115 125 135	19 34 25 22	0.77 1.21 1.50 1.77	0.332 0.275 0.273 0.242	11.6 9.6 9.5 8.4	0.55 0.58 0.61 0.63	130 163 265 361	317 243 319 353	x x x
Fe	3.1	Helium	0.70 1.38 2.04 2.10 2.80	80 95 110 120 135	5 2 4 42 24	0.64 0.90 1.21 1.26 1.76	* 0.56 0.53 0.54 0.58	19.4 18.5 18.8 20.2	0.134 0.128 0.131 0.143	- 1100 2380	211 345	x x x x
Ni	1.2	Air	0.69 1.37 3.00	30 40 57 , 5	0 7 20	0.090 0.155 0.291	0.12 0.10 0.092	26 23 20	0.0074 0.0107 0.0160	4 070 4630	365 211	x x
λ.	2.0	Air Helium Air	0.63 0.93 1.20 1.92 2.29 2.99	55 55 60 75 80 80	6 11 4 15 14 11	0.30 0.29 0.36 0.54 0.62 0.63	0.40 0.26 0.25 0.25 0.25 0.19	31. 19.9 19.6 19.6 19.0 14.9	0.050 0.049 0.053 0.053 0.046 0.052	1270 846 1700 2120 2720	432 302 322 347 397	X X X X
	3.0	Helium Air Air Helium Helium Air	0.60 0.69 1.43 2.00 2.49 3.11	75 95 110 115 135	25 3 24 23 25 35	0.50 0.56 0.84 1.16 1.32 1.70	0.53 0.55 0.45 0.47 0.44 0.44	18.4 18.8 15.6 16.1 15.1 16.0	0.18 0.16 0.20 0.22 0.23 0.25	217 491 766 960	219 275 312 269	X X X
	4.0	Air	0.58 1.21 2.98 3117	85 115 165 170	21 32 12 0	0.68 1.22 2.71 2.89	0.52 0.62 0.71 0.72	10.1 12.1 13.7 13.9	0,37 0,44 0,60 0,61	160 233 1010	285 255 524	x x x
	5.0	Air	0.20 0.81 1.99 2.69 3.08	100 135 170 190 200	28 20 27 9 8	0.92 1.78 2.82 3.60 3.99	0.74 0.95 0.87 0.91 0.91	9.2 11.8 10.8 11.3 11.3	0.78 1.02 1.11 1.13 1.19	90 210 335 688 810	273 376 365 601 637	x x x x
	6.0	Air	0.32 0.50 0.70 0.79 1.00 2.39 2.54	105 140 150 160 165 220 225	0 18 21 20 35 50 28	1.10 1.93 2.21 2.52 2.60 4.59 4.98	0.50 0.90 0.92 1.02 0.97 1.09 1.15	4.3 7.75 7.90 8.80 8.31 9.37 9.85	0.92 1.47 1.58 1.70 1.59 2.00 2.08	148 163 183 150 230 334	403 389 413 317 295 408	x x x x x x
Pt	3.0	Air	0.32 1.21 1.30 2.38	60 80 85 105	20 21 10 4	0.32 0.60 0.71 1.10	* 0.38 0.43 0.39	17.9 20.3 18.6	0.142 0.156 0.175	340 860	193 429	x x x
W	1.0	Helium	0.72 1.90	35 55	18 10	0.090	** **				223 340	
	2.3	Helium	0.60 1.39 1.98 1.99	70 95 110 110	14 27 26 25	0.47 0.83 1.142 1.15	* 0.54 0.53 0.53	46.1 45.2 45.3	0.076 0.091 0.092	1520 2420 2510	251 288 296	X X X
	3.0	Helium	0.60 1.10 2.38	90 115 145	10 36 22	0.80 1.19 2.05	1.07 0.91 0.78	53°7 45°3 38°8	0.158 0.197 0.210	1010 702 1960	443 231 378	
	4.0	Helium	0.70 1.50 2.20	120 165 185	5 20 13	1.44 2.68 3.41	1.40 1.42 1.28	39.4 39.8 35.9	0.46 0.55 0.60	908 1440	424 529	X X

* Resistance data are not available in this temperature range.

TABLE V. Averages of the analytical results for minimum energy explosions at atmospheric pressure in air and in helium for 200 μ F and 4 μ H. The averages of t_{exp}/R have been presented in Table I.

Filan Metal	D, mils	e, kcal g.atom	Mean devia- tion in e, %	Average state of filaments at time of explosions.	F, cm	K, joules
Ag	3.0	7.84	3.2	56% ± 9% melted	2,6	0,38
Au	2.9	9.72	2.5	88%±8% melted	1.8	0,31
Cu	3.1	9.19	5.4	70% ± 16% melted	2.3	0.61
Fe	3,1	19.2	3.1	Liquid at 2010 ±74° K	0.24	0,13
Ni	1.2	21.4	7.0	Liquid at 2420±180°K	0.14	0,014
	2.0	19,5	1.5	Liquid at 2190 1 40°K	0,20	0.050
	3.0	15.7	2.2	Liquid at 1750±40°K	0,49	0,22
	4.0	13,2	6.1	45% ± 19% melted	0.81	0,55
	5.0	11.3	1,8	0% ± 5% melted	1.24	1,13
	6.0	8.6	7.8	Solid at 1400 ± 100°K	1,74	1,75
Pt	3.0	18.9	4.8	Liquid	0,40	0.16
W	2,3	45.8	0.7	Liquid	0.15	0,08
	4.0	39.6	0.5	Liquid	0,35	0,49

TABLE VI. Comparison of analytical and graphical results for minimum energy explosions at atmospheric pressure, 200 μ F, and 4 μ H.

Fil: Metal	ament D, mils	e(graphical) e(analytical)	$\begin{bmatrix} e(\text{graphical}) \\ e(\text{analytical}) \end{bmatrix} = \begin{bmatrix} e_1 (l + F) \\ e(\text{analytical}) \end{bmatrix} = F_1$
Ag	3.0	1.01	0.97
Au	2,9	1.02	1.00
Cu	3.1	1.08	1.15
Fe	3.1	1.10	1.10
Ni	1.2	0,93	1.07
	2.0	0,98	1,05
	3.0	1.03	0,96
*	4.0	1.26	0,97
	5.0	1.07	0,98
	6.0	1.45	1.02
Pt	3.0	(0.96) [@]	(0.90) [@]
W	2.3	0,91	0,92
	4.0	(0.92) [@]	(0.82) [@]

@ These values are unreliable on account of graphical uncertainty.

It is seen in Table V (and also in Table I) that e decreases for both nickel and tungsten as filament diameter is increased. e, log e, and l/e were each plotted against each of the following; D, log D, 1/D, and D^2 . The most satisfactory linearity was obtained by plotting e against either D or log D (cf. fig. 3). The equations of these lines are; Ni: e - 2.72 D+24.6 and e - 10.2 log M+24.4 (2) W: e= - 3.65 D+54.2 and e = - 12.9 log M+51.6 where e is in kcal/g.atom, D in mils, and M in ug. atoms/cm. The results for nickel are more reliable than those for tungsten. Difficulty was encountered in obtaining the tungsten data. For example only two out of fifteen explosions satisfied the condition that $E_0^2 - E_r^2$ should be greater than $(E_0 - 5)^2$. The cause of this behavior is not known. A possible interpretation of the decrease of e with increasing D is that a large part of e goes into overcoming some surface phenomena, since the surface area per g. atom (for a cylinder omitting its ends) decreases with increasing D. We have already seen (page 9) that explosion properties of at least some filaments can be changed markedly by slightly amalgamating the surfaces of the filaments.

Caution should be exercised in the interpretation of the results for large diameters. It will be seen further on as well as here that most of the phenomena studied for the large diameters behave differently than those for the small ones. Anderson found that it was not possible to obtain good effects with wires larger than 5 mils. (His experiments were carried out at high voltages.) In our experiments we find (cf. Table V)




that the <u>average</u> state of 6.0 mils nickel filaments at t_{exp} is that of a solid and of 5.0 mils a solid at the melting point.

We will now examine the effect of filament length on e in the regions of constant e. It will be assumed that $e = e_0 + e_1 l$. It is seen in Table VII that e_1 increases with increasing M. In fig. 3, e_1 is plotted against M on semi-log paper. The equation represented by the line is;

e1 = 2.3 log M/6.73(3) It is interesting to note that e, eo, and e1 may be considered to be proportional to log M. In Appendix B, it is found that both log r and log r1 are proportional to log $\overline{\rho}$ (analytical). (ro is a constant equal to 0.27 ohms.) (2) End effects (Behavior of very short filaments)

If the results in Table IV are examined it is seen that some of the numerical values of E for short filaments are considerably different than those for longer filaments. The ratios of the results for short filaments to the values they would have if there were no end effects are given in Table VIII, and the trends in these results are summarized in Table IX. The results for \mathcal{L}_{\pm} 0.20 and 0.32 cm (two experiments) are tentative since there are not enough data and the error in determination of filament length is relatively large in these two experiments.

Since r does not exhibit any significant end effect, it is probable that the end effect is mainly a filament phenomenon (and therefore affects the circuit only indirectly).

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TABLE VII. Effects of filament length on e in regions of "constant e" for the data in Table IV.

