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THE BEHAVIOR OF ELECTRODE MATERIALS SUBJECTED TO ENERGETIC HIGH VACUUM R. F. SPARKING IN THE MEGAVOLT RANGE

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January 14, 1954

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ABSTRACT

Sparking characteristics for fourteen metals have been obtained in an oil pumped high vacuum cavity at 10^{-6} mm Hg. Voltages up to 1.3 megavolts were generated across the test gap at the resonant frequency of 14 m.c. The geometry was that of a hemispherically-capped cylinder between two parallel planes. A magnetic field of 8000 gauss was applied approximately normal to the planes. The energy storage in the cavity was approximately 10 joules. Sparking rates were measured as a function of gap voltage. Metals are compared as regards voltage holding ability by listing the gap voltage corresponding to the same sparking rate for each metal. Incalloy and 310 stainless steel held the most voltage. The coppers, duraluminum and silver held the least. Qualitative estimates of spark damage are made. The effects of varying several parameters are discussed.

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January 14, 1954

INTRODUCTION

The purpose of this report is to present the results of vacuum sparking tests conducted in the XC cavity. Metals have been compared with respect to ability to hold voltage and withstand spark damage.[1]

DESCRIPTION OF APPARATUS

General

The cylinder-opposite-plane geometry and the configuration of the rf cavity are shown in Figs. 1 and 2. Pulsed 14 megacycle power excites the cavity in the mode which produces a voltage maximum at the end of the quarter-wave loaded line. A magnetic field of approximately 8000 gauss is applied across the gap and normal to the surface of the side electrodes (see Fig. 15).

Two electrode geometries were used. The geometry called "standard" is that shown in Figs. 1 and 2, and a photograph of a set of side plates and a nose piece for this geometry is shown in Fig. 4. In order to test samples

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[1] Preliminary results on the first 46 tests are reported in UCRL-1962 and UCRL-2053.

of the refractory metals a set of electrode holders was constructed so that samples could be prepared with only singly curved surfaces. A photograph of this geometry which is called "refractory metal holder" is shown in Fig. 5.

Vacuum System

Two 32-inch oil diffusion pumps were used to maintain the kinetic vacuum system at operating pressures of better than 10^{-6} mm Hg untrapped and 5×10^{-7} mm Hg trapped respectively. The pumps were isolated from the main manifold by Freon baffles maintained at -40°C. A liquid nitrogen thimble, having a surface area of approximately 4-1/2 square feet, was located just outside the rf cavity.

Cavity Excitation

The test cavity was excited from a grounded-grid oscillator by means of quarter-wave transmission lines. Under typical operating conditions, 600 to 800 KW of peak power were required to give a gap voltage of one megavolt. Maximum lineal skin current densities in the electrodes at one megavolt were estimated to be 50 to 80 amperes per inch.

OPERATING TECHNIQUE

Duty Cycle

Measurements described below were conducted for pulsed operation at 25 percent duty cycle. A 176 millisecond pulse of rf was applied to the cavity with a recurrence rate of 90 per minute.

Electrode Cleaning

Before installation, electrodes were given a 30 - 50 micro inch finish, washed in a mild detergent, rinsed in concentrated HCl followed by tap water and dried with flowing C-P acetone. Exceptions to this procedure are discussed below.

Spark Detection and Monitoring Facilities

Vacuum sparks[2] were detected with the stilbene crystal photomultiplier combination shown in Fig. 6. The rf shielded photomultiplier was located outside the vacuum tank approximately ten feet from, and in line with the stem

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[2] A vacuum spark is here defined as the occurence of an abrupt drop in cavity voltage accompanied by the emission of visible light at an electrode surface and the emission of an x-ray photon burst of short duration which has a peak amplitude that greatly exceeds the background x-ray level due to electron loading.

electrode. The spark pulses were amplified, discriminated and fed to a standard scaler. Mechanical registers were used to record the total number of sparks. The sparking rates were determined by measuring the time required for 16 or 64 sparks to accrue.

The actual time that the rf was applied to the electrodes was measured by counting the cycles of a stabilized 1710 KC oscillator which was gated by the cavity voltage envelope. Because the gate circuit operates from a threshold level, all measurements of sparking rate are low by not more than 0.3 percent. For full 176 millisecond pulses the indicated time that the peak voltage is applied is not greater than 5 percent high.

Voltage Conditioning

Electrodes were voltage conditioned, that is, "baked-in" without the magnetic field by raising the voltage from approximately 400 KV in steps of 25-100 KV. All electrodes were voltage conditioned to 750 KV and frequently to 1000 KV before turning on the magnetic field. Conditioning was continued with the magnetic field starting from 500 KV.

The process of conditioning carries through the whole test in that at each voltage, the sparking rate is monitored until it is either approximately zero or constant. Each voltage step is made as small as possible so as to minimize the change in sparking rate due to a voltage change.

COMPARISON OF METALS

The metals were compared in two ways. (1) The relative spark damage was estimated by visual means taking into account total number of sparks and the voltage at which most occurred. (2) Sparking rate data were reduced and plotted as a function of gap voltage for each metal. Reproducible curves characteristic of the electrode material were obtained. Metals were classed by comparing voltages from these curves for a common sparking rate.

The two methods of comparison are in general agreement as to relative merit as electrode materials.

Damage

The size, depth and density of the spark craters was observed and compared to a reference metal (either copper or Inconel). The sparking was in general confined to the high field region, the damage being concentrated on the side plate directly opposite the end of the center electrode. Exceptions to this arose only when a flaw such as a crack or protrusion was present on one of the electrode surfaces. Such instances as these have been dropped from consideration in compiling the data.

Nearly all the damage was incurred by the closer side plate.

Estimates of spark damage divided the metals tested into two categories (see Table I). The first category is referred to Inconel as a standard. It will be noted that more refractory metals fall into this class.

The second category is standardized by comparison with copper and all metals in this group are at least as poor as copper in resisting damage. Insofar as it has been possible the metals are listed in decreasing order of merit.

Several of the metals tested contained ferromagnetic elements. Table II lists cases where sparking resulted in spray metal which became ferromagnetic.

This point was checked because in some practical applications (e.g. in cyclotrons) the magnetic dust may be collected in the high field region and may serve to aggrevate sparking. It turns out as will be seen in Table II that the use of these particular metals may be avoided in practice.

An illustrative comparison of spark damage to copper and Inconel is shown in Figs. 7, 8, and 9.

Comparison of Metals in Terms of Sparking Rates

A more quantitative estimate of the differences between metals tested in the same geometry is based on the interpretation of a plot of the averaged lowest sparking rate versus gap voltage. At each voltage the sparking rate decays from a high initial value to some mean value (see Fig. 10). This mean value is what is meant by the averaged lowest sparking rate.

Each metal exhibits its own characteristic sparking rate versus voltage curve (see Fig. 11). The curves are in general very similar when represented on a semilog plot, the distinctive difference being a displacement along the linear voltage axis. Within the statistics of the measurements the slopes are all the same. A comparison voltage has been determined for each metal tested by selecting that voltage which corresponds to a sparking rate of 10 sparks/min. (See Table II). This choice of rate is clearly arbitrary, but if another choice of rate is made, the results will be very nearly the same.

Inconel has been tested in the 5-3/8 in. gap by baking in up to 1025 KV[3] lowering the voltage 10 - 15 percent and operating for approximately 40 hours at an average rate of the order of one spark per hour. This showed that the bake-in sparking rates observed are really distinct from the characteristic rate evidenced by the metal and that the reduction in sparking rate was permanent.

Tests in Refractory Metal Holders

A special set of electrode holders was constructed to mount electrodes of simple shape in order to minimize fabrication problems encountered in working with refractory metals.

The geometry was altered in this arrangement in that the test gap was located approximately 8 in. back from the end of the center electrode instead of directly opposite the end.

