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ABC CATHODE DEVELOPMENT

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Arc Cathode Development

Harry G. Heard

April 19, 1951

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Arc Cathode Development

Harry G. Heard

Radiation Laboratory, Department of Physics
University of California, Berkeley, California

April 19, 1951

ABSTRACT

Investigation has shown that cathodes of the Phillips' design geometry do not give satisfactory performance as hot-cathode arc sources. A design of diffusion emitter has been developed which will give emission currents of the order of 1200 amps. and emission densities of the order of 200 amps. per cm^2 on pulsed and d.c. with long life. Sintered thoria cathodes have been evolved in a geometry which shows promise of eliminating back bombardment problems in a high power ion source. Low-temperature sintered BaO-W compressed cathodes and carbon cathodes are treated.

Arc Cathode Development*

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April 19, 1951

ARC SOURCE CATHODES

Introduction

The operation of a high power arc in a strong magnetic field requires a filamentary cathode to be of sufficient strength to withstand the destructive motor forces of large heating currents. For such arcs the conventional application of refractory metals can prove unsatisfactory if cathode construction requires a large effective emitting area. Tantalum, for example, is not satisfactory because it easily becomes distorted at emitting temperatures. Shorts invariably develop which cause the number of filament failures to be objectionable. In addition, the rapid embrittlement of these filaments, due to gas sensitivity and grain growth, is undesirable. Tungsten filaments of sufficient area to give the required emission and of such diameter to give the required mechanical strength and reasonable life, despite surface damage from sputtering, require several kilowatts of heating power. Accordingly, an investigation has been undertaken to seek other cathodes which, when operating in hydrogen arcs of hundreds of amperes, will have the following desirable properties:

1. Ability to withstand heavy sparking due to high gradients at the surface of the cathode.
2. Have reasonable mechanical strength at the temperature required to

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* This work is based on the results of the arc cathode investigation conducted by Dr. J. R. Woodyard and the author.

give the desired emission.

3. Yield high specific emission in the presence of an electropositive gas atmosphere on d.c. as well as pulsed operation.
4. Emit uniformly from a continuous surface of tens of square centimeters to give effective illumination of arc apertures.
5. Have a tough surface at elevated temperatures which is insensitive to surface bombardment.
6. Have an activation period in terms of minutes.
7. Capability of being scaled to large continuous emitting areas.
8. Reasonable ease in fabrication.
9. Have reasonable emission efficiencies so that the power input to the arc chamber can be used to the greatest advantage in producing arc currents.
10. Give highly reproducible emission characteristics in spite of poisoning caused by cycling to atmospheric pressure.
11. Have an operating life in terms of hundreds of hours.
12. Capability of being formed into special shapes.
13. Have such specific conductance that it may be directly heated and yet strong enough so that it will not become distorted in a magnetic field of the order of 5000 gauss.
14. Operation at low enough temperatures to permit visual ionization studies.

I. Description of Apparatus

A continuously pumped vacuum system was designed and built for emission testing. This system, shown in Fig. 1, is quite conventional and will not be discussed.

II. Test Conditions

The testing of new cathodes followed the generally accepted procedures of pulsed and d.c. emission measurements. It was not feasible nor considered desirable to attack the problem of cathode testing in the conventional high-vacuum fashion. The use of Richardson plots obtained from such tests would reveal characteristics of the cathodes which are entirely foreign to their eventual application. Of great interest, however, is the emission of various surfaces in a 3000 gauss axial magnetic field in a hydrogen arc. The general plan of measurements has been as follows:

1. D.C. Emission. Draw the maximum steady current from the cathode at a given cathode temperature and gas pressure.
2. Pulsed Emission. Draw the maximum pulsed current for a given cathode temperature and gas pressure. Pulsed operation at 1 pps with 10^{-3} sec. pulses.
3. Life Testing. Life test the cathode on d.c. emission at typical controlled operating temperatures and gas pressures.
4. Emission Poisoning. Determine the effects of emission poisoning by admitting air into the chamber while the cathode is hot or cold.

In general, it has not been possible to draw the maximum pulsed or d.c. emission currents from the emitters because of:

1. Power supply limitations.
2. Heat dissipation limits -- d.c. operation only.
3. Sparking.

Measurements of the physical properties of cathodes were made with the electrical apparatus shown in Fig. 2.

III. General Description

The cathode types investigated include the following:

1. Metallic emitters.
2. Coated emitters.
3. Diffusion emitters.

4. Sintered emitters.

Preliminary investigation has shown the first two types to be unsatisfactory. Table I summarizes these tests.

Diffusion emitters, of which the Phillip's cathode[1] is but a special case, have been found to be quite satisfactory as arc cathodes. Initial results with diffusion cathodes utilizing the Phillips design as shown in Fig. 3 were disappointing. Even though the desired high specific emission was obtained at temperatures of 1300 to 1400$^{\circ}C_B$, the life of the cathodes was very short. Few cathodes could be depended upon to last longer than 25 hours. Mechanical as well as electrical failure induced by operation in the severe arc conditions called for a re-design of the cathode. This led to the development of three new forms of diffusion emitters.

1. Soaked or impregnated cathode.
2. Thick disc cathode (Fig. 4).
3. Sintered BaO-W cathode (Fig. 5).

Thick disc and sintered BaO-W cathodes were found to be well adapted to operation in an arc. Current densities of hundreds of amperes per square centimeter have been obtained with these cathodes with long life. Sintered BaO-W cathodes were found to give higher specific emission than the Phillip's emitter when operating at the same temperature. While this was also true of the impregnated cathode, the limited storage of barium oxide makes their life short.

Directly heated cathodes of sintered thoria and molybdenum powders of the general type developed by Pomerantz[2] were found to be satisfactory. Though their emission efficiency is lower than diffusion emitters, sufficient

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[1] H. J. Lemens, M. J. Jansen and R. Loosjes, Phillips Tech. Rev. 11, 341 (1950).

[2] M. A. Pomerantz, NDRC 14-517.

arc currents are furnished from large continuous surface areas. A convergent field internal emitter (Fig. 6) was fabricated from this material.

A diffusion emitter employing a porous carbon plug has been found to give emission densities of hundreds of amperes per square centimeter. The high diffusion rate and rapid formation of barium carbide allowed arcs to run on barium ions alone. This type of operation suggests a method of injecting suitable materials into an extensive arc surface for electromagnetic separation.

IV. Diffusion Emitters

1. Sintered BaO-W Cathodes.

a. Description. A possible solution to the problem of making cathodes with reasonable size and good strength properties came out of an early desire to make diffusion cathodes in a directly heated form. The idea, which was earlier discarded on the assumption of poor electrical conductivity, was to form the emitter by pressing the oxides with a metal powder into the desired shape. The success of the soaked cathodes prompted immediate tests of sample BaO-W cathodes made in accord with powdered metallurgy techniques.

The first cathode of this type was 1 in. in diameter and 1/4 in. thick (Fig. 5). The size was determined by the available die. It contained 31 grams of 325 mesh tungsten powder and 1.8 grams of C.P. barium oxide. (The tungsten powder was obtained from the Park B. Hyde Co. in San Leandro, Calif.) The powder, which was lubricated with a solution of paraffin dissolved in benzene, was compacted to a pressure of approximately 32 tsi in five one-minute steps. The green compact was extruded in the usual fashion and placed in the emission testing unit for immediate sintering and activation.

b. Sintering and Activation. The cathode was brought up to 1500° C_B in approximately 30 minutes. Temperatures were measured with a Leeds-Northrup pyrometer and no attempt was made to correct for the unknown emissivity. Part of the activation time was required to accommodate outgassing; the remaining period was used in sintering the powders into a tough metallic mass.

c. Properties of Compressed Powders. A preliminary survey of the literature revealed no information on the techniques of producing tablets of compressed tungsten and various oxides. The moderate success of the first test cathode necessitated the further investigation of the following properties of mixed BaO-W.

(1) How much barium oxide could be added to the tunsten powder and still have a green compact capable of being handled?

(2) To what extent could higher compacting pressures be utilized to allow increased amounts of barium oxide to be used?

(3) Will these cathodes be good conductors after sintering? The green compacts were found to exhibit very high resistance.