M, <u>µg.at</u> cm	Filament Metal .oms	D, mils	el, kcal g.atom cm	eo, kcal g.atom	$\frac{e_1(l+F)}{e(analytical)}$
1.1	Ni	1.2	- 1. 84	25.3	- 0.20
2.8	W	2.3	- 1.19	47.8	- 0°05
3.1	Ni	2.0	- 0,71	20,6	- 0.07
4.2	Au	2,9	- 0,20	10.3	∞ 0 ° 09
4.4	Ag	3.0	- 0,22	8.4	- O.15
5.0	Pt	3.0	- 0.04	19.0	- 0.0l
6.8	Cu	3.1	- 0.43	10.7	- 0.27
6.8	Fe	3.1	0.04	19.1	0,00
6.9	Ni	3.0	0,00	15.7	0.00
8.5	W	4.0	0,50	39.0	0.02
12.3	Ni	4.0	0,96	10.8	0.24
19,2	Ni	5.0	0.02	11.3	0,00
27.7	Ni	6.0	1.01	7.5	0.34

compared	WICUI	ne ext	rapora	ated an	INTACTCA	I VALUES	•
Filan	nent		84102000ma waaayaa	0	Ā	r	F
M, ug.atoms cm	Metal	D, mils	l, e. cm	o + e 11	Po+Pil	r _o +rl(F'04F'1
1.1	Ni	1.2	0.69	1.08	1,28	1.0	0.78
3.1	Ni	2.0	0.63	1,54	1,52	0.94	0,62
4.2	Au	2.9	0,62	2,54	4.13	1.13	0,26
4.4	Ag	3.0	0.51	1.51	1.42	1.00	0.70

TABLE VIII. Data of Table IV for short filaments are compared with the extrapolated analytical values.

4.4	Ag	3.0	0.51	1.51].42	1.00	0,70
6.8	Cu	3.1	0,68	1.12	1.07	1.00	0,93
6.9	Ni	3,0	0.60	1.17	1,08	0,97	0,90
			0.69	1.20	1.09	0.87	0,80
8.5	W	4.0	0.70	1.00	1.00	1.00	1.00
12.3	Ni	4.0	0,58	0.99	0,93	0.94	1.01
19,2	Ni	5.0	0.20	0.81	0,90	0.90	1.00
27.7	Ni	6.0	0,32	0,58	0.86	0,93	1.08
			0.50	1.03	0.99	0,96	0,97
			0,70	1,05	1.00	1.00	1.00

TABLE IX. End effects (results for short filaments) are summarized for 200 μ F and 4 μ H.

2

Filament length range, cm	0.50 \$ 1	{ ≤ 0.70 cm	0.20 & 0.32 cm
M range, µg.atoms/cm	ζ7	>8	19.2 & 27.7
Reliability of results	Valid	Valid	Not estab lishe d
e eo+el{	>1	aa 1	< 1
Average values	1.44	1.02	0,70
Rate of change with respect to M	< 0	atin O	<u> < ٥</u>
$\frac{3}{P_0+P_1l}$	>1		<1
Average values	1.66	0,98	0,88
Rate of change with respect to M	< 0	aa O	≼ °
$\frac{r}{r_0 + r_1 l}$	Scatter about unity	. 1	<1
Average values	(0,99)	0,98	0,92
F Fo+F1	<1	m 1	>1
Average values	0.71	1.00	1.04
Rate of change with resp	pect to M		
	< 0	a 0	≥0

(3) Times at which explosions occur.

The values for t_{exp} have been calculated using the results in Appendix A3. These values range from 90 to 4,630 microseconds for the minimum energy experiments in Table IV. The results for experiments with V_r less than 5 or 6 volts have not been calculated since there was a condenser lag of about 2 volts for small voltages and since instrumental sensitivity was poor for very small voltages, probably of the order of several volts. In addition the mean deviation in t_{exp} corresponding to the mean deviation in e becomes very large for these small V_r (cf. Appendix C).

It is seen in Table IV that t_{exp} increases in most cases with increasing filament length. t_{exp}/R and t_{exp}/l are both almost independent of filament length. Whereas the values of t_{exp}/l for different metals and diameters vary from 65 microseconds per cm for silver to 1540 microseconds per cm for 1.2 mil nickel, the values of t_{exp}/R vary from 270 microseconds per ohm for 2.3 mil tungsten to 495 for 5.0 mil nickel.

Averaging over all the metals, we get for t_{exp}/R in regions of constant e for $M < 7 \mu g.atom/cm$, 295 $\mu sec/ohm$ $\pm 18\%$, and for M>8 $\mu g.atom/cm$, $424 \pm 20\%$. The values for both regions overlap. The end effects are masked by the large scatter. If we assume that there is an indeterminancy of about 4% in e in the blowing out process, then we get a corresponding scatter in t_{exp} of about 20%. This is discussed further in Appendix C.

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2. Moderate energy explosions

Three series of experiments follow in which moderate energies have been used with $C = 200 \ \mu\text{F}$ and $L = 4 \ \mu\text{H}$. In the first series, all the initial conditions have been closely reproduced with the exception of gas pressure.

a. Effects of varying gas pressure

A series of explosions were carried out using 2.0 cm lengths of 2.9 mil gold filament and $V_0 = 200$ volts. (This voltage gives a small excess of energy over that required to completely vaporize the filaments, if such a process were to occur without prior rupture.) The results in Table X show that for two large pressure ranges which overlap considerably the residual voltages remain about constant independent of pressure changes. These two pressure ranges overlap from about 50 to 135 mm. In this region either one of two processes occur, either the filament is ruptured when it is 4 to 20% vaporized or the condenser is almost completely discharged. The latter precess does not preclude the possibility that the first process occurs, followed by a gaseous discharge. A second interpretation of the almost complete discharges is that the filament is about 100% vaporized at texp. In this case the results of Smith which we have summarized on page 7 are pertinent since they would guarantee a sharp break in the electrical circuit for our conditions (small V_r). Further experimental work will be need to find out which interpretation is correct. If a gaseous discharge occurs the calculated value of e may not be even of the correct order of magnitude since the resistance of a gaseous discharge is non-Ohmic (and unknown for our system)

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TABLE X. Results of explosions using 2.0 cm lengths of 2.9 mil gold filaments at $V_0 = 200$ volts, $C = 200 \ \mu\text{F}$, and $L = 4 \ \mu\text{H}$ at a number of different pressures. The columns **C** through K have meaning for the first 12 experiments only if no gasecus discharge occurred.

Gas	Pre	mm	V _r , volts	$\frac{\Delta V^2 C}{2}$, joules	e, kcal g.atom	% Vaporized at t _{exp}	K, joules	Plates
Air		10-4	22	3,95	96.1	99 .8	0.58	2,3
		10-4	21	3,96	95.0	98,5	0,59	4,5
		1.	20	3,96	100.2	100.6	0,47	6
		2.6	17	3.97	100.0	99.8	0.47	7,8
		17.8	40	3,84	97.3	94.9	0.44	
Ammoni	a	53.4	48	3.77	100.0	97.2	0.44	
Oxyger	ı	86.1	48	3.77	95.5	91.3	0,42	
Air		87.8	40	3,84	100.0	96.7	0,44	
		102.6	51	3.74	92,1	86.9	0,43	9,10,11
		103.	39	3,85	98.3	94.5	0.42	
		103,2	58	3,66	91,2	85,6	0.43	
		135.2	40	3,84	97.5	93.0	0.43	12,13
Air		50 . 4 [@]	277	1,33	30.	12.		
		97,3	162	1,38	32	15	0.26	14,15,16
		164.5	156	1.57	36	18	0,32	17,18
		212.5	161	1.41	33	14	0.26	19
		352.3	157	1,54	36	17	0.27	
		573.6	162	1,38	32	11	0,26	
		760,	169	1.14	26	4.5	0.24	20,21
@ For	thi	s exper	riment,	V _o = 3	300 volt	S .		
Explos	ion	s with	2.0 cm	length	ns of 3.	l mil copp	er fils	ments.
Ammoni	8	81.1	142	1,98				

Ammonia 242.7 153 1.66

In order to make calculations the resistance data

have been extrapolated above 1800° K. Even though the calculated results may not be quantitatively correct, the results should be good enough to reveal the main features of the data. (The experiments at 10^{-4} mm which give the state at explosion as 99% vaporized, assuming no gaseous discharge, do not require extrapolation of the resistance data.) The spectral studies of high energy iron explosions performed by Anderson (cf. page 8) show that at different pressures the spectral characteristics change, the pressure regions show a striking similarity to those which we have found. The main features are listed below;

pressure, mm 10°	⁴ to 3	20	50 to 135	150-760
V _r ,volts	20	40	46 & 162	161
$\Delta v^2 c$, joules	3,96	3.84	3,78 & 1,36	1.41
% vaporized at t _{exp}	100 [@]	95 [@]	92 [@] & 14	13
Fe spectra	= En	lission	Appreciable continuous background & reversal	Continuous background. Only absorption lines.
t _{exp} , µsec	1690 [@]	1380 [@]	$1290^{@} \& 104$	105
texp/R, usec/ohm	460 [@]	320 [@]	294 [@] & 42	43
Largest ball sizes on slides, microns	3	a	11 & 28	100

@ These values are valid only if it is shown that gaseous discharges do not occur.

The appearance of the deposits in high vacuum indicates complete vaporization (whether or not accomplished directly or by gaseous discharge). These deposits are transparent and are green to transmitted day light. As pressures are increased the density of deposit increases

-004

In fig. 4 we show the results of the calculations assuming no gaseous discharge. We shall not try to give arguments to show whether or not the filaments are completely vaporized since none of these have been decisive.