The results obtained did not agree voltage wise with the standard geometry. The gap voltage calibration and magnetic field were not sufficiently different in the two geometries to explain the observed difference. The electric field on the center electrode however did vary appreciably and the observed difference is attributed to this variation.

The metals tested in this geometry were: stainless steel no. 316, titanium, molybdenum, Dural 52-S0 (see Table II). No direct method of correction to "standard" geometry exists for these tests because there were no quantitative comparison tests of the same metal in the two geometries. It was clear however that metals did hold a higher voltage for a given sparking rate in this geometry as compared to the standard geometry. On this basis Dural 52-S0 is listed as poorer than copper.

Titanium appeared to be one of the best metals tested but here too there is no quantitative evidence. Difficulties in procurement and fabrication of satisfactory electrodes have caused this test to be postponed until such time as sufficient interest developes in its possible use.

Relative comparison data for metals tested in the refractory metal holders are given in Table III.

X-ray Yield

The x-ray yields were monitored with an integrating ionization chamber. The high level x-ray bursts occuring during a spark were not recorded by the

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[3] At the 5-3/8 in. gap spacing no sparking characteristic of the metal was to be expected below 1350 KV.

chamber because of the short time duration of the spark discharges and low repetition rate of applying voltage.

The observed x-ray yields decayed with time at fixed tank voltage. This decay was independent of sparking rage, i.e. the decay was the same whether sparking occurred in the test chamber or not.

The yield increased exponentially with voltage (see Fig. 12).

The relative x-ray intensities for the various metals tested varied a factor of two from the norm which was also of the same order as the spread on different runs with the same metal.

The data does suggest however that copper yields more x-rays than Inconel.

EFFECT OF VARYING PARAMETERS

Gas Pressure

The gas pressure in the test chamber was recorded continuously on both trapped and untrapped ionization gauges located remote from the pumps and proximal to the test gap.

There was no significant correlation between the ionization gauge readings and the sparking behavior below 10^{-5} mm Hg. Above 10^{-5} mm Hg it was difficult to excite the cavity because of glow discharges.

The effect on the sparking rate of admitting hydrogen was studied in one run with Inconel by admitting the gas while operating at 1090 KV with an average sparking rate of 20 per minute. No change in average rate was observed.

There was no change observed in the sparking behavior by admitting H_2 gas during the bake-in.

Magnetic Field

With zero magnetic field, sparking at the highest voltages available (1.3 megavolts) produced no marking of the electrodes except for small craters on the cylindrical electrode visible only under a microscope.

Damage to the side electrodes began to appear after the magnetic field had exceeded some threshold value dependent on the gap distance (e.g. 1000 gauss for Inconel at 1-3/8 inches and 2000 gauss for copper at 5-3/8 inches).

All tests were carried out with a field of approximately 8000 gauss or more. The damage suffered by the side plates was always clearly evident while the center stem remained relatively unmarked.

Cleaning Technique

In most of the runs, the electrodes were cleaned with concentrated HCl, rinsed in tap water and dried with flowing C.P. Acetone.

For some tests with copper a cyanide deplating technique was used. The effect of the cleaning technique was not discernible in comparing various copper runs.

The interior of the cavity was cleaned at several different times with abrasive paper, water and acetone. This caused no observed effect on sparking rate. In interpreting the above results it must be mentioned that this cavity is entirely unsuited to the determination of anything other than very gross effects due to surface contamination.

Voltage Conditioning

The method of voltage conditioning has been described above. It was always necessary to allow the sparking rate to decay to an approximate equilibrium value in order to obtain meaningful data.

The method of voltage conditioning was not varied in this work. The time required to voltage condition a given metal has varied considerably. The most extreme variation occurred during the run on Inconel with nickel molybdate backing in which the bake-in time was approximately five times as long as a normal Inconel bake-in. The sparking rate versus voltage curve obtained after this long bake-in gave results within a few percent of the mean of previous Inconel runs.

Duty Cycle

The sparking rate dependence on duty cycle was checked roughly at the beginning of these tests. Both the pulse length and repetition rate affected the sparking rate observed. Increased pulse length and increased repetition rate correlate positively with increased sparking rate.

In order to minimize effects due to varying duty cycle the pulse length and repetition rate were fixed at the values of 176 ms and 1.5 per sec. respectively.

Variation of Gap Distance

It has been remarked earlier that the central electrode was not centered between the parallel side electrodes. The two gaps differ by 1/2 in. The sparking nearly always took place across the shorter gap and therefore a voltage-distance scaling relation exists.

Tests were made in three different gaps (1-3/8 in., 2-3/8 in., 3-3/8 in.) with Inconel and the results show that over the range of gaps and voltages studied the square of the gap voltage is approximately proportional to the gap distance, see Fig. 13. (Voltage here means that voltage at which the same characteristic sparking rate is observed.) This shows that a variation of about 10 percent in gap would produce a variation in observed voltage values of about 5 percent.

Nearly all tests of metals were carried out in the 3-3/8 in. gap in which the variation in gap was about 1/8 in., hence the gap variation did not contribute an appreciable error.

OTHER TESTS

Welded and Soldered Joints

Welded and soldered joints were tested by making plug welds and inlays on the side plates. Table IV summarizes the results of a test in which OFHC plugs were heliarc welded into an OFHC surface. As noted in the table, the spark damage to the welded plugs was not significantly different from that to the parent metal.

Table V shows the results of spark damage to solder inlays. Damage was greater to the solders than to the parent material.

Cracked Inconel

A set of Inconel side plates were fabricated with minute stress corrosion cracks in their surfaces. The purpose of the test was to see how detrimental to the voltage holding characteristics these cracks might be.

The results are compared with a normal sample of Inconel in Table VI. The damage was incurred by the side plate furthest removed from the center electrode which was the converse of what normally happened. Since the poorer plate was located in the widest gap and it sustained the most damage, it is evident that cracks can lead to difficulties in holding down sparking rates and spark damage.

See Figs. 14 and 15 for an illustration of the relative damage to the two side electrodes.

Inconel with Nickel Molybdate Backing

In a test of Inconel, back surfaces of the electrode were covered with nickel molybdate in order to increase heat radiation. The final sparking rate vs. gap voltage characteristic which was reached after bake-in was the same within the experimental uncertainty as ordinary Inconel, and there was no significant difference in the spark damage. The time required to bake-in was longer (600 minutes of rf on time) for Inconel with nickel molybdate backing than for ordinary Inconel (100-200 minutes of rf on time.) The trapped and untrapped ionization gauges did not read significantly different during this run than during an ordinary Inconel run.

Chrome-Plated Copper

A set of ETP copper electrodes was high-temperature plated with a 0.005 inch hard chrome plate.[4] These electrodes were run in the 5-3/8 inch gap geometry.

After a few sparks at 750 KV with the magnetic field, the chrome plate had been removed and the sparking rate was similar to that found with copper. It is concluded that 0.005 inch hard chrome plate does not furnish a satisfactory electrode surface in a high energy storage cavity.

Graphite

Graphite was tested using one inch gap to provide high gradient at low voltage. The highest gap voltage reached was 310 KV where the sparking rate was about 750 sparks/min.

Viscious sparks were observed to pass between the electrodes but no detectable damage was done.

The power loss associated with graphite electrodes was considerably larger than that for metal electrodes, e.g., with comparable oscillator efficiency the number of kilowatts input to the oscillator required in order to produce a 500 KV gap voltage was 156 for copper, 171 for Inconel and 203 for graphite.

Copper-Inconel Combinations

Table VII summarizes tests in which DHP copper and Inconel electrodes were used in all four combinations as stem and side plate samples. The results indicated that both copper-Inconel combinations held less voltage than

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[4] The high-temperature chrome plate results in less occluded gas, see Brenner, Burkhead and Jennings, Jour. of Res. Bur. of Stds., U.S. Dept. of Comm., RP-1854, V. 40, January, 1948.

the all copper or all Inconel arrangement. This result is in contradiction to what was expected particularly in the case where Inconel was used as the side plate with the copper stem electrode. At the conclusion of this experiment it was found that the Inconel spark dust which had been transferred to the stem was very loosely bonded.