The following information (Figs. 7-10 and Table II) has been assembled:

1. Considerable quantities of barium oxide can be added to the tungsten powder without adversely affecting its mechanical properties. Test data show that a 50 percent by volume addition is permissible.
2. Greater quantities of oxide can be accommodated if higher compacting pressures are convenient. For most mixtures, a compacting pressure of at least 50 tsi is recommended.
3. Cathodes must be fired as soon after pressing as possible. Delays of over a few hours are detrimental. Structural weakness of the green compacts is found with all additive materials but it is particularly bad for hygroscopic materials such as the alkaline earth oxides.
4. It has been found that sintering and activation may be accomplished simultaneously. If the material is to be sintered before activation,

the operation must be carried out in a vacuum furnace.

5. All cathodes tested were found to have a surface resistance so small that it could not be read on a common ohmmeter (less than 0.1 ohm) and were found to emit copiously. Though the actual data should be checked by high vacuum testing, there is evidence that these sintered cathodes gave high emission densities at temperatures a few hundred degrees lower than those of the Phillip's laboratories. This suggests higher emission efficiencies and, more important, higher peak emissions. The immediate application of these cathodes does not require knowledge of these properties.

Results of tests made on sintered BaO-W cathodes suggest the practicability of directly heated emitters. No effort has been made to extend the development in this direction.

d. Emission Testing.

(1) Pulsed Emission. Characteristics of the 1-in. sintered BaO-W cathode were obtained shortly after activation (Figs. 11-13). Total emission at the same cathode temperature continued to improve with time. Though the quantitative characteristics were not obtained, it is noted that currents of 1500 amps. or approximately 300 amps./cm^2 were obtained at the operating temperature of Fig. 11.

(2) D.C. Emission. The first BaO-W cathode to be fabricated was tested on d.c. emission. Current densities of 10 amps./cm^2 were immediately obtained at 1050° C_B. Power supply limitations precluded drawing higher current densities from the 1-in. diameter cathode. A similar 1/2-in. diameter cathode was constructed and tested. Again the power supply limited current densities to 40 amps./cm^2 on d.c. There is no

experimental evidence that pulsed and d.c. emission from this cathode are different.

e. Life Testing. Tests have shown that the life of diffusion emitters is directly associated with the presence of the oxides. Loss of the oxides correlates with the loss of copious emitting properties. In life tests of a Phillip's emitter, it was found that at 1400° C_B cathode life can be estimated in terms of approximately 30 hours per gram of oxides. Extrapolating the life of the latest model in terms of these data, this cathode, with 12 grams of oxides, would last 360 hours. No life test was run.

f. Emission Poisoning. Sintered BaO-W emitters have not been subjected to emission poisoning tests. There is reason to believe that emission recovery will not be a problem.

2. Thick Disc Emitters.

a. Description. Early experience with the Phillip's type geometry has shown that these cathodes operate on a diffusion principle. There was good reason to believe that the problem of mechanical failure and short life could be solved by modifying the geometry of this cathode. Results of previous tests had shown that it was possible to utilize a thick slab of sintered tungsten to gain mechanical strength. (Sintered tungsten, density of 11.55, was obtained from Carboloy Corp.) This was amply verified in the soaked cathodes. Also, if a longer diffusion path could be tolerated, longer life would result. A greater volume of sintered materials would alleviate the sealing problem somewhat. The remaining problem was to find a storage space of the oxides. It might seem, in terms of vapor pressure, that the oxides could not be stored in the hot molybdenum cathode holder. This was not found to be true. A pocket machined into the back of the support served admirably. The 1-in. diameter by 1/4-in. pocket was loaded with a tablet of an equal weight mixture of BaO and SrO. A thick sintered tungsten slab was clamped over the tablet and the cathode (Fig. 4) was ready for activation.

b. Activation. The cathode was brought up to the operating temperature (1100-1300 $°C_B$) in approximately one hour. Most of the evolved gas came off at low temperatures and was condensible. The remaining out-gassing was due to carbonate impurities in the oxides. If one obtained very dry, pure oxides, this cathode would have a negligible activation time.

c. Emission Testing.

(1) Pulsed Emission. Characteristics of the 1 1/4-in. diameter thick disc emitter are given in Figs. 14-16. As in the previous case, the curves stop at points where the current waveshape deteriorates from a square wave. Higher currents and current densities than shown for the conditions of Fig. 14 were later obtained at 25 microns of hydrogen (corrected). Densities of 200 amps./cm^2 were not uncommon.

(2) D.C. Emission. The available anode power limited d.c. arc current densities to approximately 7 amps./cm^2. In one test, a 50-ampere d.c. arc was maintained for over 5 hours. Later inspection of the cathode showed no ill effects. This was certainly not true of the Phillip's design.

d. Life Testing. After 35 integrated hours of intermittent pulsed operation, the cathode was removed and found to be in excellent condition. The oxide seal was so tight that it was necessary to break the tungsten disc to inspect the contents of the holder. From the quantity of oxide remaining, the useful life could be judged to be a few hundred hours.

e. Emission Poisoning. Emission measurements of this cathode before and after poisoning have shown that the emitting properties are completely recovered after exposure to air. The extent of the poisoning depends on the length of exposure and the temperature of the cathode at the time of the exposure. Cathodes so maltreated require heating for 15-30 minutes at approximately 200 $^{\circ}C_B$ above the normal operating temperature, depending on the extent of the poisoning. Under normal operating conditions, i.e., when the unit is continuously pumped, cathodes require no re-activation. They may be turned off and on at will and suffer no deleterious effects from exposure to diffusion pump oils resulting from the usual back-streaming encountered in demountable units. In one test, this cathode was operated on 6 different day shifts. During this time, the cathode was down to air 7 times and in addition had its emission poisoned 6 times while at various elevated temperatures. In all cases the emitting properties were completely duplicated when fired in accord with the above schedule.

V. Sintered Thoria Internal Emitter

1. Description. An experimental cathode of compressed thorium oxide and molybdenum powders was tried as a hot cathode arc source. The cylindrical sleeve of emitting materials was platinum brazed to thin molybdenum stock in a vacuum furnace (Fig. 6). This cathode was designed to operate as an internal emitter which would be positioned in a favorably convergent magnetic field.

2. Activation. Sintered thoria cathodes were heated to the emitting temperature by passing current through the emitting sleeve. The cathode was heated as fast as the pumping system would remove the sorbed gases. This required less than 15 minutes for a new cathode. No activation phenomena other than out-gassing was observed. Arcs were struck immediately on application of pulsed voltages. The particular geometry of materials employed requires a filament voltage of 10-15 volts at 200 amperes to give emitting temperatures between 1600-2000 $^{\circ}C_B$.

3. Emission Testing.

a. Pulsed Emission. This cathode was under test at the time of this writing so that data are not complete. Preliminary results show that with a favorable magnetic field this emitter will give 500 ampere (11 amps./cm^2) arcs. These cathodes have been known[2] to give current densities of 100 amps./cm^2.

b. D.C. Emission. No d.c. arc tests have been run with the sintered thoria cathodes. D.C. emission currents of at least 2 amps./cm^2 have been obtained by other investigators.[2]

4. Emission Poisoning. Sintered thoria cathodes are not affected by exposure to air after initial activation.

VI. Tungsten Spiral Filaments

1. General.

Tests made with various cathodes were compared with results obtained from a 2 1/2-turn spiral of 150 mil tungsten wire. (Fig. 17-19) It is interesting to note that the oxide cathodes gave greater peak currents at a 3 to 1 reduction in power input and ran at lower gas pressures. Peak arc currents of slightly more than 400 amperes were obtained at operating temperatures which render the life of the rod in terms of hundreds of hours.

VII. Discussion

By accepting the power dissipation problem as inescapable, the spiral tungsten filamentary cathode, with its gas-enhanced emission, is a good emitter for a low current arc source. Because of the required operating temperature, it will not have long life if subjected to high energy bombardment unless the diameter of the wire is quite large (150 mil or greater). It will not give perfect illumination of arc apertures, but may do an acceptable job. It is doubtful that this cathode could become a worth-while competitor for a higher powered arc.

Sintered thoria internal emitters have desirable properties in that they require less heating power, operate at lower magnetic fields and furnish more emission at higher emission efficiencies than does tungsten. They offer a possible solution to the problem of back bombardment from high energy ions in that the cathode is parallel to their direction of motion. These emitters do require special fabrication techniques, i.e., platinum brazing in a vacuum furnace.