In the plates which follow we have presented typical slides in the different pressure groups both at low and at high powers. One feature that distinguishes the study of the metal slides from that of high speed photographs is that, although they both look alike at low powers, the metal slides may be studied further at powers for details such as ball size. (We do not wish to imply here that the significance of the metal deposits is the same as that of the photographs but that they do frequently have a similar appearance.)

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Plate 2. 4.7x Plate 3. 632x 10⁻⁴ mm of Hg, cf. Table X for further details.

Most of the film is transparent and appears green with transmitted daylight. At high power, most of the film was smooth. The central metallic region has been photographed since it is only here that details were observed. The streaks on plate 3 are attributed to motion of tiny globules of metal along the glass.



Plate 4.4.7xPlate 5.4.7xPressure; 10⁻⁴ mm.

Plate 4 is similar to plate 2 at high power. The slide was wiped vigorously with lens tissure to see how much of the deposit adhered to the glass. It is apparent in plate 5 that the translucent films were wiped off but the heavier deposits were not.



Plate 6. 4.7x

Pressure; 1mm

The appearance of this plate is less cloud-like than the appearances of plates 2 and 4. This plate is comparable in appearance to parts of plate 7 and 8.



Plate 7. 4.7xPlate 8. 632xPressure: 2.6 mm

This slide appears to be different at low powers than plates 2 and 4. At high powers the differences become small. The essential difference appears to be in the thickness of the deposit.



Plate 9. 4.7x

Pressure: 102.6 mm

On this plate there is a well defined central region which has the appearance of a slightly crumbled wire. This space is empty when looked at through transmitted light. Photographs at 632x are shown in plates 10 and 11.



Plate 10. 632x

Plate 11. 632x The background in plate 9 has no prominent globules of metal. In plate 10 we apparently have a portion of the original filament which did not vaporize completely. It appears as if the filament moved from one position to another during the vaporization or rupture processes. In plate 11 we show the occasional irregularities in the background.



 Plate 12.
 4.7x
 Plate 13.
 632x.

 Pressure: 135.2 mm

Although similar to plate 9 at low power, difference appear at high power. The balls at 632x along the central axis are large. They are located at the end of streaks (the formation of these streaks are undoubtedly due to motion of the balls). There are larger globules scattered about.



Plate 14. 4.7x Pressure: 97.3mm

Only the regions where the filament was clamped to the slide show prominently. Photographs at 632x are shown in plates 15 and 16.



Plate 15. 632x

Plate 16. 632x

Plate 15 has been taken at a boundary between bright metallic deposits and fine vapor deposit of plate 14. The balls are distinctly larger than any observed in preceding plates.

Plate 16 shows an area similar in appearance to plate 13.





 Plate 17.
 4.7x
 Plate 18.
 632x

 Pressure:
 164.5 mm

The surface of this slide was wiped vigorously with lens tissure. The vapor film has been removed (as is evidenced by the non-reflecting dark background), only the large deposits have adhered strongly. The 632x slide was photographed before the slide was wiped.

The large ball is about 100 microns in diameter.



Plate 19. 4.7x Pressure: 212.5 mm

The black streaks are dark translucent deposits which appear green with transmitted light. If plates 2,4,6,7,9, and 19 are examined, it is seen that these black films are prominent for pressures above 1 mm. At lower pressures the films appear more metallic.





Plate 20. 4.7x Plate 21. 632x

Pressure: 1 atmosphere.

The filament appears to have been bent vigorously during the explosion.

b. Effects of varying initial condenser voltage.

The experiments discussed in this section were run in air at atmospheric pressure using 2.0 cm lengths of filaments. When Vo is plotted against Vr. cf. fig. 5, it is seen that these two quantities are directly proportional to each other over a large range of Vo. Vr drops sharply for low voltages at which minimum energy explosions occur, this possibly indicates that rupture processes at moderate energies are different than those at lower energies. At high initial voltages, Vr drops sharply on account of gaseous discharges. The equations of the straight lines in fig. 5 are of the form, A1 and A2 are listed in Table XI. The graphical scatter for the tungsten experiments is large. (Trouble with tungsten has been encountered before. Cf. pg. 21) On plotting M against A2 it is seen that satisfactory linearity is obtained. From fig. 6 we obtain For W; A2 = 71.3 M[±] = 36 For Ni; $A_2 = 30.4 \text{ M}^{\frac{1}{2}} = 7$

The situation with respect to A_1 is not as simple. Apparently A_1 increases with increasing M for small M, becomes constant for values of M from about 3 to 7, then decreases with larger M (becoming less than unity only for M greater than 8). The values of both A_1 and A_2 from Table XI are seen to depend on the metal.

If Vo is increased it is seen in eq. 4 that unless a new phenomenon occurs, a voltage will be reached at which rupture takes place without <u>any</u> energy input. In several experiments we have been able to get within about 10 volts of these points but gaseous discharges obscured the results





Fig. 5

TABLE XI. Summary of results of moderate energy explosions in which the initial voltage is varied and filament length (2.0 cm) kept constant. 200 μ F, 4 μ H, air at atmospheric pressure.

F • Met	ilament al D, mils	A1	A2, võlts	K, joules	- Zo, joules	z _l x10 ⁴ , joules volt	-z2x10 ⁴ , j <u>oules</u> volts ²
Ag	3.0	1.06	48	0,39	0,325	54	0.06
Au	2,9	1.06	42	0.27	0.234	47	0.06
Cu	3.1	1.12	74	0.57	0,63	93	0.13
Fe	3.1	1.34	92	0.13	0,82	165	0.40
Ni	1.2	1.10	23	0.013	0.038	28	0.10
	2.0	1.15	42	0.061	0.198	56	0.16
	3.0	1.16	72	0.23	0.46	97	0.17
Pt	3.0	1.19	72	8	0.47	102	0,21
Ŵ	1.0	1.06	17	-	0,020	19	0,06
	2.3	1.30	81	0.085	0.60	137	0.34
	3,0	1,33	119	0.24	1,38	210	0,38
	4.0	(0,98	151	0,62	1,40	145	-0,02)
	6.0	0.71	275	1.24	2.53	139	-0.25

at the points themselves. Experiments could be run with more equipment such that current and voltage would be measured as functions of time. This might yield information as to what kind of new phenomena arise as the voltage is increased past this point. In this way we could find out if there are any fundamentally different processes occuring at very high voltages (used in the experiments discussed in the appendix) and at the moderate voltages used in the present experiments.

We will now examine eq. 4 to see what its consequences are. It is seen in Table XII that the energy dissipated in the apparatus, K, is constant for a given filament (excluding a few of the extrapolated calculations), and in Table XV that the numerical values of the average K in this and in the next series of experiments and the averages for the minimum energy explosions all have about the same value for a given filament. The assumption of constancy of K will be discussed further in connection with Table XV. Combining the assumption that K is constant and that the filament length is constant (2.0 cm) with equations 1 and 4, we obtain,

 $E = z_0 + z_1 \ Vo + z_2 \ V_0^2$ where $z_0 = - (A_1^2 A_2^2 C/2 + K)/l$ $z_1 = A_1^2 A_2 C/l$ $z_2 = -\frac{1}{2} (A_1^2 = 1) C/l$ (6)

Thus when experiments are carried out so that the only initial condition that is varied is Vo, then the result, eq. 4, implies that E is given by the simple second degree polynomial of eq. 6.

The effect of filament diameter on e may be clearly

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TABLE	XII.	Resul	ts for	moder	ate en	nergy ex	plosions	s in wh	nich Vo
is va	ried f	or l:	2.0 0	em, air	at 1	atmosph	iere, 200) uF, 4	4 uH.
Filar Metal	ment D, mils	L, cm	Vo, volts	Vr, volts	<u>AV²C</u> , joules	kcal g.aton	K, joules	t <u>exp</u> , <u>R</u> <u>psec</u> ohm	Vr/ X, volts/cm, for gaseous discharges.
Ag	3.0	2.00 2.02 1.94	110 200 300	65 165 267	0.79 1.39 1. 9 6	10.5 27.1 (40)	0.39 0.37 (0.42)	119 45 25	
Au	2,9	1.98 2.00 2.10 2.00 2.00	105 200 300 325 340	67 169 274 300 311	0.66 1.44 1.49 1.57 1.90	10.7 26.1 (34) (37) (46)	0.29 0.23 (0.26) (0.27) (0.30)	99 34 18 16 18	
Cu	3.1	2.00 2.00 2.00 1.99 2.01	110 150 200 250 300	40 87 146 199 253	1.05 1.49 1.88 2.28 2.60	8.7 16.8 23.6 (29.2) (33.6)	0.55 0.52 0.53 (0.61) (0.66)	215 115 66 48 36	·
Fe	3.1	2.04 1.99 1.95 1.95 2.01 2.02 1.97 1.91	110 125 200 215 225 250 275 300	4 45 146 165 62 65 74 64	1.21 1.36 1.90 Gaseon Gaseon Gaseon	18.5 * * s disch s disch s disch	0,13 * * harge harge harge	204 63 52	31 32 38 34
Ni	1,2	2.02 2.00 1.89 1.99 1.98	50 70 100 150 200	7 50 87 138 100	0.245 0.240 0.241 0.340 Gaseou	(25) (25) (26) 35.6 as disch	(0.014) (0.014) (0.011) 0.013 narge	67 28 17	50
	2.0	2.02 1.92 2.00 1.96 2.00 1.98	70 75 100 150 200 250	28 15 67 125 184 230	0.41 0.54 0.55 0.69 0.61 0.95	13.9 (19) (19) (24) (21) 34.6	(0.050) (0.060) (0.061) (0.063) (0.065) 0.062	183 321 79 36 17 16	
	3.0	1.96 1.96 1.92 2.00	125 200 250 300	59 150 204 51	1.21 1.75 2.09 Gaseou	(17) (26) 33.3 us disch	(0.22) (0.24) 0.23 harge	150 58 41	26