CONCLUSIONS

In general, metals which hold the most voltage suffer the least damage even for comparable numbers of sparks.*

The metals tested fall into two categories as indicated by estimation of spark damage. Metals of the poorer class are:

(1) copper
(2) tantalum
(3) Dural or aluminum
(4) silver

The better metals are:

(1) Inconel
(2) Incalloy
(3) stainless steel 316 and 310
(4) nickel
(5) molybdenum
(6) titanium
(7) K-monel

In the latter group, nickel, K-monel and stainless steel 316 produce magnetic particles as a result of sparking. Of the remaining metals, Inconel, Incalloy and stainless steel 310 have been most thoroughly tested and for this reason should be tentatively described as the best metals.

ACKNOWLEDGMENTS

Other people who were responsible for this project were: P. R. Byerly, Jr., E. J. Lofgren and R. M. Richter.

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* The exceptions to this general rule are molybdenum which sparks quite regularly over a wide range of voltages yet exhibits little damage and graphite which sparks incessantly and shows no damage.

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TABLE I

QUALITATIVE RANK OF METALS BY SPARK DAMAGE

GROUP I
(Least Damaged)

Molybdenum
Titanium
Incalloy, Stainless Steel 310 and 316,
Inconel, , K-Monel, Nickel

GROUP II
(Most Damaged)

Tantalum
All coppers
Silver
Duraluminum 52-S0

TABLE II

METALS LISTED IN DECREASING ORDER OF THE GAP VOLTAGE AT WHICH THE SPARKING RATE IS 10 SPARKS/MIN. FOR 2-3/8 3-3/8 AND 5-3/8 INCH GAPS

Gap (In.)	Metal	Voltage at which 10 spk/min was observed KV	Max. voltage applied during test KV
2-3/8	Inconel[1]	900	960
	*Stainless Steel 316	760 to 880	930
3-3/8	Stainless Steel 310	1150	1250
	Incalloy	1150	1320
	Inconel	960 to 1080	1170
	Copper, OFHC	810 to 880	980
	Copper, DHP	840 to 870	950
5-3/8	Inconel	>1140	1140
	Copper, ETP	1070	1250
	*K-monel	980	1050
	Nickel	970	1000
	Tantalum	870	1110
	Copper, DHP	840 to 900	1020
	Silver	670	790

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[1] See Table VIII for composition of alloys.

* The spark dust from these metals was magnetic.

TABLE III

SEVERAL METALS TESTED AT INTERMEDIATE GAP DISTANCES IN REFRACTORY METAL HOLDERS, GAP VOLTAGE AT WHICH THE SPARKING RATE IS 10 SPARKS/MIN. COMPARED WITH INCONEL INTERPOLATED TO THE SAME GAP DISTANCE

Metal	Gap (In.)	V (KV) 10 S/M	V (KV) 10 S/M Inconel
Molybdenum	2-1/8	670	850
Dural	1-15/16	600-700	810

TABLE IV

OFHC COPPER OVERLAY WITH OFHC WELDED PLUGS COMPARED WITH ORDINARY OFHC COPPER - 3-3/8 INCH GAP

Metal	Voltage at which 10 spks/min was observed KV	Max. applied test voltage KV	Damage
Ordinary Sides	810 to 880	980	
Overlay Sides	750	1020	Similar to ordinary copper, sparking did not concentrate on the welded plugs; a soldered joint opened up and sparked badly.

TABLE V

COMPARISON OF SPARK DAMAGE OF SOLDERS

Side plate electrode material	Stem electrode material	Solder Name	Solder Percent Composition	Method of solder application	Flux used	Resistance to sparking damage
E. T. P. Copper*	E. T. P. Copper	BT	72 Ag; 28 Cu	Oxy-Acetylene Torch	Handy Flux	Good
		RE-Mn	65 Ag; 28 Cu; 5 Mn; 2 Ni		Handy Flux	Bad
		RE-Sn	60 Ag; 30 Cu; 10 Sn		Handy Flux	Bad
		Sil Phos	15 Ag; 80 Cu; 5 P		Handy Flux	Bad
		Phos Cu	92 Cu; 8 P		None	Bad
D. H. P. Copper**	O. F. C. H.*** Copper	Allstate 175	75 Ag; 25 Cu	Heliarc	Allstate 200	Good
		Incosil	65 Ag; 25 Cu; 10 In		Handy Flux	Fair
		Wes Go Gold	65 Cu; 35 Au		Borax Glass	Bad
		Easy Flo	50 Ag; 15-1/2 Cu; 18 Cd; 16-1/2 Zn		Handy Flux	Very Bad
		BT	72 Ag; 28 Cu		Handy Flux	Good
D. H. P. Copper	O. F. H. C. Copper	Easy Flo		Oxy-Acetylene Torch	Handy Flux	Very Bad
		Wes Go	72 Au; 28 Cu		Handy Flux	Good
		Decarbonized	Zn, Cd and C free			
		Incosil			Handy Flux	Fair
		Allstate 175			Handy Flux	Good
		BT			Handy Flux	Good

* E. T. P. = Electrolytic Tough Pitch

** D. H. P. = Phosphorus De-Oxidized

*** O. F. C. H. = Oxygen Free High Conductivity

TABLE VI

COMPARISON OF "CRACKED" INCONEL SIDE PLATES WITH ORDINARY INCONEL SIDE PLATED (ORDINARY INCONEL NOSE IN BOTH CASES) - 3-3/8 IN. GAP

Metal	V (KV) 10 S/M	V (KV) Max.	Damage
Ordinary Inconel	960 to 1080	1170	
"Cracked" Inconel	990	1130	Similar to ordinary Inconel on North (close) side plate, very heavy damage to South side plate-sparked through cracks.

TABLE VII

INCONEL-DHP COPPER COMBINATIONS AT 3-3/8 IN. GAP

Sides	Nose	Run	Voltage at which 10 spks/min was observed KV	Max. applied Test voltage KV	Remarks
Inconel	Inconel	39	1080	1170	
Copper	Copper	44	840	956	
Copper	Inconel	43	790	926	
Inconel	Copper	46	630	765	Damage to Inconel side plate similar to ordinary Inconel, no damage to copper nose, Inconel dust deposited on nose.
Copper	Inconel	41	960	1050	
Copper	Inconel	42	930	1040	

Note: Runs 43 and 44 had the <u>same</u> copper side plates.

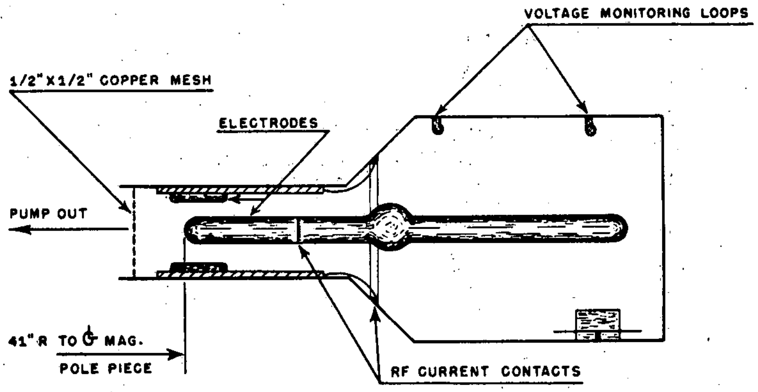
Runs 44 and 46 had the <u>same</u> copper nose piece.

Runs 41 and 42 had a different set of copper sides from runs 43 and 44.