Both the sintered BaO-W and the thick disc diffusion emitters are superior to the tungsten spiral in terms of emission efficiency, independence of life from surface bombardment, very high specific emission, and capability of being scaled to very high powers. Life with these newly developed forms is no longer a problem. Their tested life compares favorably with that of the tungsten spiral. The BaO-W emitter requires a compressed and pre-fired cathode which does not compare favorably with the readily fabricated thick disc emitter.

The Phillip's design as well as the soaked cathode can immediately be scrapped; the former from mechanical considerations and the latter in terms of stored oxides. The position of the new carbon cathode, due to insufficient data, is not clearly defined at this time.

VIII. Conclusions

On the basis of experience with the above emitters and in light of the above considerations, the relative rank of high power arc cathodes is as follows:

1. Thick Disc Diffusion Emitter (Fig. 4).
2. Tungsten Spiral (large diameter wire).
3. Sintered Thoria Internal Emitter (Fig. 6).
4. Sintered BaO-W emitter (Fig. 5).

Research Problems

During the course of an investigation one often comes in contact with problems, which for several reasons are either not solved or for which a solution was not attempted. Some of these problems are rather simple and others may involve a very careful theoretical investigation. Possible extensions to the above work may well come from some of the following suggestions:

1. Oxide cathodes are known to be quite sensitive to backing materials. One might try diffusion emitters using sintered Ni, Zr, and Ti separately or in combination.
2. Diffusion emitters of sintered oxides and metal powders such as barium aluminate, the rare earth oxides and W, Ta, Mo, Co, Ni, Zr, Ti, etc.
3. Positive ion extraction is affected by the condition and shape of the plasma at the ion-electron sorting surface. One might investigate the possibility of shaping the plasma with special cathode geometry (not surface geometry).
4. Investigate positive ion-electron secondary emission from refractory metals at various temperatures with variable ion flux densities and energies.
5. Measure the high vacuum properties of the new sintered BaO-W and the thick disc diffusion cathodes on pulsed and d.c. emission.
6. Measure the thermal and electrical properties of the BaO-W cathodes and investigate the possibilities of construction of directly heated emitters from this material.
7. Develop carbon cathodes for use in mass spectrograph isotope separation where rapid diffusion of materials is desirable.

Acknowledgments

The author is indebted to Charles Henry, our mechanical engineer, for his assistance in obtaining data on the mechanical properties of compressed powders.

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Information Division
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Table I

Properties of Metallic and Coated Emitters

Cathode	Emitting Material or Charge (By Weight)	Life (Hours)	Arc Current (Amps.)	Arc Pressure Microns H_2 (Corrected)	Remarks
7/8" dia. Phillip's	50% $BaCO_3$ 50% $SrCO_3$	10	120	5	Sintered W is warped
1-1/4" dia. Phillip's	same	56	40-100	4	Cathode down to air 10 times. Recharged after approximately 25 hours operation. Disc broken at 56 hours.
2" dia. Phillip's	same	18	40-100	3.5	Recharged after 10 hours of operation. Disc cracked at 18 hours.
1-5/64" dia. LaB_6	LaB_6 sintered on Ta button between Ta wires	4	20-40	5	Cathode is hard to heat. Surface bombardment removed 50% of LaB_6
LaB_6 annulus O.D. = 1-3/16" I.D. = 13/16"	LaB_6 in graphite holder	2-1/2	25	14	25% of LaB_6 sputtered away.
5/16 x 1-1/4 Ta coated	50% W 50% ThO_2 trace $Th(NO_3)_4$	1	10-30	10	Coating comes off. Would not stand sputtering
5/16 x 1-1/4 Ta coated	80% ZrO_2 10% ThO_2 5% MgO 5% CaO trace $C_{12}H_{22}O_{11}$	5	15-50	7.5	Coating shrinks. Would not stand sputtering

Table II

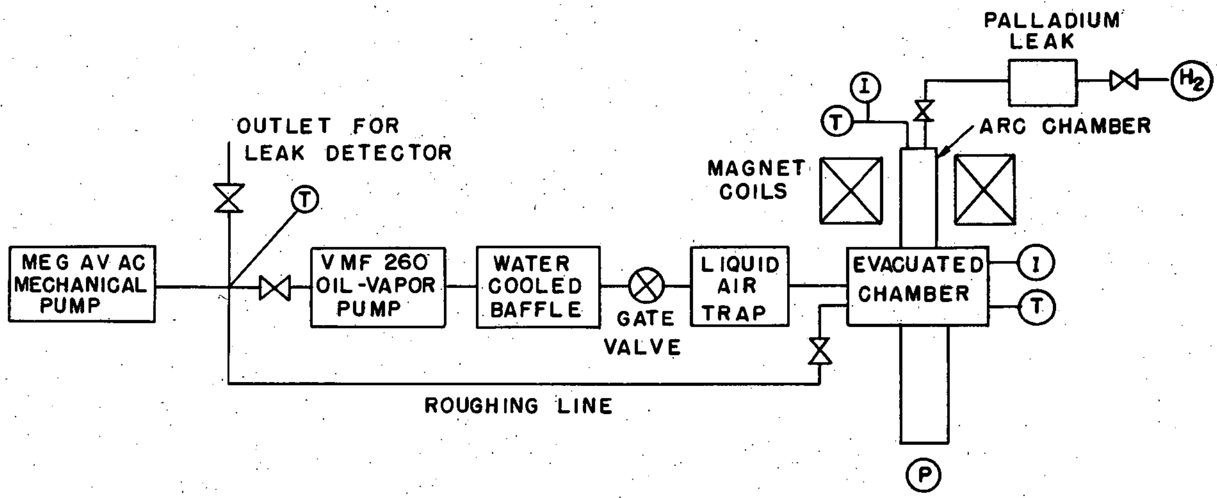
Test Data of 1/2-in. Diameter x 3/16-in. Long (approx.)

Specimens of Various BaO-W Mixtures

Test Specimen	Mixture Ratio W/BaO_2	Compacting Pressure tsi	Crumbling Pressure tsi	Wt. Gms.	Ht. In.	Density Gms/cm^3
1	14:1	100	25.5	6.955	0.173	12.9
2	14:1	70	20.4	5.560	0.145	12.3
3	14:1	50	15.3	8.110	0.221	11.8
4	14:1	30	5.1	6.610	0.188	11.3
5	10:1	100	37	6.98	0.178	12.25
6	10:1	70	23	6.83	0.186	11.4
7	10:1	50	12.75	5.75	0.170	10.55
8	10:1	30	5.1	6.62	0.207	9.96
9	7:1	100	35.8	6.95	0.191	11.35
10	7:1	70	23	6.52	0.192	10.6
11	7:1	50	7.65	7.39	0.233	9.9
12	7:1	30	3.84	6.45	0.214	9.38
13	3.8:1	100	25.5	7.--	0.209	10.2
14	3.8:1	70	16.4	7.--	0.224	9.7
15	3.8:1	50	10.3	7.--	0.246	9.1
16	3.8:1	30	5.1	7.--	0.268	8.1

Table III
Comparative Characteristics of Arc Cathodes

Characteristic \ Cathode	Thick Disc Emitter	Tungsten Spiral	Sintered BaO-W	Sintered Thoria	Soaked Cathodes
High specific emission a. Pulsed b. D.C.	Hundreds of amps/cm^2 Hundreds of amps/cm^2	Tens of amps/cm^2 Tens of amps/cm^2	Hundreds of amps/cm^2 Hundreds of amps/cm^2	Tens of amps/cm^2 Tens of amps/cm^2	Hundreds of amps/cm^2 Hundreds of amps/cm^2
Sensitivity to emission poisoning	Yes but recovery is complete	Slight	Yes but recovery should be complete	Slight	Yes but recovery is complete
Effect of surface bombardment on emission and life	None	Reduces life	None	Reduces life	None
Emission efficiency Power consumed for present arc source	High 1000-1500 watts	Very low 5000 watts	Very high 1000 watts	Intermediate 3000 watts	Very high 1200 watts
Easily produced	Yes	Yes	Requires pressed and pre-fired cathode	Requires platinum brazing in a vacuum furnace	Yes
Life in ion source	Hundreds of hours	Hundreds of hours	Should be hundreds of hours	Should be hundreds of hours	Very short
Effect of high voltage sparking on emission	None	None	None	Probably none	None
Possibilities in terms of a high density high current source	Excellent	Poor	Excellent	Good	Excellent
Can be formed into special shapes for plasma, focusing, etc.	Yes	To some extent	Yes	Yes	Yes
Can be directly heated	No	Yes (only)	Yes	Yes	Yes
Emission from large continuous areas	Yes	No	Yes	Yes	Yes