TABLE XII. (continued)

Metal	D	l	۷o	Vr	$\frac{\Delta v^2 c}{2} \epsilon$	•	K	texp R	Vr/1
Pt	3.0	1.92 2.00 2.01 1.90 1.99 1.98	125 160 200 225 250 300	62 107 150 63 51 64	1.18 1.41 1.75 Gaseous Gaseous Gaseous	* * discha discha discha	* * rge rge	140 81 58	33 26 32
W	1.0	1.90 2.00 2.00 2.00 1.99 2.00 2.00	55 50 67 ¹ /2 100 150 200 300	10 35 51 89 140 194 64	0.29 0.13 0.20 0.21 0.29 0.23 Gaseous	* * * * * discha	* * * * *	71 56 23 14 6	32
	2.3	2.00 1.98 1.99 1.96 1.91 2.00 1.92 1.94	100 110 120 140 150 170 200	54 26 25 49 78 93 110 57	0.710 4 1.14 4 1.15 4 1.20 4 1.35 (4 1.38 (4) 1.69 (7) Gaseous	27.2 45.2 45.3 48.2 56) 57) 70) discha	0.070 0.090 0.091	123 288 296 179 117 96 87	29
	3,0	2.03 2.01 2.06 2.01 2.04	150 175 200 225 250	30 83 106 140 79	2.16 2.38 2.88 3.12 Gaseous	47.3 * * discha	0.24 * * *	32 1 149 127 95	39
	4.0	1.90 2.00 1.96 1.98 2.00 2.01 1.94 1.99 1.91 2.00 1.96 1.99	200 200 210 220 225 235 250 260 275 300 300	50 47 82 70 59 88 65 96 95 110 76 72	3.75 3.78 3.75 3.93 4.49 4.30 5.10 5.33 5.86 6.37 Gaseous Gaseous	46.2 44.3 44.8 47.0 * * * * * * * discha	0.63 0.63 0.62 % % % % arge	277 289 188 219 263 188 257 192 201 183	39 36
	6.0	2.00 2.00 1.99	300 325 340	20 32 48	8.96 10.7 11.3	40.6 * *	1.24 * *	540 456 391	

* Data not calculable on account of lack of adequate resistance-temperature data.

Metal	D, e, mils	kcal/g.atom	Vo,volts
M	2.3	45-48	110-120
	3.0	47.3	150
	4.0	44-47	200-210
	6.0	40.6	300
Ni	1.2	24-26	50-100
	2.0	24.5	150
	3.0	26,2	200
Ni	1.2	35.6	150
	2.0	34.6	250
	3.0	33,3	250

Thus, roughly, to obtain the same state at t_{exp} , on increasing D by 1.0 mil we must increase Vo by about 50 volts.

Since R is greater than 2.5 ohms for most of the experiments, we can calculate t_{exp}/R for these experiments without knowing R, the method being given in Appendix A3. The formulae for t_{exp}/R in terms of eq. 4 are complicated so that in order to see the consequences of eq. 4 on t_{exp}/R we examine the calculated values themselves. When t_{exp}/R is plotted against Vo linearity is not obtained, when plotted against log Vo satisfactory linearity is obtained, the slopes being of the order of magnitude of -1.9. Values of $\frac{t_{exp}}{R} \frac{v_{exp}^2}{2}$ have been plotted against M on log-log paper (fig. 6). It is seen that the results for tungsten are considerably different than for the other metals. The results are;

for W, $\frac{\text{texp}}{R} = \frac{\text{Vec}}{2} = 58.1 \text{ M}^{1.45}$, and for Ni, 29.4 M^{1.08} ... (7)







Fig. 6

For those experiments in which gaseous discharges occur, $Vr/\lambda = 26$ to 39 volts/cm (with one exception of 50 volts/cm) compared to 2 to 156 volts/cm for the rest of the experiments in this section. These results are not surprising since a gaseous discharge might cease conducting under somewhat comparable conditions.

The series of gold filament explosions are shown in plates 22 through 33. As Vo is increased, the vapor-like deposits on the slides become more readily observable. Also the hemispherical gold deposits observed at 632x decrease in size as Vo is increased. At 4.7x the deposit changes appearances with increasing Vo, more of the filament is deposited, cylinders about the filament axis appear, and the details on the cylinders become sharper.

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1.98 cm gold filament, Vo = 105 volts, e= 10.7 kcal/g.atom Plate 22. 4.7x Plate 23 632x



Heavy splatter is seen at 4.7x. The high power photographs, plates 23 and 24, have been taken in this region. The background has less vapor deposited than does plate 27 for which $e \pm 26.1$ kcal/g.atom. At the small e used, it is evident in plates 23 and 24 that the original filament shape has not been completely destroyed. Even at high magnification the background is devoid of metallic deposits. Plate 24. 632x. An enlargment of plate 22.



2.00 cm gold filament, Vo = 200 volts, e = 26.1 kcal/g.atom Plate 25. 4.7x Plate 26. 632x



(This is another copy of plate 20 and of 21 included here for the sake of completeness of the present sequence.) The background is markedly different from the one in plates 22,23, and 24. 2.10 cm gold filament, $V_0 = 300$ volts, e = (34) kcal/g.atom Plate 27. 4.7x Plate 28. 632x



On this plate and on plates 29 and 32 (i.e. on all plates with still higher Vo), the complete filament pattern is imprinted on the slide. The balls in plate 28 are a little smaller than those of plate 26 (for which Vo was smaller).
2.00 cm gold filament, Vo = 325 volts, e = (37) kcal/g.atom Plate 29. 4.7x Plate 30. 632x





The appearance of this pattern is more uniform than the one on plate 27 for which e = (34) kcal/g.atom. However, parts of the two patterns are almost identical in appearance. The background in plate 28 is very shiny under high power when viewed under the microscope, whereas that background in plate 30 is duller. Plate 31. 632x. Part of background of plate 29.



2.00 cm gold filament, Vo \pm 340 volts, e \pm (46) kcal/g.atom. Plate 32. 4.7x Plate 33. 632x.





The filament deposit appears to have several cylindrically symmetrical regions. The heavier deposits at the end may be due to the fact that the filament was clamped against the glass slide at its two ends. If we compare plates 24, 26, 28, 30, and 33, we see that there is a trend towards smaller ball starting with plate 26. In plate 24 the filament has not broken up into globules - at least not the protions deposited on the glass slides. c. Effects of varying filament length

If the data are examined (Table XIV) we see that we may assume that:

K is independent of filament length for a given filament ...(9) Combining equations 1,8, and 9 and using the condition of these particular experiments, namely that $V_0 \equiv 200$ volts, we obtain,

 $E = W_{-1} + W_{0} + W_{1} l$ where $W_{-1} = V_{0}^{2}C/2 - G_{2}^{2}C/2 - K$ $W_{0} = -G_{1}G_{2}C$ $W_{1} = -G_{1}^{2}C/2$

These coefficients of powers of filament length are listed in Table XIII.

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TABLE XIII. Results for experiments in which filament length is varied for Vo = 200 volts, C $= 200 \mu$ F, and L $= 4 \mu$ H for explosions in air at atmospheric pressure.

Fil: Metal	D, mils	volts cm	G2, volts	K, joules	W_1, joules	joules cm	$\frac{- w_1 x 10^4}{\text{joules}}$
Ag	3.0	2,60	167	0.37	0,94	0.087	6.8
Au	2.9	6.4	181	0,24	0.48	0.231	41.
Cu	3.1	4.5	156	0.61	0,95	0.140	20.
Fe	3.1	10.6	174		(0.93)	0.369	113.
Ni	3.0	9.4	168	0,25	0,92	0.314	88.
Pt	3.0	8,5	168	0,20	0.97	0.286	72.
W	1.0	2.0	198	0,0083	0,06	0.079	4.0
	2.3	(10.8)	(170)	0,13	(0.97)	(0.367)	(117.)
	3.0	(30.5)	(181)	0,26	(0.46)	(1.10)	(930.)
	6.0	22.	30	1.96	1,95	0,132	485。