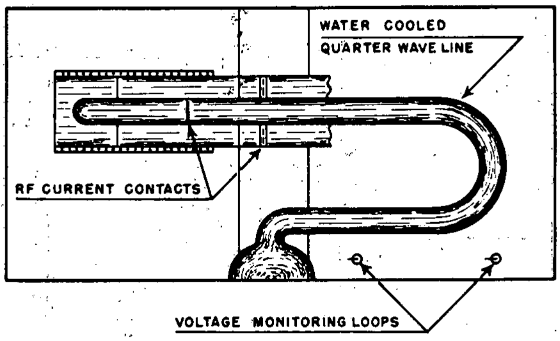
TABLE VIII
COMPOSITION OF THE ALLOYS TESTED

Name	Percent				
	Cr	Ni	Mn	C	Cu
Stainless steel 310	24-26	19-22	2 max.	0.25 max.	0
Incalloy	19-22	32-36	1.5	0.1	0.05
Inconel	14	78.5	0.25	0.08	0.2
Stainless steel 316	16-18	10-14	---	0.05	--, 2-3% Mo
K-monel	---	66	---	---	30, 3% Al, 0% Fe

Copper, ETP	electrolytic tough pitch copper
Copper, OFHC	oxygen free high conductivity copper
Copper, DHP	phosphorous deoxidized copper



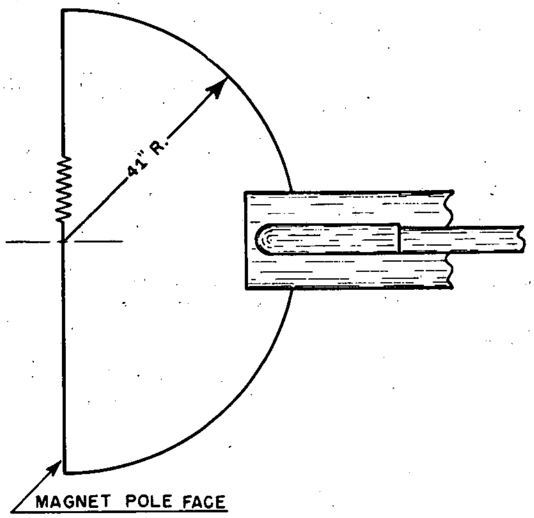
TOP VIEW



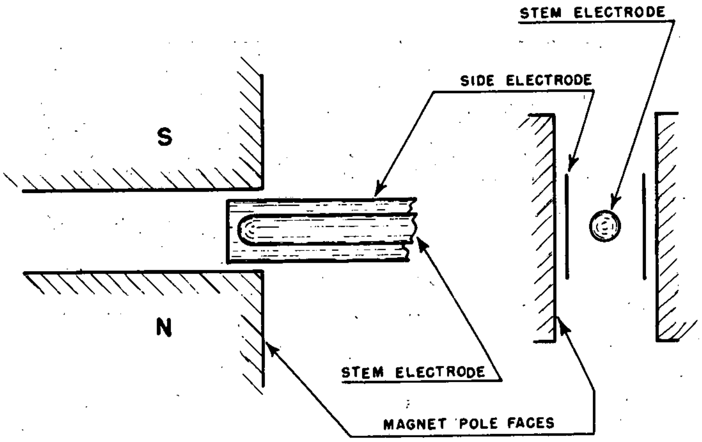
OPEN SIDE VIEW

FIGURE 1

GENERAL LAYOUT OF CAVITY



SIDE VIEW



END VIEW

Fig. 2—Electrode geometry.

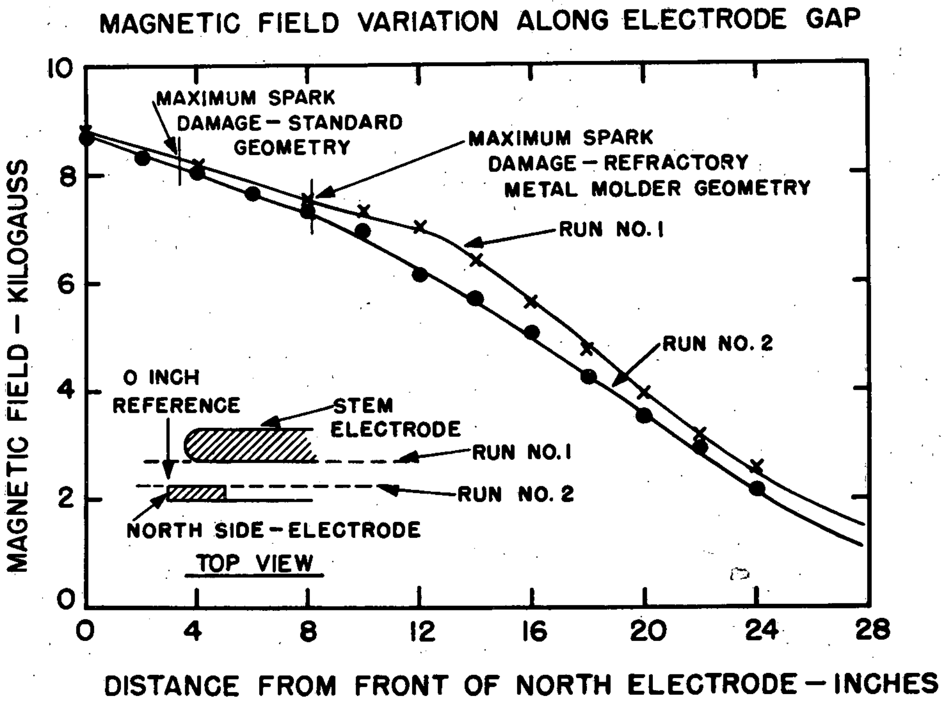

MAGNETIC FIELD VARIATION ALONG ELECTRODE GAP
MAXIMUM SPARK DAMAGE – STANDARD GEOMETRY
MAXIMUM SPARK DAMAGE – REFRACTORY METAL MOLDER GEOMETRY
RUN NO. 1
RUN NO. 2
0 INCH REFERENCE
STEM ELECTRODE
RUN NO. 1
RUN NO. 2
NORTH SIDE – ELECTRODE
TOP VIEW
MAGNETIC FIELD – KILOGAUSS
0
2
4
6
8
10
0
4
8
12
16
20
24
28
DISTANCE FROM FRONT OF NORTH ELECTRODE – INCHES