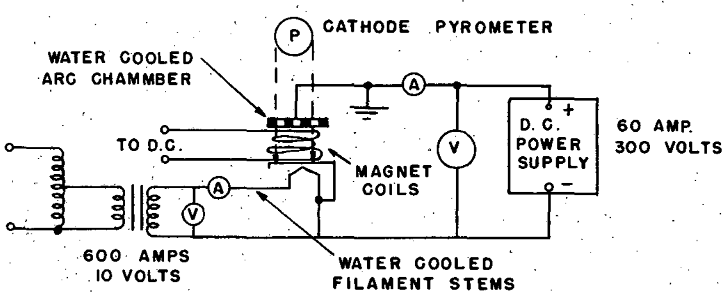
P = L & N PYROMETER

I = W.E. ION GAGE

T = N.R.C. THERMOCOUPLE

FIG. I SCHEMATIC - ARC CATHODE TEST

MU 1895



CIRCUIT FOR D.C. ARC TESTS

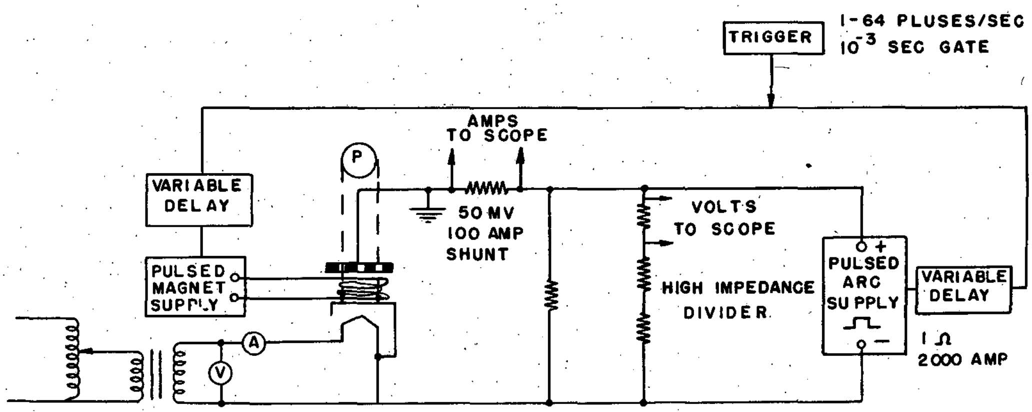


FIG. 2 CIRCUIT FOR PULSED ARC TESTS

MU 1896

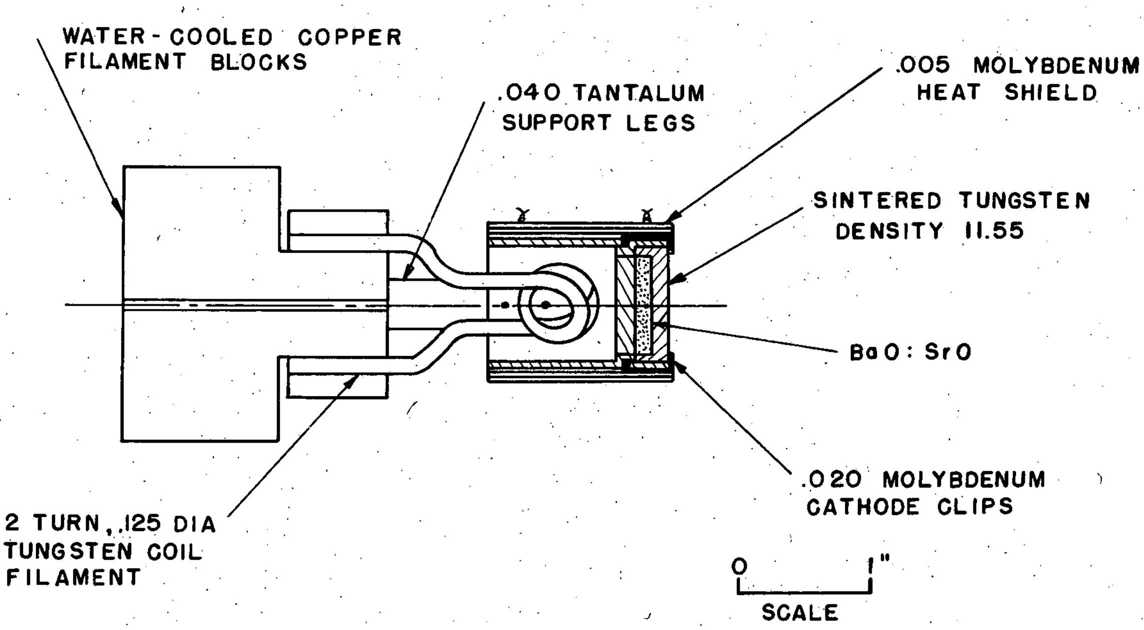


FIG. 3 ASSEMBLY - $\frac{7}{8}$" DIA. PHILLIPS CATHODE

MU 1897

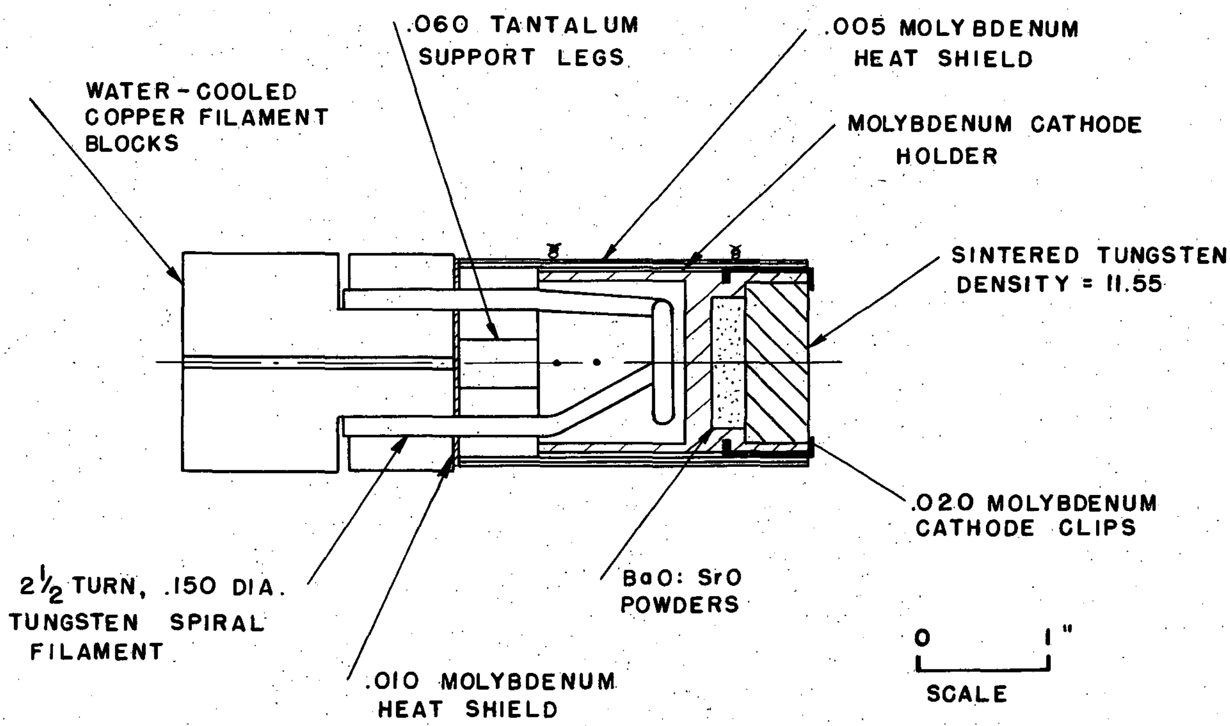


FIG. 4 ASSEMBLY - 1¼" THICK DISC EMITTER

MU 1898

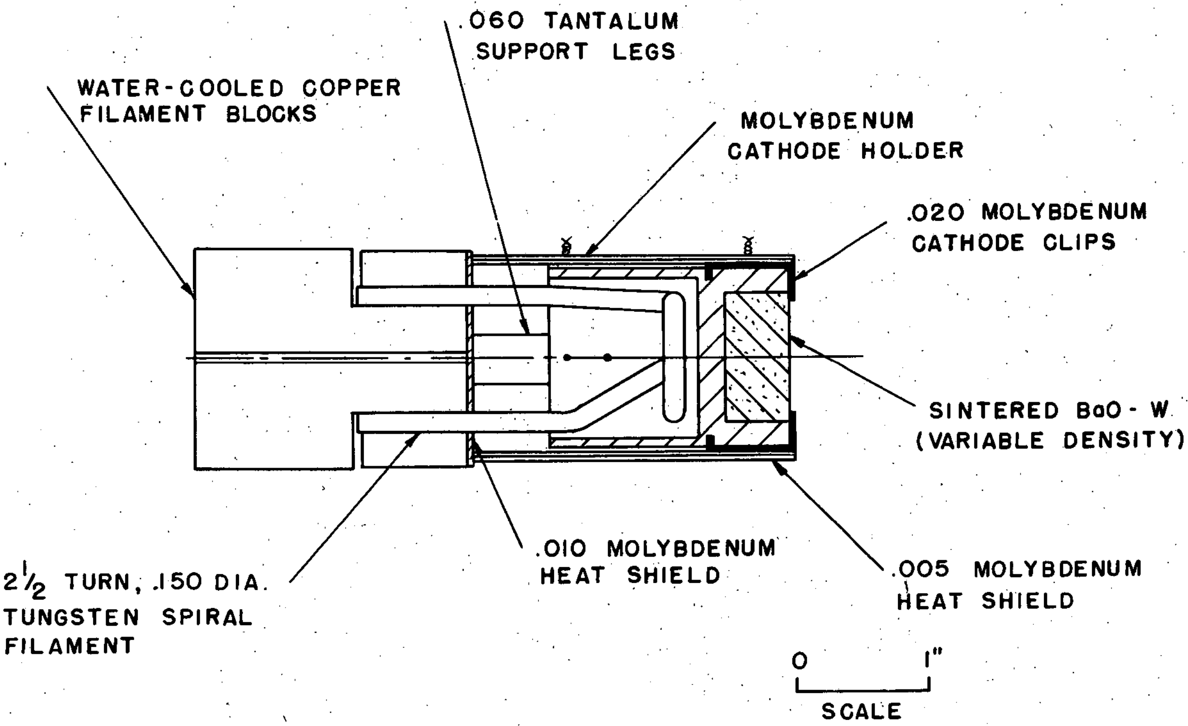


FIG. 5 ASSEMBLY - 1" SINTERED BaO-W EMITTER

MU 1899

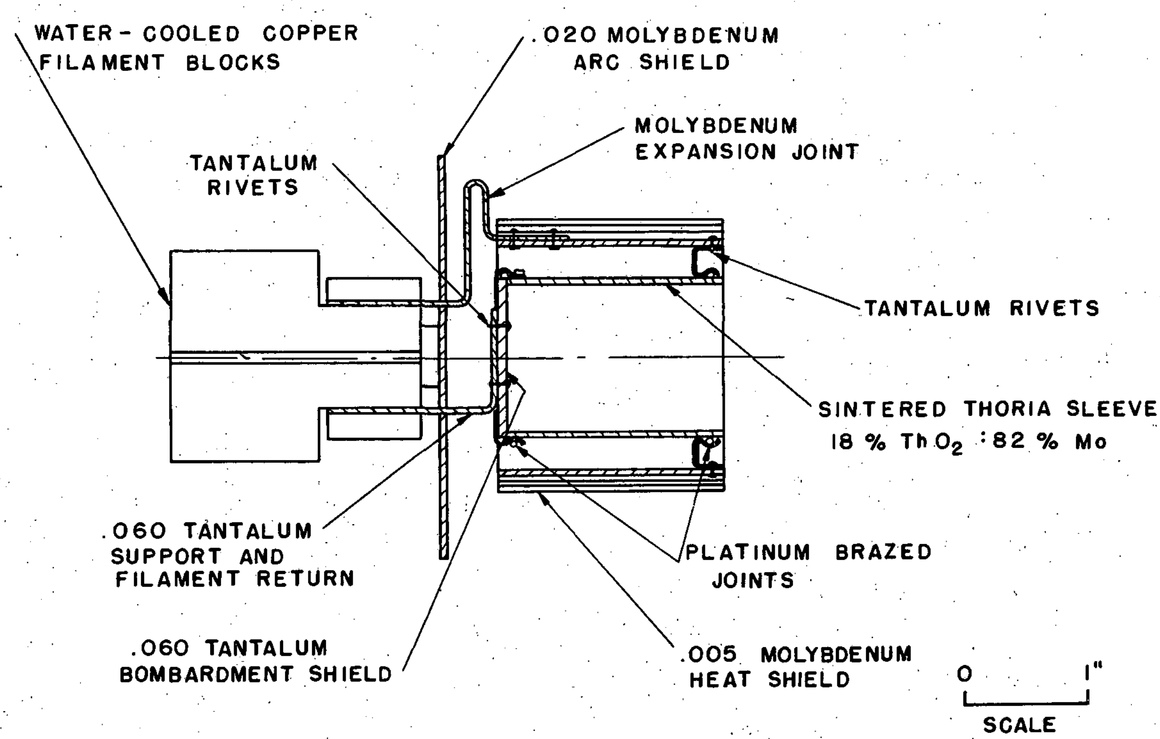