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TABLE	XIV.	Result	ts for	modera	te ener	gy expl	osions	in which X
is va	ried i	for Vo	= 200	volts,	air at	, 1 atmo	sphere	, 200 µF, 4 µH.
<u>Filar</u> Metal	ment D, mils	l, cm	Vr, volts	$\frac{\Delta v^2 c}{2}$, joules	e, kcal g.aton	K, joules	$\frac{t_{exp}}{R}$, $\frac{usec}{ohm}$	Vr/l, volts/cm, for gaseous discharges.
Ag	3.0	0,89 1.40 2.02 3,35	45 164 162 159	3.81 1.32 1.39 1.48	Gaseou (36) 27.1 18.0	us discha (0,38) 0,37 0,36	arge (42) 45 49	51
Au	2.9	0.40 0.73 2.00 3.07 4.98	15 176 169 161 149	3.98 0.90 1.14 1.41 1.78	Gaseou (52) 26.1 2118 17.1	us disch (0 .23) 0.23 0.23 0.23 0.29	arge (28) 34 44 60	38
Cu	3.1	0.34 0.66 0.98 1.02 1.42 2.00 3.10 4.00 4.47 5.28	23 45 62 64 150 146 142 137 135 136	3.94 3.80 3.62 3.59 1.75 1.87 1.98 2.12 2.18 2.15	Gaseou Gaseou Gaseou (29) 23.4 15.6 12.7 11.8 10.0	15 disch 15 disch 15 disch 15 disch (0.57) 0.52 0.60 0.67 0.67 0.64	arge arge arge (62) 66 73 80 83 81	68 68 63 63
Fe	3.1	0.91 1.30 1.60 1.95 2.39 2.97 3.32	45 67 145 146 141 131 127	3.80 3.55 1.90 1.87 2.01 2.28 2.39	Gaseou Gaseou * * * *	is disch is disch * * * * *	arge 64 63 70 85 91	49 52
Ni	1.2	1,98	100	3.00	Gaseou	us disch	arge	50
	2.0	2.00	184	0.61	(21)	(0.066)	17	
	3.0	1.31 1.96 3.02	156 150 140	1.56 1.75 2.04	35.1 (26) 20.0	0.22 (0.24) 0.28	50 58 71	
Pt	3.0	1.30 2.01 4.41	157 150 134	1.54 1.75 2.20	* * 21 . 5	* * 0;20	48 58 80	

TABLE XIV. (continued)

Metal	D	l	Vr	$\frac{\Delta v^2 c}{2}$	e	K	texp R	vr/l
W	1.0	2.00 2.70 4.00	194 192 190	0.23 0.31 0.39	* * 43	* * 0.0083	6 8 10	
	2,3	0.47 1.94 2.60 2.90 3.12 3.89 5.09	40 57 138 137 136 129 114	3.84 3.68 2.09 2.12 2.15 2.33 2.70	Gaseous Gaseous * * 48.3 43.1	discha discha * * 0.12 0.13	rge 75 76 77 88 112	85 29
	3.0	0.98 1.50 2.06 2.50 2.65 2.70 2.91 3.21 3.27	59 66 106 104 103 101 94 76 82	3.65 3.56 2.87 2.92 2.94 2.98 3.12 3.42 3.33	Gaseous Gaseous * * 49.3 49.2 47.0	s discha s discha * * 0.26 0.26 0.26	rge 127 131 132 137 151 193 178	60 44
	4.0	0.40 0.80 0.99 1.08 1.13 1.20 1.40 1.40 1.60 1.60 1.68 1.79 1.80 1.90 2.00 2.60	39 60 69 77 65 69 80 65 55 65 65 55 65 40 547 0	3.85 3.64 3.41 3.58 3.52 3.36 3.52 3.36 3.64 3.50 3.58 3.58 3.58 3.58 3.58 3.58 3.75 3.78 No exp	Gaseous * * * * * (50) 46.8 (50) 46.2 44.4 losion.	discha * * * * * * * * * * * * * * * * * * *	rge 241 241 191 225 213 183 241 225 258 225 225 225 321 277 289	98
	6.0	0.13 0.39 0.71 1.00	14 22 15 0	3.98 3.95 3.98 No exp	Gaseous * 35.5 losion.	discha * 1.96	rge 442 517	108

* Data are not calculable on account of lack of adequabe resistance-temperature data.

The net result of these experiments is that E is simply related to filament length. This equation is very suggestive. If the minimum energy experiments are recalled, it was found that for filament longer than 0.7 cm, E could be adequately represented by $E = Eo + E_1 k$. In addition, E_1 is negative for small diameters and w_1 negative for all diameters. It is possible that the end effects of E for short filaments for minimum energy explosions could be taken care of without special treatment by use of a term, $E_1 k$.

Since K is practically independent of filament length for the present set of experiments, we have compared these values of K in Table XV with those obtained previously. The values of K for a given filament is the same for many cases.

If we examine the values of w_{-1} we see that these are about equal to 0.95 joules for silver, platinum, copper, iron, and nickel filaments. Furthermore the values of w_{-1}/M for the tungsten filaments are 0.11, (0.35), (0.10), and 0.10 for the 1.0, 2.3, 3.0, and 6.0 mil tungsten filaments respectively, and 0.11 for the gold filament. Hence it appears that w_{-1} is a function of filament cross-section and is considerably different by a factor of about two for gold and tungsten and for the other metals studied.

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As may be seen in the following summary of the results of Table XIV, to obtain the same e as we increase D we must first increase filament length, then start decreasing it again.

Fi: Metal	lament D, Mils	Filament length, cr	e,kcal/g.atom
Ni	2.0	2.00	21.1
	3.0	3.02	20.0
W	1.0	4.00	43.3
	2.3	5.09	43.1
	4.0	2,00	44.4
W	2,3	3,89	48.3
	3.0	3.27 3.21 2.91	47.0 49.2 49.3
	4.0	1,90 1,79 1,68 1,80	46.2 46.8 (50) (50)

We will now examine t_{exp}/R . Since the equations are very involved, instead of deriving the behavior of t_{exp}/R , we will use the calculated values to find its properties. It is seen in fig. 6 that t_{exp}/R versus filament length is linear on log-log paper, this being true of all the filaments studied except tungsten for which the scatter is so large that no trends are obtainable.

When gaseous discharges occur, we might expect that the gap potential at which conduction ceases is a function of gap length. For the experiments in which Vo was varied, $Vr/\lambda = 33$ whereas for those of the present section in which filament length is varied, it is equal to 65. There is no obvious reason why the two groups of experiments should have different gap potentials at which conduction ceases. Therefore we calculated $Vr/\sqrt{\lambda}$ to see if this function improved the agreement. We obtain; for variable Vo, $Vr/\sqrt{\lambda} = 46$ 4 volts/cm^{$\frac{1}{2}$}(11) for variable λ , $Vr/\sqrt{\lambda} = 53$ 10 volts/cm^{$\frac{1}{2}$}(11) Thus for all the available experiments at atmospheric pressure, $Vr/\sqrt{\lambda}$ has about the same value for all the filaments.

The series of gold filament explosions are shown in plates 34 through 45. The heavy metallic cylindrical deposits are very wide for short filament length at 4.7x. Ball size as seen at 632x does not seem to be affected by gaseous discharge. The background deposit is considerably brighter for gaseous discharge. This may be caused by the heat of the discharge after the filament metal has been deposited. Ball size appears to increase, then to decrease as filament length is increased.

A series of plates, 46 through 54, are given to show how typical filaments of the remainder of the metals for moderate energies look at 4.7x. These may also be compared with plate 55 for indium and plate 56 for gold leaf (632x).

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0.40 cm gold filament, Vo = 200 volts, Vr = 15 volts, gaseous discharge.

The deposit is very wide compared to the deposits on plates in the preceding section. At 632x the background is bright, the balls are small.

Plate 34. 4.7x

Plate 35. 632x

Plate 36. 632x. An enlargement of plate 34.



This enlargement shows the intersection of three regions each with different characteristics. The colors of the background are different in each region as are the ball sizes. 0.73 cm gold filament, Vo = 200 volts, Vr = 176 volts, e = (52) kcal/g.atom

Plate 37, 4.7x Plate 38, 632x



The enlargment shows a typical group of spheres. Comparison with plate 35 indicates that the balls are about the same size. Thus the sizes of the balls on plate 35 has not been affected much by the gaseous discharge. Plate 39. 632x. Enlargment of background in plate 37.



This plate is very different from plate 36 as regards backgrounds. Plate 36 is very bright and smooth. This may have been a results of the heating by the gaseous discharge. 2.00 cm gold filament, Vo = 200 volts, Vr = 169 volts, e = 26.1 kcal/g.atom

Plate 40. 4.8x

Plate 41. 632x.



This is a duplicate of plate 20. The differences between this plate and plate 37 are numerous. Since e for plate 37 is two times as large as e for plate 40, this is not surprising. The main differences are the width of the cylinders, the characteristic details of the cylinders, and the heavy black deposit on plate 40. The balls in the enlargment are considerably larger than on plates 35 and 38. 3.07 cm gold filament, Vo = 200 volts, Vr = 161 volts, e = 21.6 kcal/g.atom

Plate 42. 4.7x

Plate 43. 632x



Not much metal has been deposited on the slide. Very few balls were found. These balls are smaller than those on plate 41 and larger than those on plate 43. 4.98 cm gold filament, Vo = 200 volts, Vr = 149 volts, e = 17.1 kcal/g.atom Plate 44 4.7x Plate 45 632x



Only a portion of the scant metallic deposit has been photographed.

Plate 46. 4.7x Tungsten 4.0 mil filament Air at 1 atmosphere Length = 1.96 cm

The condenser was charged to 150 volts and discharged through the filament without blowing it out. A second surge with Vo = 300 volts blew it out. A gaseous discharge occured. The large white cloud has a bluish tinge.



Plate 47. 4.7x Tungsten 4.0 mil filament Air at 1 atmosphere Length = 2.00 cm

A single surge with Vo = 275 volts blew out the filament. Unlike plate 46 there is only a small amount of cloud.