Fig. 3

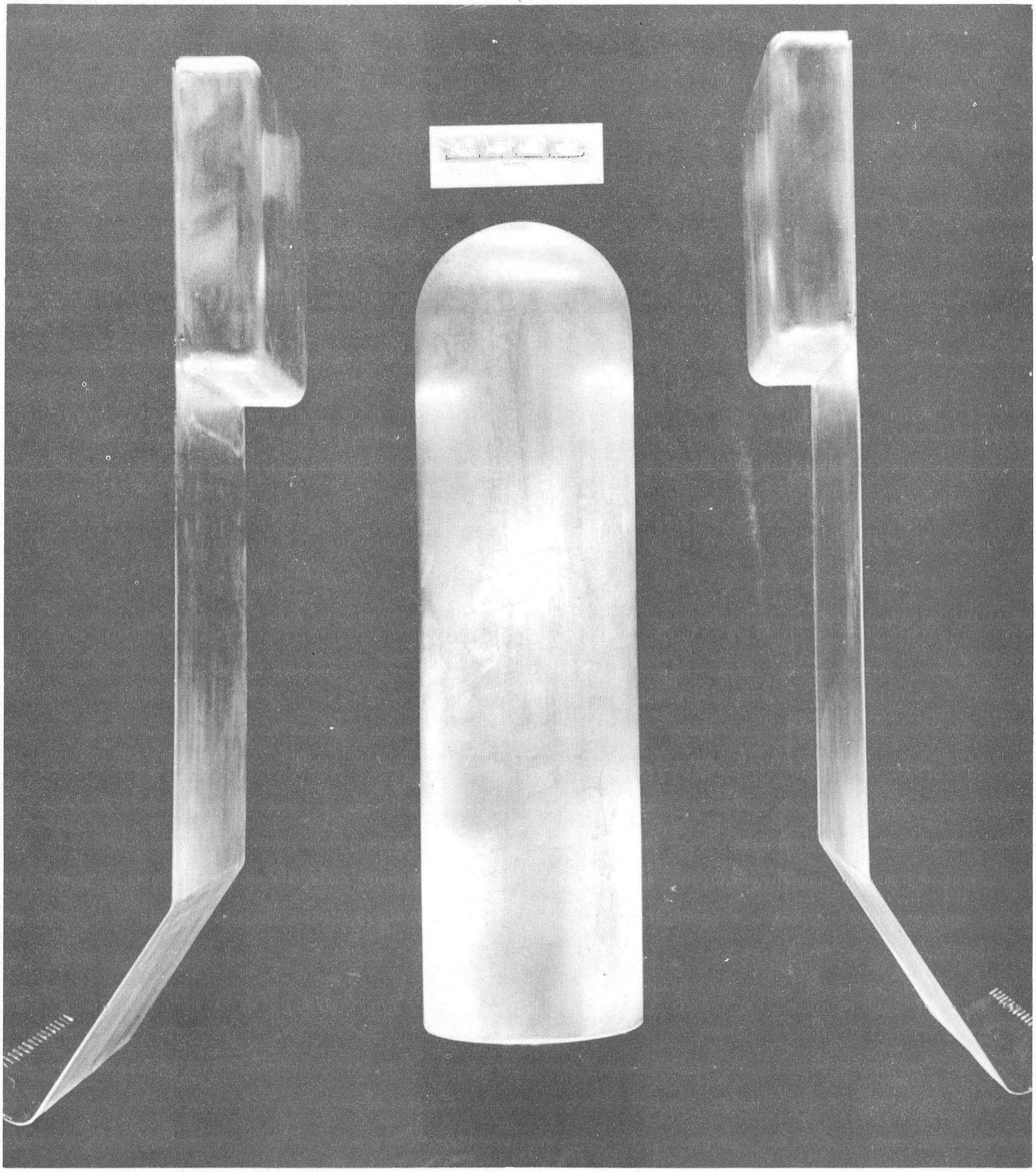


Fig. 4

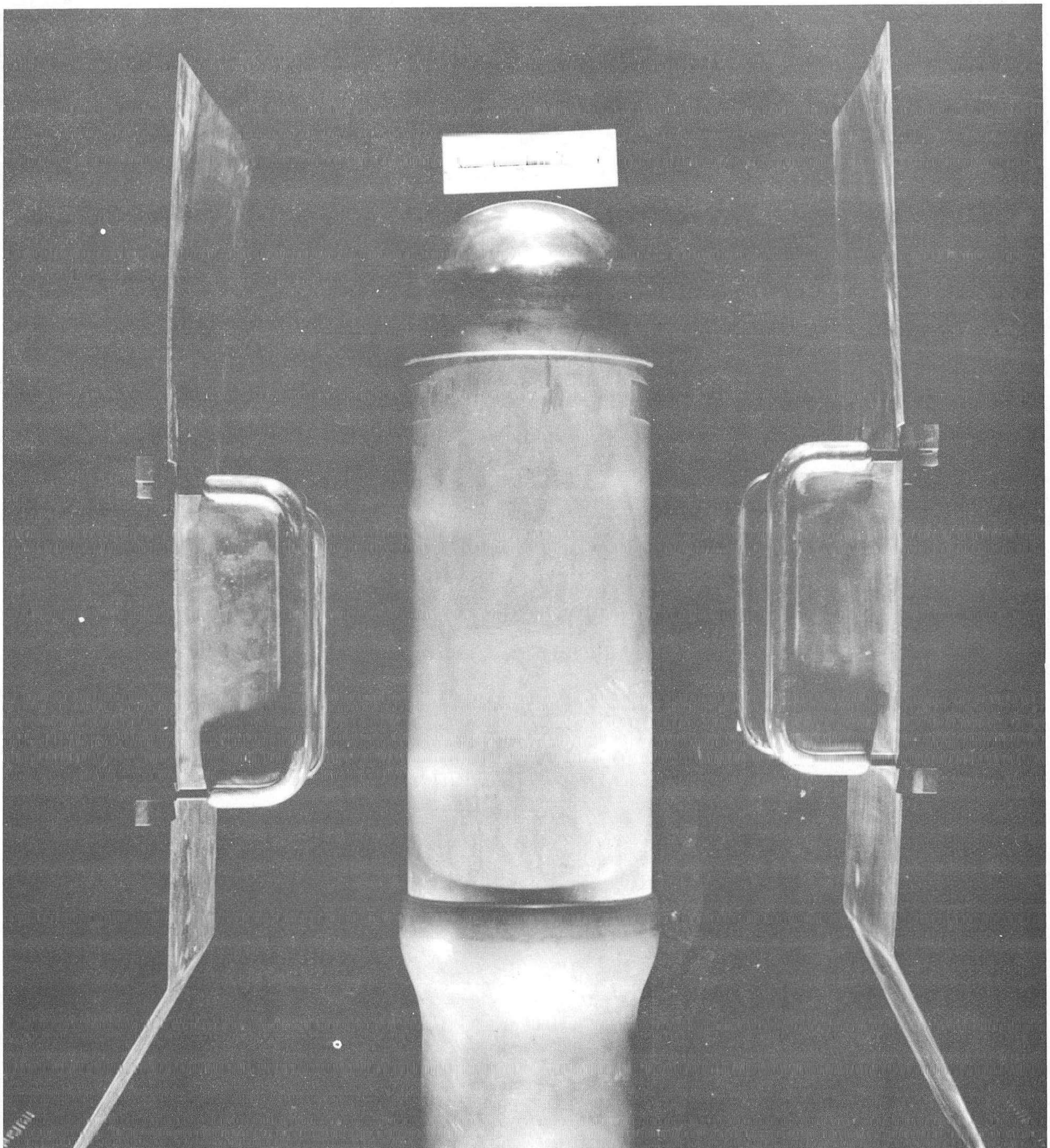
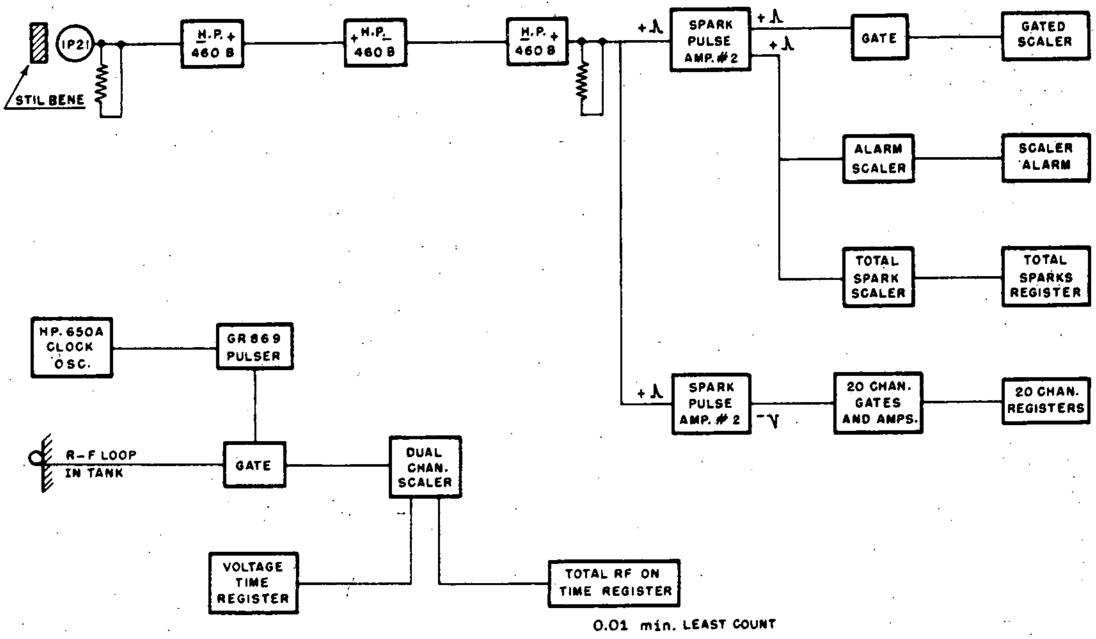


Fig. 5



SPARK MONITORING AND TIMING CIRCUITS.