FIG. 6 ASSEMBLY- SINTERED THORIA INTERNAL EMITTER DIRECTLY HEATED

MU 1900

COMPACTION SETUP
FOR $\frac{1}{2}$ DIA. SPECIMENS

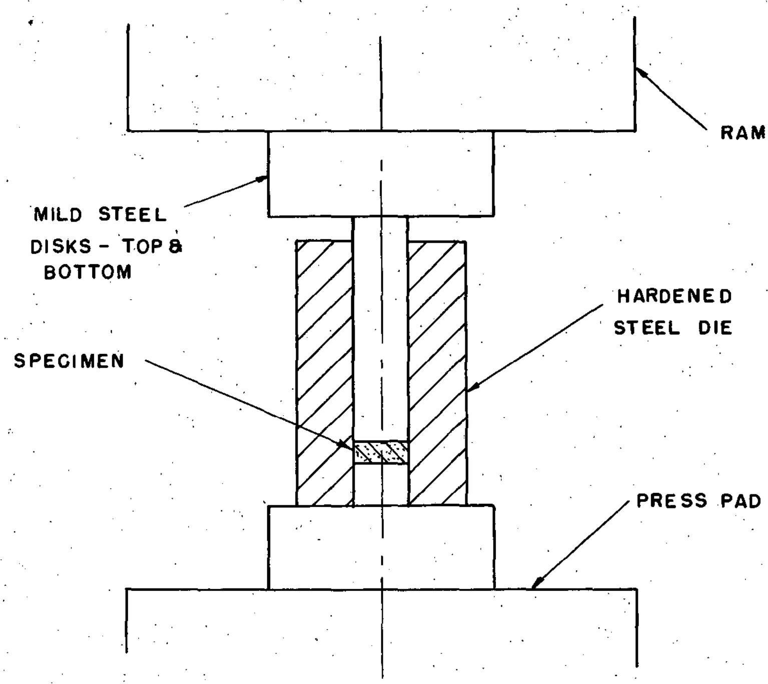


FIG. 7

MU 1901

TEST SETUP
FOR
CRUSHING SPECIMENS

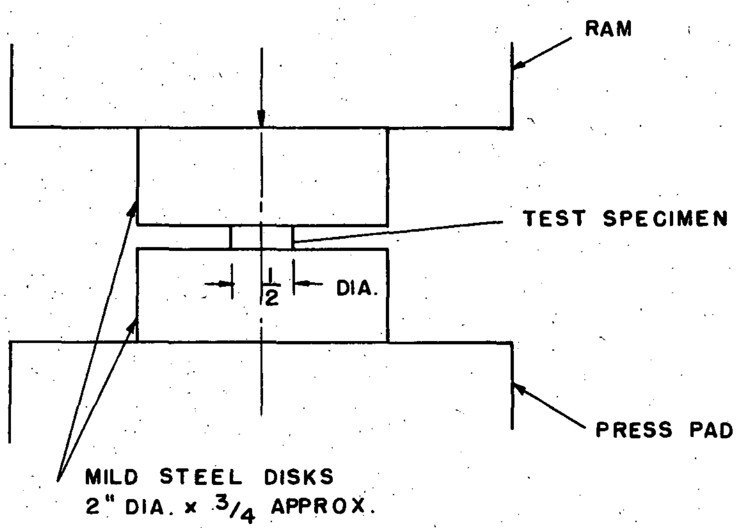


FIG. 8

MU 1902

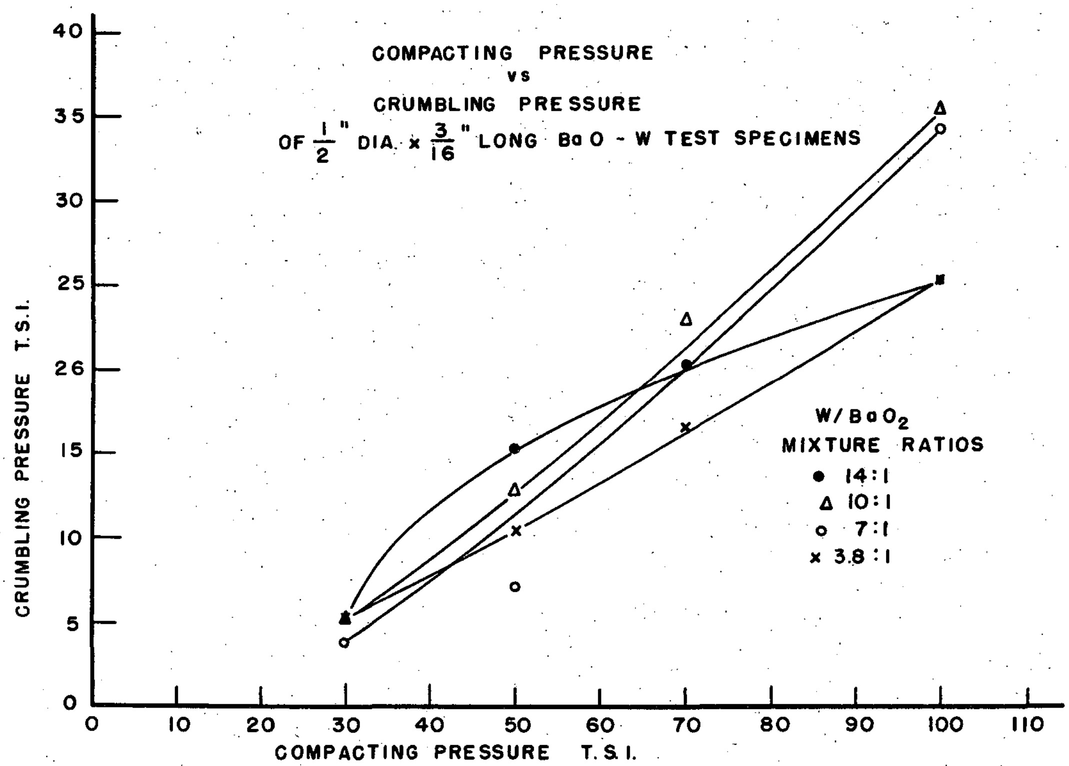

COMPACTING PRESSURE
vs
CRUMBLING PRESSURE
OF 1/2" DIA. x 3/16" LONG BaO - W TEST SPECIMENS
CRUMBLING PRESSURE T.S.I.
COMPACTING PRESSURE T.S.I.
W/BaO2
MIXTURE RATIOS
14:1
10:1
7:1
3.8:1
0
5
10
15
26
25
30
35
40
0
10
20
30
40
50
60
70
80
90
100
110