Plate 48 4.7x Tungsten 1.0 mil filament Air at 1 atmosphere Filament length = 2.00 cm Single surge, Vo = 100 volts Vr = 89 volts

There is a distinct blue cylindrical film on this slide that is more like plate 46 than 47.



Plate 49 4.7x Nickel 3.0 mil filament Air at 1 atmosphere Filament length = 2.00 cm V_0 = 300 volts Vr = 51 volts Gaseous discharge.



Plate 50 4.7x Platinum 3.0 mil filament Air at 1 atmosphere Filament length = 1.90 cm V₀ = 225 volts Vr = 63 volts Gaseous discharge



Plate 51	4.7x
Copper 3.	l mil filament
Air at l	atmosphere
Filament	length $= 2.00$ cm
Vo = 200	volts
Vr = 146	volts
e = 23.6	kcal/g.atom



Plate 52 4.7x Silver 3.0 mil filament Air at 1 atmosphere Filament length = 1.40cm Vo = 200 volts Vr = 164 volts



Plate 53 4.7x Iron 3.1 mil filament Air at 1 atmosphere Filament length = 1.97 cm Vo = 275 volts Vr = 74 volts Gaseous discharge Plate 54 4.7x Constantan 3.1 mil filament Air at 1 atmosphere Filament length \pm 2.48 cm Vo \pm 275 volts Vr \pm 220 volts C \pm 200 μ F L \pm 1 μ H



We will now examine the constants for the moderate energy explosions relations. At Vo = 200 volts and filament length equal to 2.00 cm, the residual voltages in equations 4 and 8 are equal. Thus we obtain,

2.0 $G_1 + G_2 = A_1$ (200 - A_2)(12) This equation is used to calculate A_1 for comparison with A_1 obtained directly from the experimental data (cf. Table XV). As is obvious, the comparison for tungsten is poor.

Since it has been assumed that K is constant for both series of experiments, the average K for each set is listed in Table XV along with K for minimum energy explosions for both the graphical and analytical values. It is apparent that these average values of K are about the same for experiments carried out under a wide range of conditions for a given filament. In a sense this result is reassuring since, if the average values of K are about the same, smaller changes in conditions caused by changing Vo or filament length should not have more pronounced effects on K. TABLE XV. The energy dissipated in the apparatus, K, is compared for a variety of conditions. In addition the constant A₁ obtained from the experimental data by means of eq. 4 is compared with A₁ obtained from eq. 12. Agreement between these two values is a test of consistency of the variable initial voltage experiments with the variable filament length experiments at moderate energies.

Filament		K, joules				Al	
Metal	D, mila	Moderat	te energy	Minim	am	Eq.4	Eq. 12
			explos	energy			
		varied	varied	graph	anal-		
				ical	ytical		
Ag	2,9	0.39	0.37	0,38	0.38	1.06	1.06
Au	3.0	0.27	0.24	0,29	0.31	1.06	1.06
Cu	3.1	0,57	0.61	0.87	0.61	1,12	1.17
Fe	3.1	0.13	0	(0.04)	0.13-	1,34	1,41
Ni	1.2	0,013	~	(0,03)	0.014	1.10	
	2.0	0,061	0.066	0.061	0.050	1.15	0
	3.0	0.23	0.25	0.19	0.22	1,16	1,16
Pt	3.0	3	0.20	(0.17)	0.16	1,19	1,18
W	1.0	63	0.0083	(0.0084	4) -	1.06	1.06
	2.3	0.085	0.13	0.18	0,08	1,30	1,24
	3.0	0.24	0.26	0.41	-	1,33	1.48
	4.0	0,62	0.62	(0.61)	0.49	(0,98)	-
	6.0	1.24	1,96	-	660	0.71	0.19

3. Study of chemical reactions of Electrically Exploded Filaments with a number of gases.

Initial experiments indicated that exploded copper filaments reacted strongly with ammonia. A number of other gases were then tested at pressures less than 100 mm, namely, O_2 , CO_2 , C_2H_4 , C_2H_2 , PF_3 , H_2O , H_2S . There was no reaction of the exploded copper filaments with any of these gases within experimental error which was rather large since a meter stick was used to take readings. In these experiments $C = 50 \ \mu$ F, Vo = about 270 volts, but r and L are unknown. The reaction was followed for 24 hours. An upper limit to the amount of gas that might have disappeared would be at most O_22 mole of gas per mole of copper filament.

The reactions with ammonia were re-investigated with refined apparatus. A cathetometer was now used. With $C = 200 \mu F$ and $L = 4 \mu H$, a 3.0 mil gold filament 1.90 cm long was placed in an ammonia atmosphere at 82.5 mm pressure. It took four days before the pressure became constant at 82.5 mm pressure. Apparently the brass in the apparatus reacted with or adsorbed the ammonia. After the explosion (VO = 200 volts, Vr = 48 volts) there was no change in pressure for 19 hours.

A 3.1 mil, 2.00 cm copper filament was exploded in an ammonia atmosphere. Three days were required for the system to attain a constant pressure of 81.1 mm. After the explosion (Vo = 200 volts, Vr = 142 volts) no observable change in pressure was noted in 24 hours. An upper limit to the amount of gas that might have disappeared would be at most 0.02 moles of gas per mole of copper filament.

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4. Experiments with indium filaments

Indium filaments were prepared by drawing out a glass tube, with an indium metal pellet inside, in an oxygen gas flame. The glass was removed in hydrofluoric acid. Uniformity of the filaments was poor. In plate 44 is seen a typical slide at 4.7x of an explosion of an indium filament. The results for indium are given below;

Vo = 200 volts, C = 200 μ F, L = 4 μ H, Air at atmospheric pressure, l = 1.98 to 2.98 cm.

> D, mils Vr, volts 3.2 72 3.7 66 4.0 71 4.8 125 5.3 68 5.7 123 6.1 120 7.3 99 8.3 22 9.7 59

Plate 55 4.7x Indium 4.0 mil filament Air at 1 atmosphere Filament length = 1.98 cm Vo = 200 volts Vr = 71 volts

		-
Plate	56	632x
Gold 1	eaf	
2.8	cm	long
1.9	cm	wide
Air at	1	atmosphere
Vo = 2	00	volts
Vr = 1	76	volts



5. An explosion using gold leaf.

An explosion with gold leaf is shown in plate 56 at 632x. It is of interest mainly to show that the features found on the slides for gold filaments are characteristic both of the gold and of the filament shape. The gold leaf pattern is unlike that of any of the gold filaments. E. Summary and conclusions

The study of the low voltage electrically exploded wire was undertaken to see if it could be used as a source of metal vapor. Finding that filaments did not vaporize as expected, we studied the nature of the processes occuring by determining the amount of energy dissipated in the filaments and by collecting the metal on glass slide for microscopic inspection to ascertain the nature of the exploded metal.

It was found experimentally that for minimum energy explosions in which filament length was varied the total energy dissipated, i.e. the energy lost by the condenser, was directly proportional to the filament length. From this fact we were able to obtain the total energy dissipated in the filaments per cm. The temperatures corresponding to these filament energies decrease as filament diameter is increased. The average filament temperature decreases a little as filament length is increased for small diameter There appears to be an effect due to changing filaments. capacity and inductance, but this has not been established quantitatively. When helium is substituted for air at atmospheric pressure the minimum energy explosions seem to be unaffected. In order to test the hypothesis that the filaments blow out on account of vaporization, we have examined the glass slides on which the exploded metal is deposited. As yet no metallic deposit have been found that would indicate that vapor was present with minimum energy explosions.

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Summary of Voltage Relations found Experimentally. TABLE XVI.

1. Minimum energy explosions

$$\frac{\Delta v^2 c}{2} \propto l$$

2. Moderate energy explosions

a. Variable pressure (gold, 2.0 cm, 3.1 mils) 4.00 joules available $\frac{\Delta V^2 C}{2}$ = 3.66 to 3.97 joules 10^{-4} to 135 mm $\frac{\Delta v^2 c}{2}$ = 1.14 to 1.57 joules 50 to 760 mm Vr = A1 (Vo - A2), b. Variable V. $A_1 \ll A_2$ $Vr = G_1 l + G_2,$ c. Variable 1 $|G_1| \ll G_2$

TABLE XVII. Summary of the Effects of the Variables Studied on E.

l. Minimum energy explosions	
Filament length (l) 0.7 cm)	$E = E_0 + E_1 l$, where $ E_1 \ll E_0$
Filament diameter	$d(E/D^2)/dD < 0$, so the explosion temperature (average) decreases with increasing D.
Filament metal	E is strongly dependent on the filament metal.
Gas	E is the same in air and in helium for nickel.
C and L	There appears to be an effect.
2. Moderate energy explosions	
a. Variable pressure for 2.0 cm 3.1 mil gold. 4.00 joules available.	E = 0.46 to 0.62 joules/cm, 4-18 % vaporized at explosion, for 50 to 760 mm.
b. Variable V _O	E = 1.60 to 1.76 joules/cm, 85 to 100% vaporized at explosion, for 10^{-4} to 135 mm. er gaseous discharges occur. E = $\sum_{i=1}^{2} i V_{i}^{i}$. For K = constant, the z_{i} are directly obtainable from the equations in Table XVI.
Diameter	To obtain the same state at explosion, on increasing D by 1.0 mil, Vo must be increased by about 50 volts.
Metal	E is strongly dependent on the filament metal.
c. Variable	$E = \frac{1}{2} w_i l^i$. For $K = \text{constant}$, the w_i are directly obtainable from the equations in Table XVI.
Diameter	To obtain the same state at explosion, on increasing D, A must first be increased then decreased.
Metal	E is strongly dependent on the filament metal.