Fig. 6

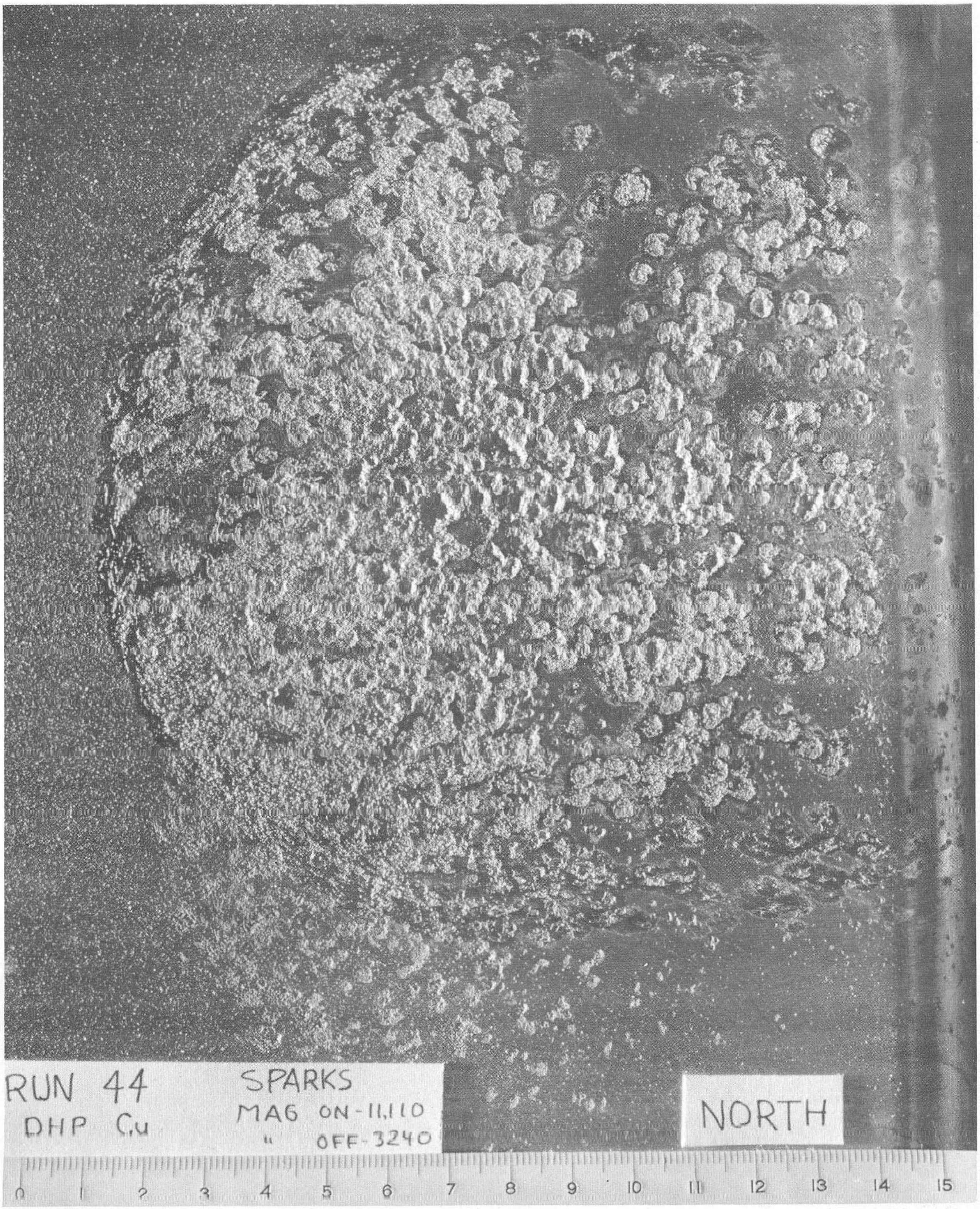

RUN 44
DHP Cu
SPARKS
MAG ON-11,110
" OFF-3240
NORTH
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

Fig. 7

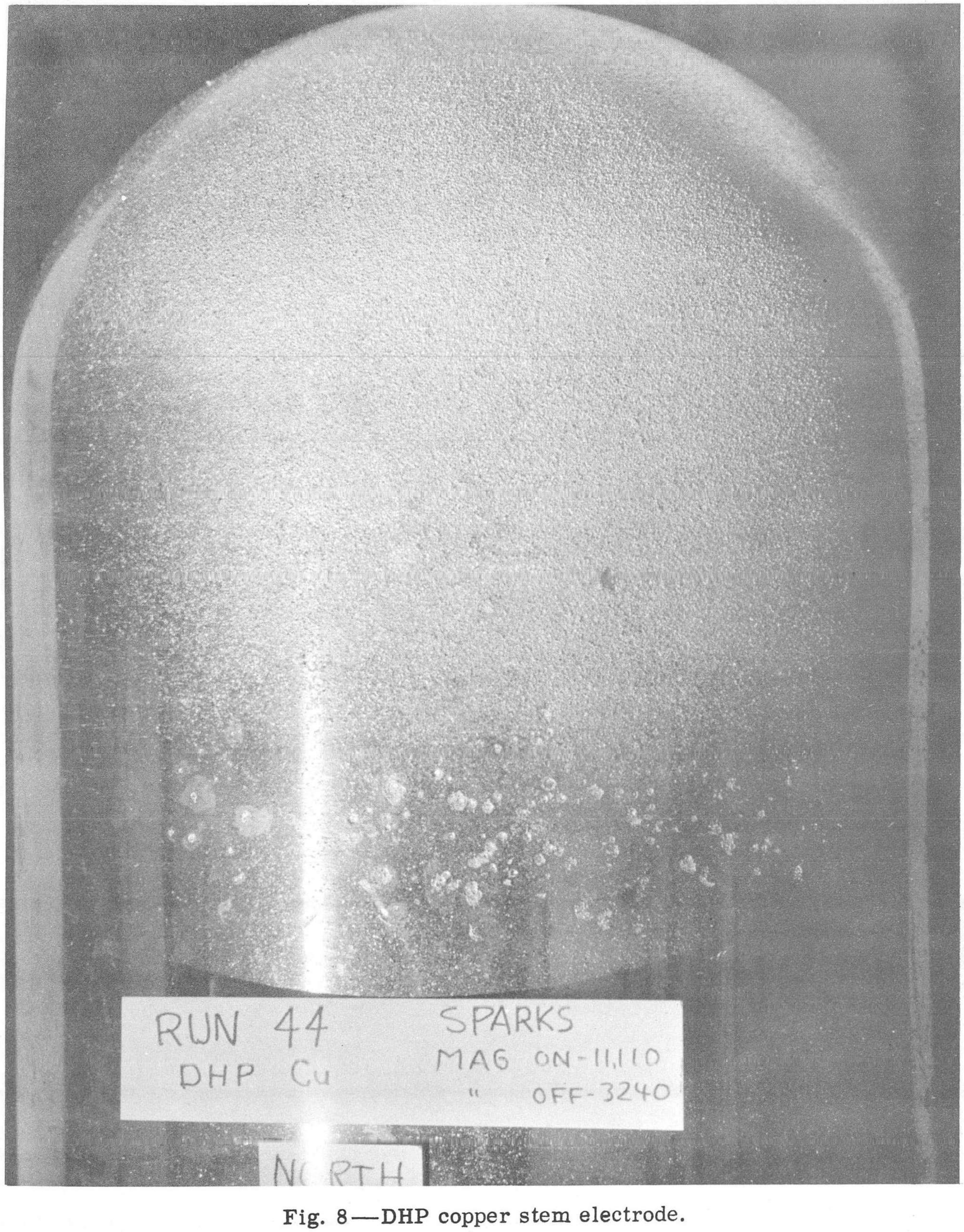


Fig. 8 — DHP copper stem electrode.