FIG. 9

MU 1903

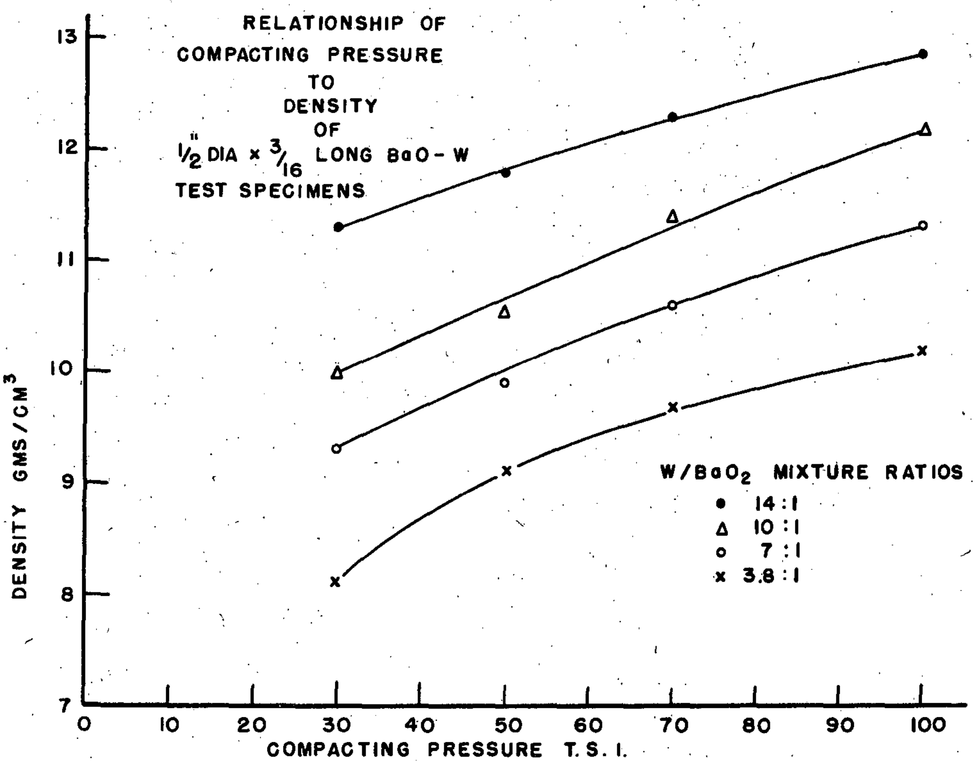


FIG. 10

MU 1904

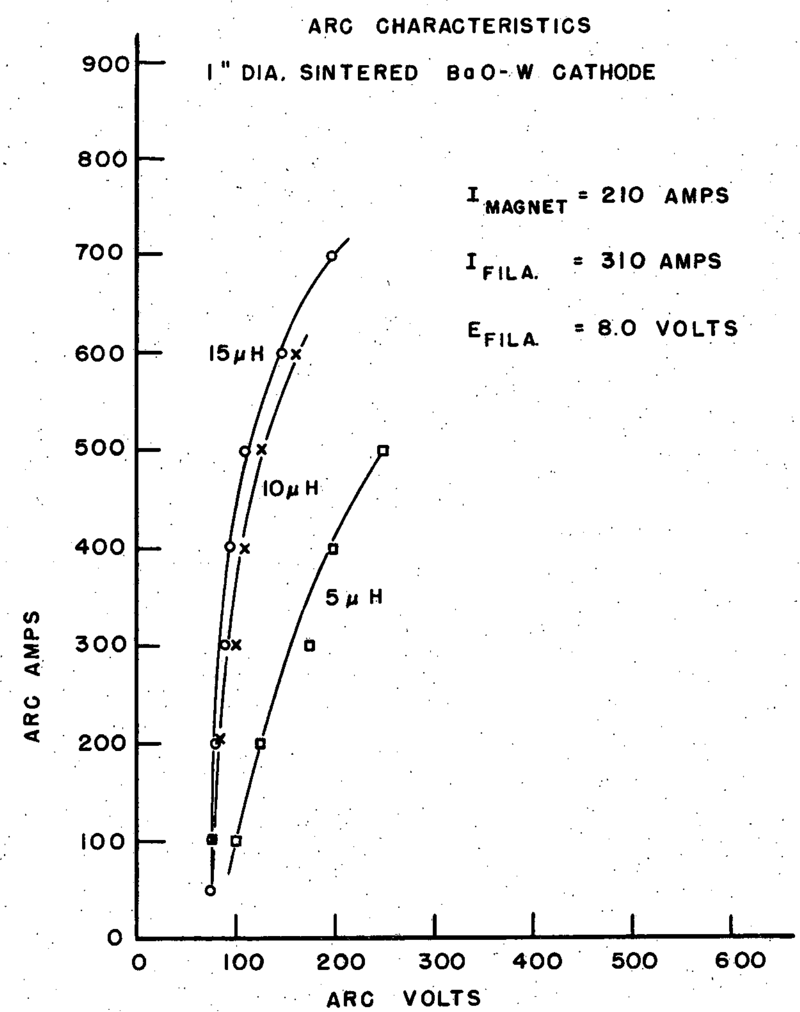


FIG. 11

MU 1905

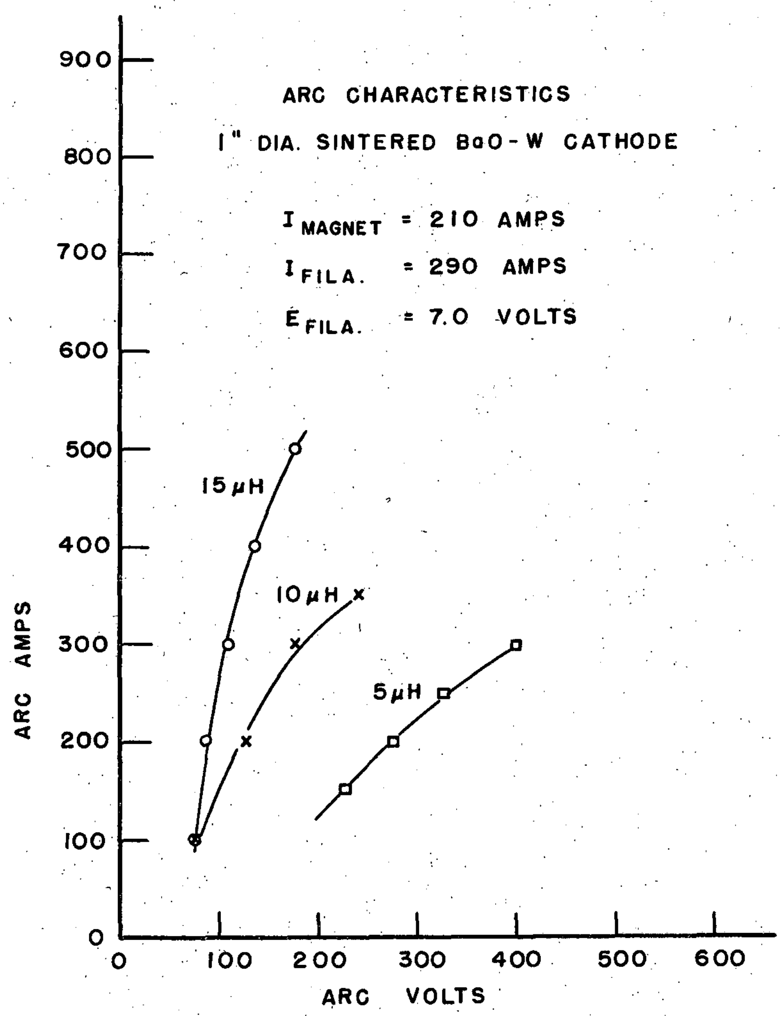


FIG. 12

MU 1906

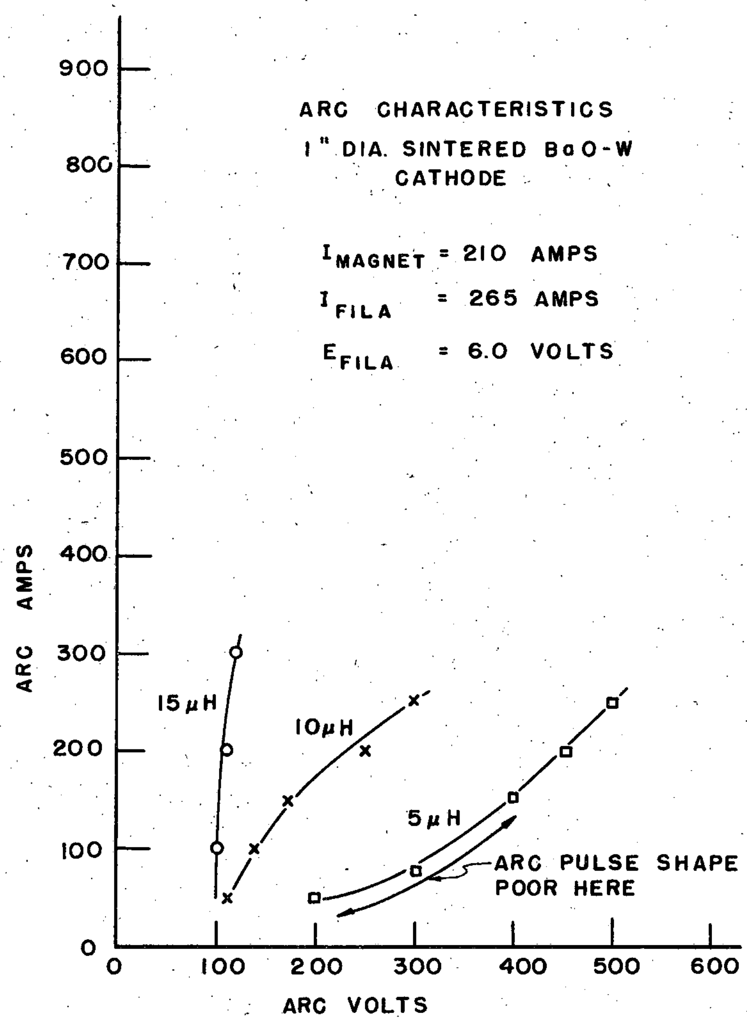