A series of vacuum explosions were carried out at moderate energies. It was found that from 50 to 760 mm the explosions were unaffected by changes in pressure from the standpoint of the energy dissipated in the filaments. However the mean size of metal globules deposited on the glass slides decreases with lowering of pressure.

A different process occurs from 10^{-4} to 135 mm. One or the other of the two processes occurs in the pressure range from 50 to 135 mm. This second type of process is characterized by a much larger total energy dissipation and decrease in size of metal globule on the glass slides. At 10^{-4} to 5 mm the metal deposits appear to have been largely of vapor origin. The states of the filaments corresponding to the high vacuum results are ambiguous. Further data is need to determine whether the above processes are due to gas discharges or to the calculated states at time of rupture of 85 to 100% vaporized.

Two further series of moderate energy explosions were carried out at atmospheric pressure. In one series, the initial condenser voltage was varied, all the other initial conditions being reproduced as closely as possible. It was found that the residual condenser voltage was proportional to the initial condenser voltage. This result implies that the energy dissipated in the filaments is a simple function of the initial voltage. At higher energies than the minimum explosion energies, the assumption that the energy dissipated in the apparatus for a given filament is a constant leads to an error of less than about 5%. On using this assumption we are able to determine the total energy dissipated in the

-40a

filament per cm directly from the experimental results without need of such data as resistivities, heat capacities, etc.

In a second series of experiments, the initial voltage was kept constant and the filament length was varied. Here it was found the the residual condenser voltage was proportional to the filament length. Using the same assumption as for the variable initial voltages, we arrive at corresponding results, namely that we may determine the total energy dissipated in the filament per cm directly from the experimental results with only initial conditions specified.

As an example of the significance of these results, suppose we have a metal filament into which we wish to introduce a given amount of energy. By performing a series of minimum energy explosions and a series of moderate energy explosions we will be in a position to specify the initial needed to give us the desired result.

A series of experiments have been carried out to see whether any changes in pressures result from exploding filaments in a number of different gases. We obtained negative results in our experiments.

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Appendix A. Derivations

In this section we shall present the derivations of the principal equations used in this paper. In all this work we assume that C and L are constant during the surge. In addition we assume that the principal energy effects of the electrical surges are the Joule heat dissipation, phase changes in the filament metal, and skin effects in the apparatus. Radiation losses, heat conduction losses, the Thomson effect, and the Peltier effect amount to less than 0.03 joules under the most extreme conditions encountered for times less than 400 microseconds. These effects have been neglected in all cases. There was a maximum condenser lag of 4 volts which has been neglected even though it may be of importance in some cases. The derivations are restricted to explosions in which gaseous discharges do not occur since Joule's Law is not applicable to these discharges.

1. Derivation of Equation 1.

The energy dissipated in the region of filament x to x + dx at time t to t + dt is equal to $\mathcal{O}(x,t)$ $t^2 dx dt$. The total energy dissipated in the filament is equal to $E = \int_{x=0}^{L} \int_{t=0}^{t \exp i^2} \mathcal{O}(x,t) dt dx$ From Joule's Law. $= \int_{x=0}^{L} \int_{t=-\infty}^{t \exp i^2} \mathcal{O}(x,t) dt dx$ i = 0 outside of t=0 to texponent $= \int_{x=0}^{L} \mathcal{O}(x) dx \cdot \int_{t=-\infty}^{t \exp i^2} dt$ By definition.

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The total energy dissipated in the apparatus (excluding the filament) is equal to $\int_{t=0}^{texp} i^2 r dt = \overline{r} \int_{t=-\infty}^{+\infty} i^2 dt$

The total energy dissipated is therefore given by, $\frac{\Delta v^2 c}{2} = E l + \frac{\overline{r} E l}{\int_{x=0}^{l} \overline{g(x) dx}}$

If
$$\tilde{\rho}(\mathbf{x}) = \bar{\rho}(\mathbf{x})$$
 which is independent of \mathbf{x} , then

$$\frac{\Delta \mathbf{v}^2 \mathbf{c}}{2} = \mathbf{E} \left[\mathbf{1} + \frac{\bar{r}}{\bar{\rho}} \right] \cdot$$

Thus the simplest derivation of eq. 1 is that in which it is assumed that the filament resistance is uniform at any time t.

If $\widetilde{\rho}(x)$ is not independent of x the situation is more complicated. We will make a few simple assumptions to see what happens. Let us assume that the filament blows out for minimum energy explosions because of vaporization of hot points. We now replace the term, $\widetilde{\rho}(x)$, by two terms, one for the hot points (h) and the other for the main portion of the wire (m). Let f be the fraction of the wire occupied by the hot points. Then $\int_{x=0}^{4} \widetilde{\rho}(x) dx = (1-f) \int_{x=0}^{2} \widetilde{\rho}_{m} + f \int_{x=0}^{2} \widetilde{\rho}_{h}$

and
$$\frac{\Delta v^2 c}{2} = E \left[\lambda + \frac{\overline{r}}{(1-f)\overline{o}m + f\overline{o}h} \right]$$

If the number of hot points is distributed from the macroscopic viewpoint uniformly along the filament so that f is independent of filament length, then the above equation may be in agreement with eq. 1.

2. Current

The system is a circuit in which an inductance, a capacitance, and a resistance are in series. To avoid mathematical complexity, we assume that R is a constant during the surge. Our system is always overdamped so that $R^2 > 4L/C$ (13). The well known solution to the above is;

 $i = \frac{Vo}{mL}$ e sinh mt where $a = \frac{R}{2L}$ and $m = \sqrt{\frac{a^2}{a^2} - \frac{1}{LC}}$

3. Time at which the Explosion Occurs

The total energy dissipated is equal to $\int_{t=0}^{texp} i^2 R dt$, which is integrable for constant R if we use eq. 14. After integration we neglect two terms which are negligible compared to the terms retained in almost all cases. For example for some of the copper filaments the values of these terms are 10^{-26} , 10^{-15} , and 10^{-5} . Solving for t_{exp} we obtain,

$$texp = \frac{2.303 \text{ C}}{4} \left[R + \sqrt{R^2 - 4L/C} \log \left[\frac{R(R + \sqrt{R^2 - 4L/C})}{2(R^2 - 4L/C)} \left(\frac{V_0}{V_r} \right)^2 \right] \dots (15)$$

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4. Effect of Variation of E and F with Filament Length on E(graphical) for Minimum Energy Explosions.

We will assume that E and F may be adequately represented by $E = E_0 + E_1 l$ and $F = F_0 + F_1 l$. We have by definition, $E(\text{graphical}) = \frac{d \frac{\Delta V^2 C}{2}}{d l}$. Combining these with eq. 1, we obtain for the amount of energy dissipated in the filament, $e = \frac{e(\text{graphical})}{1+F_1+(l+F)e_1/e}$(17) If we assume that the analytical results are satisfactory we may re-write this as,

5. Mean Filament Resistance Hypothesis and Skin Effect Corrections

When $\Delta V^2 C/2$ was plotted against filament length for minimum energy explosions a straight line fit was found to be valid within experimental error. The reliability of the numerical values of the constants defining these lines was adequate to enable us to interpret the results. Since these straight lines were obtained it appears that the assumption that E and F are fairly constant for minimum energy explosions appears to work. However the numerical values of F (which is equal to $\overline{r}/\overline{\phi}$) are incompatible with the use of the direct current resistance for \overline{r} . If the direct current apparatus resistance is used, values of $\overline{\rho}$ (obtained as \overline{r}/F) are found to correspond to 300 to 500°K instead of reasonable values of the order of 1000°K for copper, silver, and gold.

Another example of this difficulty is furnished by the constantan data. Constantan filaments were used for exploratory experiments. For 200 μ F and 1 μ H, F = 0.56 cm.

Since the resistance of constantan 3.1 mil wire is 1.0 ohms/cm from room temperature to the melting point, it is probable that $\overline{\rho}$ is of the order of 1.0 ohm/cm. Therefore, $\overline{r} = Fx \overline{\rho} = 0.56$ ohms, which is about 5 times as large as the direct current apparatus resistance.

Since the values of ρ are needed to make skin effect corrections, it is necessary to assign reasonable values to $\bar{\rho}$ in order to obtain $\bar{\rho}$. It is assumed that $\bar{\rho}$ is equal to the filament resistance when E/2 joules have been dissipated in one cm of filament. When the state of the filament corresponding to E/2 is that of a partially melted solid then $\bar{\rho}$ is obtained by assuming that the liquid and solid are distributed uniformly along the filament. When the state corresponding to E/2 is that of a partially vaporized liquid, then $\bar{\rho}$ is obtained by assuming that this resistance is equal to the resistance of the unvaporized liquid at that temperature.

The use of skin effect corrections is reasonable since the rate of change of current is rapid during a surge and since there are several conductors in the apparatus with relatively large cross-sections. These include switch blades, coaxial cable, brass standard taper joint, and soldered joints. The filament diameters are too small to have pronounced skin effect corrections. We assume that the apparatus resistance \overline{r} is proportional to the square root of the frequency and the effective frequency is inversely proportional to the time at which the current attains its maximum value. The curve in fig. 7 is drawn to satisfy the above as well as to pass through the point for copper.