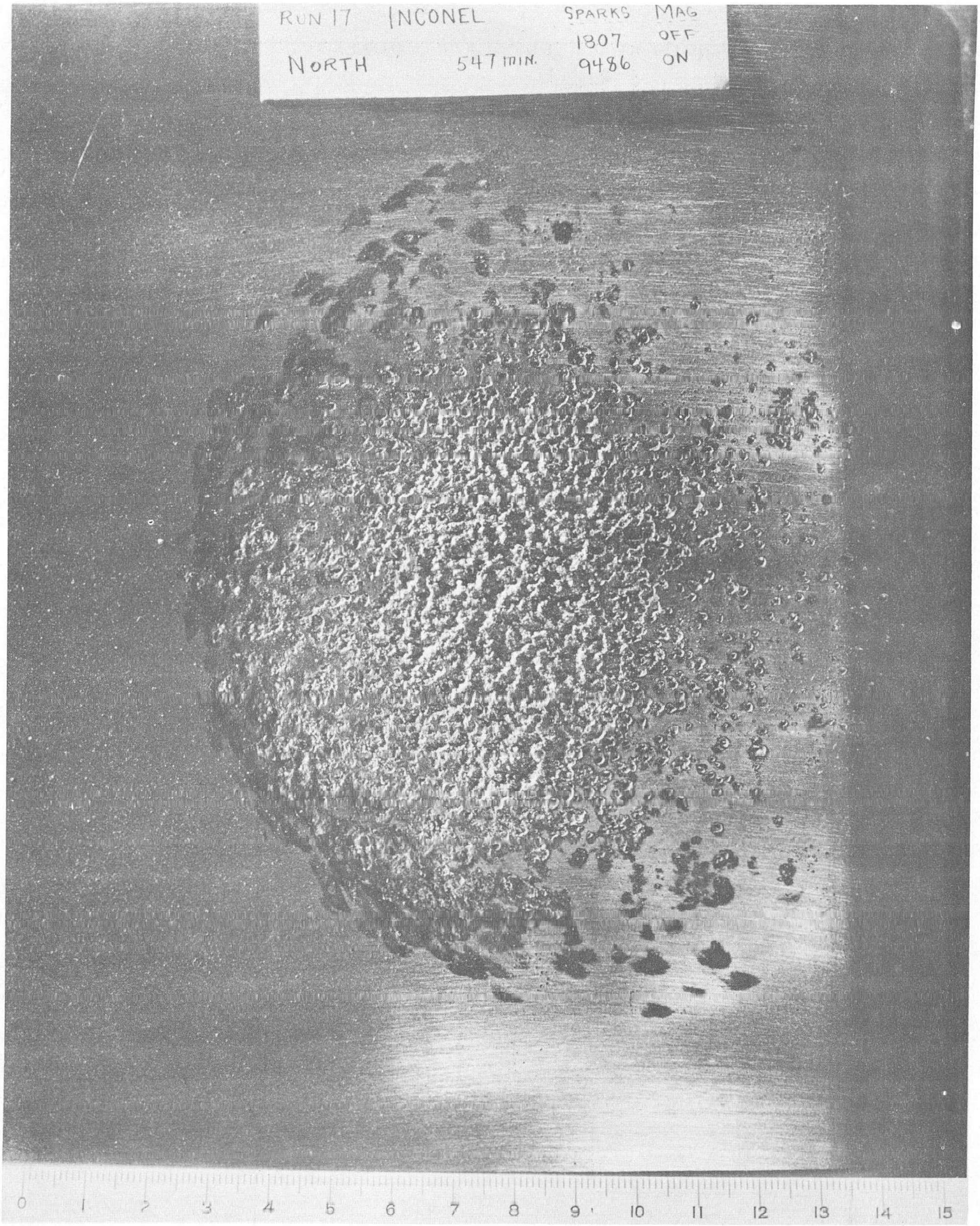

RUN 17 INCONEL
SPARKS MAG
1807 OFF
NORTH 547 min. 9486 ON
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

Fig. 9

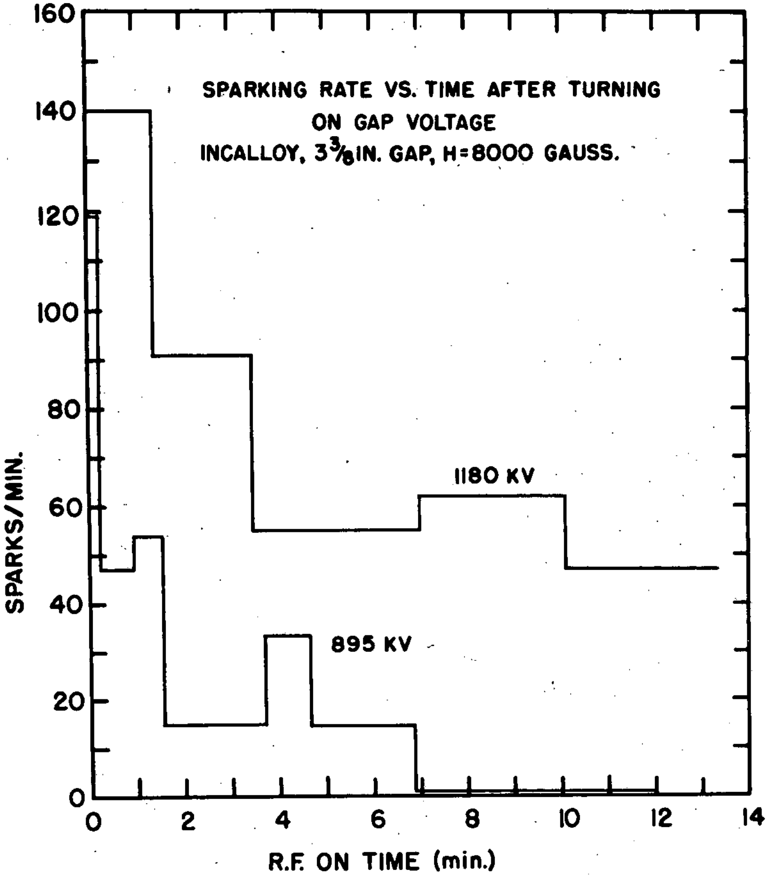

SPARKING RATE VS. TIME AFTER TURNING
ON GAP VOLTAGE
INCALLOY, $3\frac{3}{8}$ IN. GAP, H=8000 GAUSS.
1180 KV
895 KV
SPARKS/MIN.
0
20
40
60
80
100
120
140
160
R.F. ON TIME (min.)
0
2
4
6
8
10
12
14