FIG 13

MU 1907

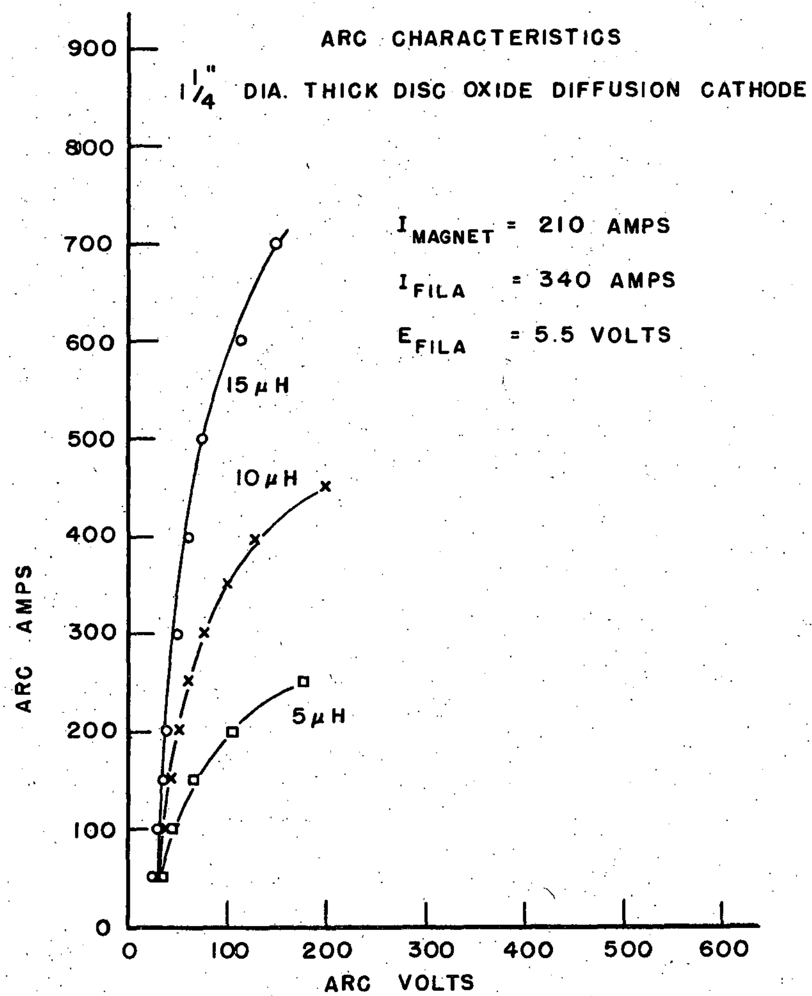


FIG. 14

MU 1908

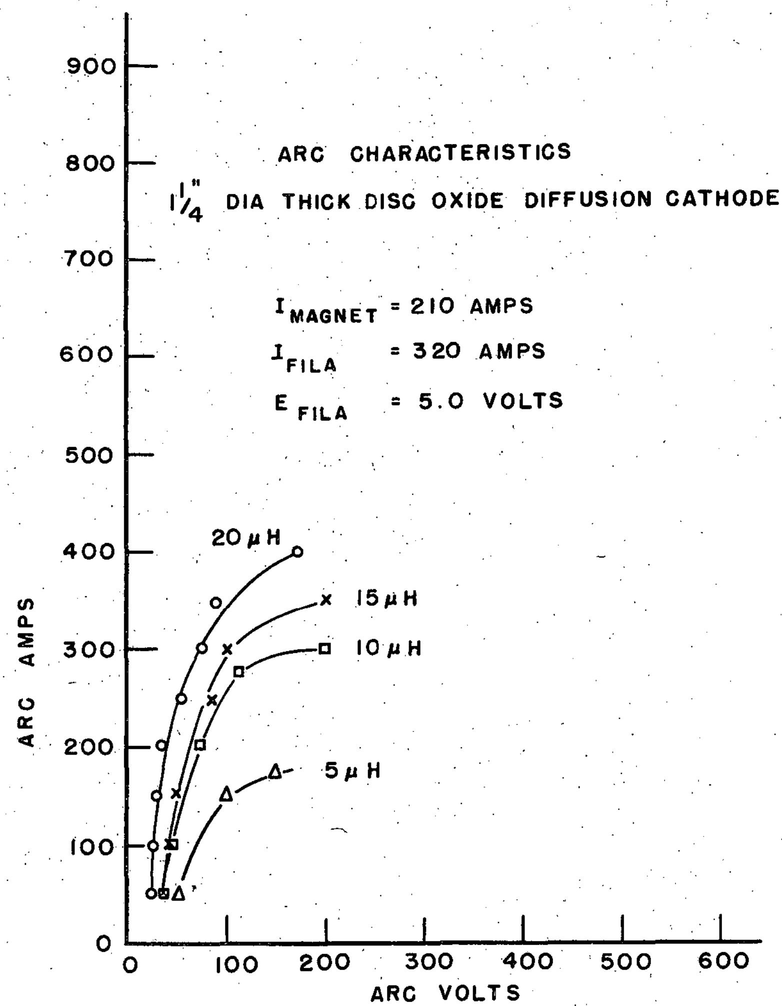


FIG. 15

MU 1909

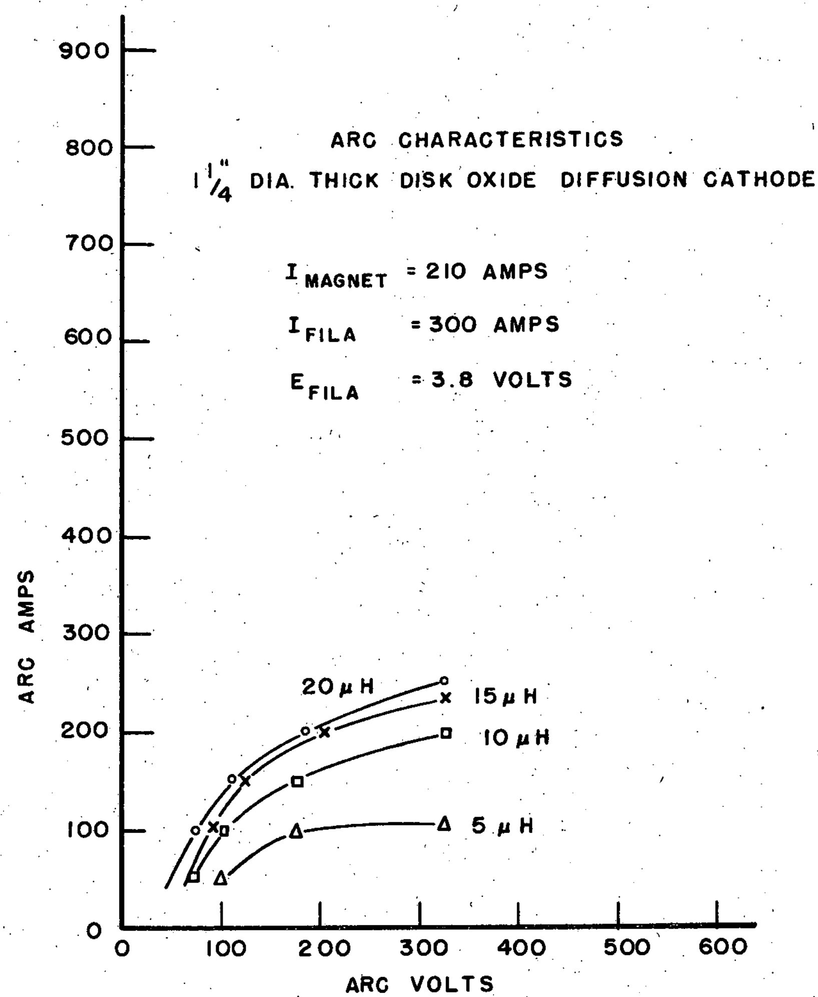


FIG. 16

MU 1910

ARC CHARACTERISTICS OF TUNGSTEN FILAMENTS