Fig. 7

Appendix B. Relations between Mean Filament Resistance and Effective Apparatus Resistance for Minimum Energy Explosions.

We have been using fig. 7 to evaluate r. If this curve is replotted on log-log paper it is found that the relationship becomes almost linear. We wished to see how r(analytical) was related to $\overline{\rho}$ (analytical). The situation is too complicated mathematically to derive the relation directly so we have examine the analytical results themselves. The linearity of r versus $\overline{\rho}$ (on log-log paper was suggestive, so we plotted both r(analytical) and r_1 against $\overline{\rho}$ (analytical) on log-log paper. It is seen in fig. 7 that satisfactory linearity is obtained. The value of r_0 has been assumed to be 0.27 ohms.

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Appendix C. A possible Source of the Large Mean Deviations in Explosion Times.

The mean deviations in t_{exp}/R is about 20% whereas that in e is about 4%. Most of the scatter in the former may be accounted for if we assume that the scatter in e is due to the possibility that a given filament may blow out anywhere in the energy range, e - 4% to e + 4%(and not restricted to the given e). An order of magnitude calculation with the copper results yields the result that the scatter in t_{exp}/R , due to indeterminancy in e of 4%, is 11 to 22% which is of the same order of magnitude as the value of 14% for copper.

For small Vr the corresponding mean deviation in t_{exp} becomes very large. On account of the logarithmic nature of the functions involved, the values of t_{exp} corresponding to e + 4% may become very large or infinite or imaginary (which simply means that the filament does not explode) whereas the values for e - 4% will be only a little smaller than those for e_{exp}/R in Table IV but no excessively small ones.

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Appendix D. Minimum Energy Explosions with Constantan Filaments for a Number of Different Circuit Constants

In most of the exploratory experiments for minimum energy explosions, constantan filaments were used to test the behavior of the system. This exploratory data is not as closely controlled as the data for the other metals. In addition to this, when much of the early work was done, a high resistance voltmeter had not yet been built so that in some of the calculations we have had to neglect Vr. In the results summarized bewow, the <u>possibility</u> appears that the inductance affects E more than does the capacity. A series of experiments to examine this more fully would be interesting.

Minimum energy explosions of 3.1 mil constantan filaments in air.

Capacity,	Inductance uH	, Type of lead to filament contact.	E(graphical), joules	F, cm
50	1	Monel capillary	0,268	0.39
200	(1)	Monel capillary	0,255	0.56
Experiment	ts for whic	ch Vr has been omitted.		
50	1	Gold capillary	0,242	0.69
50	1	Solder	0.240	0.84
50	11	Solder	0.275	0.29

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Appendix E. Bibliography

Anderson: Proc. Nat. Acad. of Sci., 6, 42 (1920); 8, 231 (1922) Anderson: Astrophysical Journal, 51, 37 (1920) Anderson and Smith: ibid., 64, 295 (1926) Dechene: J. de Phys. et la Rad., 7, 59 (1926) Eckstein and Freeman: Z. Phys., 64, 547 (1930) Fukunda: Inst. Phys. Chem. Res. Tokio Sci. Papers, 6, 1 (1927) Futagami: ibid., 31, 1 (1937) Hori: ibid., 4, 59 (1926) Menzies: Proc. Roy. Soc. London, A 117, 88 (1927) Nagaoka and Futagami: Imp. Acad. Tokio Proc., 2, 254,387 (1926); 3, 499, 643(1927); 4, 106, 201 (1928); 11, 43, 171 (1935) Nagaoka and Futagami: Inst. Phys. Chem Res. Tokio Sci. Papers, 8, 269 (1928); 25, 111 (1934) Nagaoka, Futagami, and Machida: Ibid., 19, 169 (1932) Nagaoka, Futagami, and Machida: Imp. Acad. Tokio Proc., 2, 328 (1926); 4, 195, 198 (1928) Nagaoka, Nukiyama, and Futagami: ibid., 3, 208, 212, 258, 262, 319, 324, 331, 392, 398, 403, 409, 415 (1927) Nipher: Proc. Amer. Phil. Soc., 52, 283 (1913) Nipher: Experimental Studies in Electricity and Magnetism. Blakiston, 1914 Rosen: Bul. Soc. Roy. Sci. Liege, 405 (1941) Rosen: ibid., 176 (1944) Rosen: Nature, 156, 570 (1945) Sawyer and Becker: Astrophysical Journal, 57, 98 (1923) Singer: Philosophical Magazine, 46, 161 (1815) Singer and Crosse: ibid., 46, 259 (1815) Smith: Proc. Nat. Acad. of Sci., 10, 4 (1924) Smith: Astrophysical Journal, 61, 186 (1925) Sponer: Die Naturwissenschaft, 12, 619 (1924) Suyehiro and Nagaoka, Nagaoka Anniversary Volume 23 (1925) Vaudet: Compt. Rend., 198, 1217 (1934) Wendt and Irion: J. Am. Chem Goo, 44. 1887 (1922)

Propositions Submitted by Sam Naiditch

Ph.D. Oral Examination: April 25, 1947; 9:00 A.M., Crellin Conference Room

Professors Yost (Chairman), Badger, Epstein, Lucas, Niemann, Pickering, Schomaker, Swift, and Dr. Davidson

Inorganic Chemistry

1. Gomberg¹ states that he has obtained perchlorate free radical, ClO_4 . An alternative hypothesis is more reasonable on the basis of his facts, namely, the formation of $IClO_4$.

¹Gomberg: J. <u>Am. Chem. Soc.</u>, <u>45</u>, 398 (1923).

2. A scheme for classification of boron compounds is suggested:

I	II	III	IV	v
CaB ₆	B ₂ H ₆	$K_2B_2H_4(OH)_2$	NizB	H3B03
CaB ₆	B ₄ H ₁₀			
Mg3B2	B5H9			BC13

Chemical Kinetics

3. Fundamental contributions to our understanding of chemical kinetics might result from thorough investigations of kinetics in the liquid ammonia-sodium system.

Since one of the reactants in such studies would be a particle in a box (electron or electron pair in a hole), it is possible that the interpretation of experimental results could be carried out more satisfactorily than in the case in ordinary solutions. The situation is in some ways similar to electron scattering experiments.

- 4. Kinetic studies of the reaction of deuterium with B₂H₆ might yield positive information regarding the structure of diborane.
- 5. The data of Burg and Schlesinger¹ for the decomposition of BH_3CO are incompatible with some simple mechanisms involving $(BH_3)_2CO$ as an intermediary. The authors are correct in assuming that the data can be accounted for by assuming BH_3 as an intermediary, although they have not proved that this is so.

¹Burg and Schlesinger: <u>J. Am. Chem. Soc.</u>, <u>59</u>, 780 (1937).

Low and High Pressures and Temperatures

 6. Unlike the method described by Strong, the procedure below does not require evaporation of the aluminum as soon as a non-conducting vacuum has been reached.

Heat the glass (in vacuum), then vaporize enough aluminum to form a thin non-opaque film. Allow the glass to cool. Then deposit aluminum until the desired thickness is obtained. The operations are arranged in such a manner as to reduce the number of pin-holes, avoid bloom, and increase adhesion and hardness of the aluminum film.

¹Strong et al: <u>Procedures in Experimental Physics</u>, Prentice-Hall, Inc., 1941, p. 176.

- 7. In certain industries fluorescent materials have been developed for many uses. Since these materials are now available commercially, it seems reasonable to use them for laboratory practice. The following is suggested as a method to detect vacuum leaks: First, immerse the unit with the leak in a fluorescent penetrant. Then drain, wash with cold water to remove excess penetrant, and dry with a warm air current. Next, apply developing powder. This draws out the penetrant, thereby magnifying cracks. Then inspect the unit under black light.
- 8. An experimental study of the sodium-ammonia system at moderate pressures would be of great value. The minimum result might be the solution of the current dispute as to whether the solid system is a super-conductor. Optical as well as electrical properties should be closely observed since a sudden transition may occur if Ogg's theory of electrons trapped in holes is correct.
- 9. Tungsten may not have a critical point, that is, it may not be possible to go from the liquid to the vapor state without going through an intermediate state in which there is a boundary between two phases. This question could be investigated by means of the high energy electrically exploded Thermochemistry wire.
- 10. A re-assignment of the values of the heats of formation for BCl_3 and BBr_3 is proposed. In addition we may assign a set of tentative numerical values for the heats and free energies of formation of B_4H_{10} , B_5H_{11} , B_2H_5Cl and $B_2H_5Br_6$.
- 11. The first and second acid ionization constants of potassium hydroxylamine disulfonate may not differ from each other by more than a factor of three.

Aesthetics

12a. On the basis of the experiments of Weber¹, a theory of change in taste in art and a theory of the differences in taste between the artist and the public can be proposed. A series of new experiments may be suggested to test these theories.

Lueber: J. Applied Psych., 15, 310 (1931).

12b. The philosophical foundations of a satisfactory theory of modern art have much common ground to those of modern science. Chess

13. A knight sacrifice gives white a lively attack against Tarrasch's refutation of the Reti attack. That is:

1.	N - XB3	P - Q4
2.	P - B4	P - 95
3.	P - QN4	P - KB3
4.	P - K3	P - K4
5.	N x XP	

¹Tarrasch: The Game of Chess. McKay, 1935, p. 407.