Fig. 10

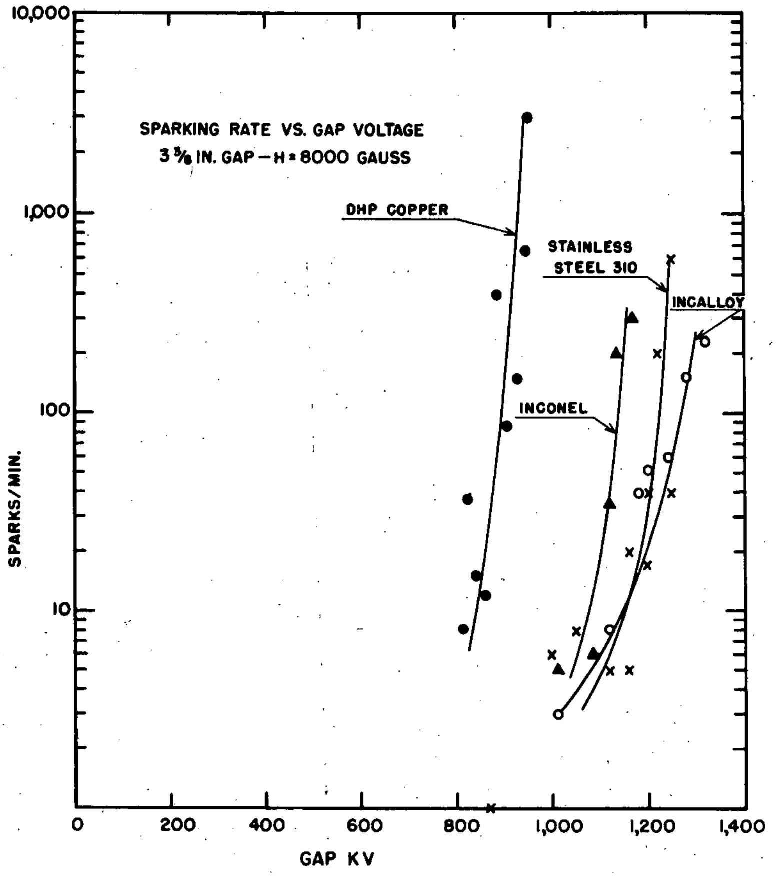

SPARKING RATE VS. GAP VOLTAGE
$3\frac{3}{8}$ IN. GAP – H = 8000 GAUSS
DHP COPPER
STAINLESS
STEEL 310
INCALLOY
INCONEL
SPARKS/MIN.
10
100
1,000
10,000
GAP KV
0
200
400
600
800
1,000
1,200
1,400

Fig. 11

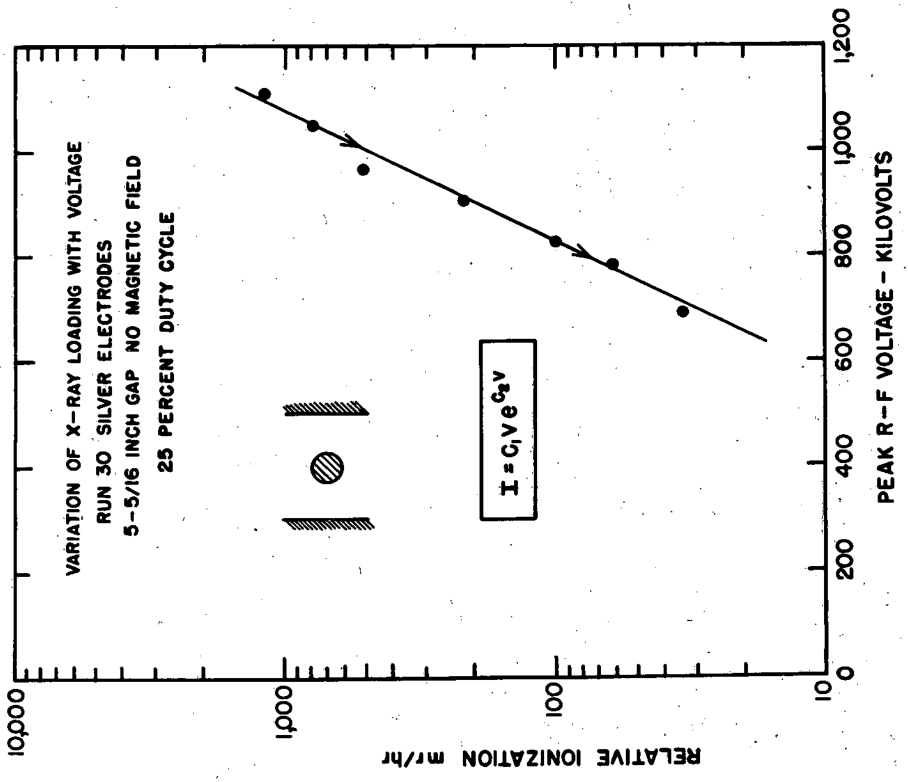

VARIATION OF X-RAY LOADING WITH VOLTAGE
RUN 30 SILVER ELECTRODES
5-5/16 INCH GAP NO MAGNETIC FIELD
25 PERCENT DUTY CYCLE
$I = C_1 V e^{C_2 V}$
RELATIVE IONIZATION mr/hr
10,000
1000
100
10
PEAK R-F VOLTAGE - KILOVOLTS
0
200
400
600
800
1,000
1,200

Fig. 12

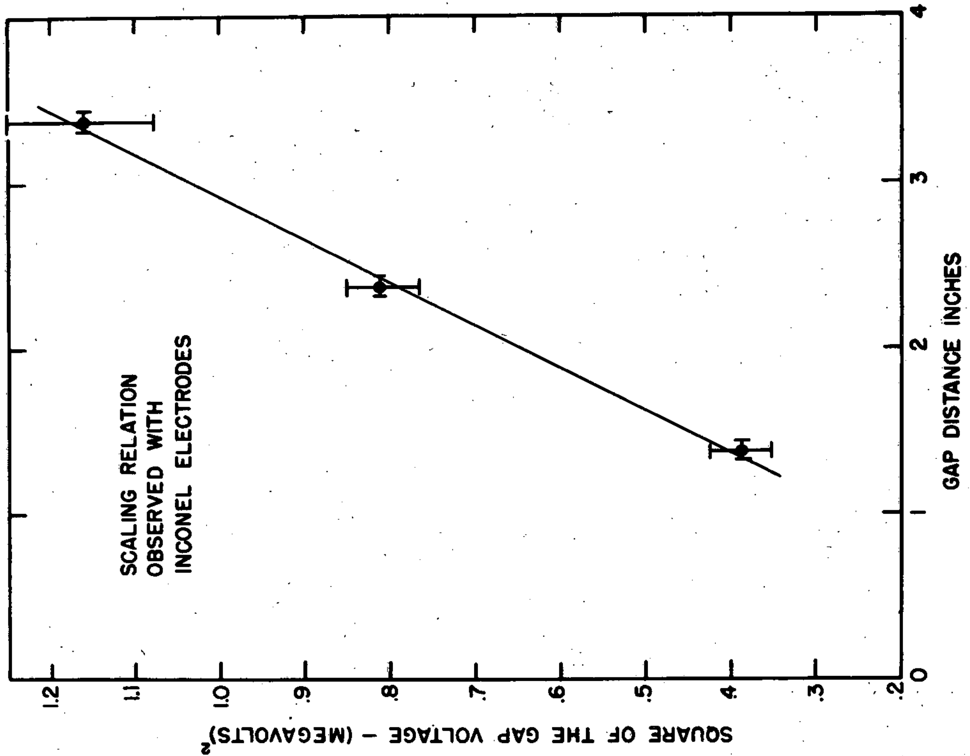

SCALING RELATION
OBSERVED WITH
INCONEL ELECTRODES
SQUARE OF THE GAP VOLTAGE - (MEGAVOLTS)²
1.2
1.1
1.0
.9
.8
.7
.6
.5
.4
.3
.2
GAP DISTANCE INCHES
0
1
2
3
4

Fig. 13


RUN 49 CRACKED INCONEL
12-19-52 NORTH
SPARKS MAG.
3,612 OFF
14,000 ON
16
0
1
2
3
4
5
6

Fig. 14


RUN 49 CRACKED INCONEL
12-19-52 SOUTH
SPARKS
3,62
14,030
MAG.
OFF
ON
0
1
2
3
4
5
6

Fig. 15