.150 DIA. WIRE 2 1/2 TURN FLAT SPIRAL

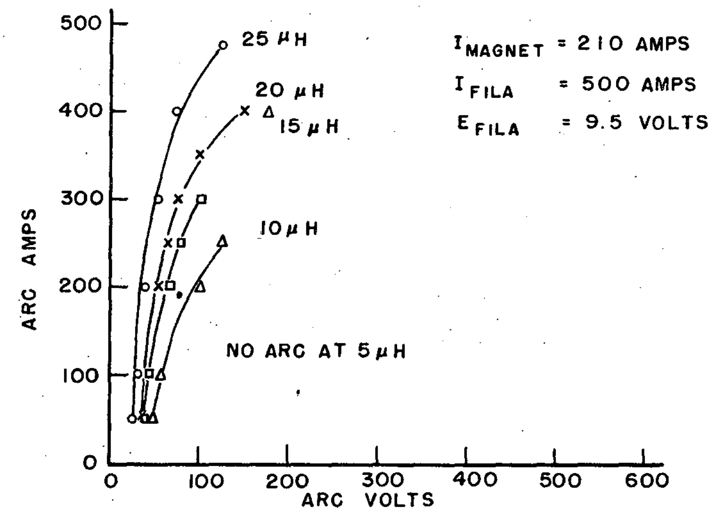


FIG. 17

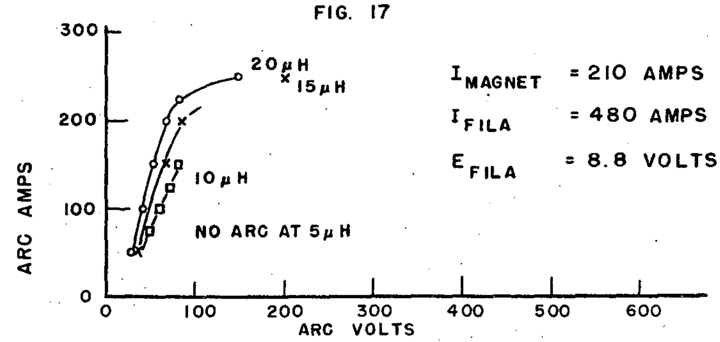


FIG. 18

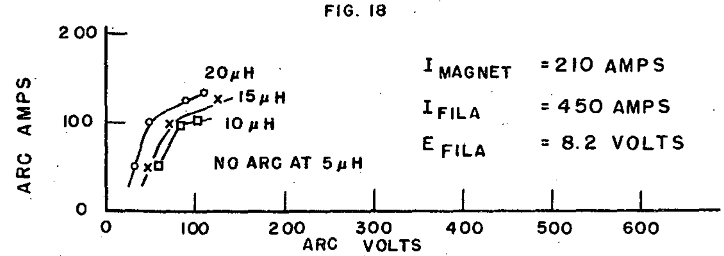


FIG. 19

MU 1911

DECLASSIFIED

~~CONFIDENTIAL~~