A HIGH OUTPUT, LOW VOLTAGE SPREAD POSITIVE ION-SOURCE

by

Walter S. Michel

A thesis submitted to the Faculty
of Graduate Studies and Research
of McGill University, in partial
fulfilment of the requirements for
the degree of Doctor of Philosophy

Radiation Laboratory,
McGill University,
September, 1948

INDEX

ACKNOWLEDGEMENTS

The author wishes to thank-

Prof. J.S. Foster, supervisor of this research, for his encouraging interest in this work and his invaluable advice and suggestions;

Prof. A.N. Shaw, Chairman, Dept. of Physics, for his kind and understanding help during the author's years at McGill University;

Prof. H.M. Cave, Queens University for his helpful advice and encouragement during the author's first attempt at experimental work;

The National Research Council for providing two studentships which aided greatly in making this work possible

Thanks are also due to the staff and students of the Radiation Laboratory for creating an atmosphere in which it has been a pleasure to work; in particular to Mr. D.A. Anderson, Mr. D.W. Hone, Mr. J.A. Carruthers, and Mr. J.S. Fraser for many fruitful discussions on electronic aspects of this work; to Mr. J.F. Mathison for his unflagging assistance in the difficult matter of operating the cyclotron magnet; finally, to Miss Mulligan, technician, the late Mr. Genereux, and Messrs. Doig, Masse, and Marchand, machinists.

LIST OF SYMBOLS

(1) THE HEIL SOURCE

i_A, V_A : anode, or discharge, current and potential

i_p, V_p : probe current and potential

i_o : output current after acceleration (25" from source)

i_c : current to Faraday cup, 2 cm from source

V_{acc} : intermediate accelerating potential

V_K : main accelerating potential

V_s : reflecting-shield potential

i_f : filament heating current

i_g : ionization gauge current

(2) THE COLD CATHODE SOURCE

Note: all potentials are referred to the top-cathode (i.e. the non-extracting cathode) as zero(*)

V : anode potential

V_L : potential of lower, or extracting, cathode

V_g : suppressor grid potential

V_a : accelerator potential

V_c : collector disc potential (or potential of chamber when the ion current is simply received by the floor of the chamber)

i_T : total current to both cathodes (positive for electrons leaving cathodes)

i_L : current to lower, or extracting, cathode (do.)

i_o : collector current; also referred to as output current (positive for positive ions reaching collector)

(*) except in the case of Figs. 30,31

(A) GENERAL INTRODUCTION

For many years there has been a well-sustained interest in ion-sources which are of vital importance for the efficient operation of positive ion accelerators such as Van de Graaffs, high tension sets, and cyclotrons.

In the present search two types of oscillating electron beam sources have been tried. One employs a hot filament cathode, the other a cold cathode.

The hot filament source appeared to be very promising at the time. An ion output of 2 mA, containing an estimated 50% of atomic ions, was obtained from it. Difficulties such as contamination by evaporation from the filaments, a tendency toward instability, and a cathode life of only 1-2 days were observed. It is concluded, however, that these might be largely overcome.

At this time Lorrain (L4) showed how high percentages of atomic ions could be obtained from a cold cathode source. This discovery gave great weight to the arguments in favor of the cold cathode source which had been gaining ground for some years.

It was therefore decided to turn attention to the development of a high output cold cathode source.

As a result of this work, two modifications are described. These were found to increase the output of the cold cathode source considerably. The first of these is an "ejector" anode which provides a high electrostatic extracting field for positive ions inside the source; the second is a form of "asymmetric operation in which the two cathodes are kept at different potentials.

The following table shows the maximum ion currents obtained:

TABLE I

	LOW MAGNETIC FIELD ≅ 1000 oersted		HIGH MAGNETIC FIELD 16,000 oersted	
	steady (mA)	pulsed (mA)	steady (mA)	pulsed (mA)
Ejector Anode - symmetric	0.08	0.04	1.5	1.3
Ejector Anode - asymmetric	5	60	< 1	-
Cylinder Anode - symmetric	2	-	< 0.2(*)	-
Cylinder Anode - asymmetric	10	-	10	90 -

It appears that in asymmetric operation the oscillating electrons leave the source proper and reach out into the low pressure region outside the source.

(*) but: see p.53

(B) REQUIREMENTS FOR A SATISFACTORY ION-SOURCE FOR HIGH VOLTAGE ACCELERATORS.

1. The power consumption should be small. Since it is usually preferable to have the target at ground potential, the ion-source and its associated equipment are at the high voltage end and can therefore not be supplied from a grounded power source.

2. The dimensions of the source and its associated equipment should be small. The reason for this is similar. It applies in particular to pressurized Van de Graaff generators.

3. The gas consumption should be low. This aids in obtaining a low pressure in the main tube, desirable in order to reduce the chances of electrical breakdown occurring, (cf. below).

4. The source should be capable of being pulsed to furnish short spurts of ions of high intensity. A pulsed source may be used for a number of experiments such as velocity analysis of thermal or near-thermal neutrons, investigations of short-lived artificially radioactive materials, and cloud-chamber work.

5. The source should have a long life and simplicity of construction and operation. In high pressure Van de Graaff machines the source is rather inaccessible, hence few controls are desirable, and replacements are difficult, hence long life is important.

6. The beam yielded by the source should have low energy spread

7. The output should consist predominantly of atomic ions.

8. The beam should be well focussed.

9. The source should supply a high output of ions.

One source of trouble with a beam which does not meet requirements 6-8 is that ions of different initial energy, mass, or direction will be affected differently by the various lenses. Ions will therefore hit the walls and electrodes, causing secondary electrons to be emitted there. These travel toward the source, producing ions on their way. This process may lead to electrical breakdown.

An added reason for requiring 8. is that most accelerators employ successive electrodes with equal potential differences of which, therefore, only the first can have an appreciable focussing effect. Thus, if the beam is not well focussed before it reaches the first main accelerating electrode, part of the useful output from the source will not reach the target and represents a loss in efficiency besides contributing to electrical breakdown.

Requirement 7. ensures that the power handling capacity of the generator and the cooling facilities of the target shall not be taxed unnecessarily by the presence in the beam of molecular ions. A 90 degree magnet at the target would also overcome this difficulty.

A low energy spread in the ions emerging from the source and a high output current are very important requirements. The canal ray ion-source used at present on the Ottawa H.T. set has an energy spread corresponding to a potential of 40 KV. This source cannot be relied upon to give an output current of more than 80 microamp. at the target. With a total acceleration of 600 KV the stated voltage spread represents about 7% of the total voltage. This percentage becomes correspondingly higher when the Set is operated at less than maximum acceleration. While for many experiments such a spread is allowable, no work requiring high resolution can be carried out with the present source. For instance, it would be gratifying if neutron resonances could be investigated with the Set. Neutrons with velocities 10-600 KV have been obtained by using the (γ,Be) or (γ,D) reactions; but the thresholds are 1.63 and 2.18 MeV respectively and extremely high voltage X-ray equipment is required. A (d,n) or (p,n) reaction with negative energy release may also be used, e.g.

$$Li^7(p,n)Be^7 \quad (Q = -1.62 \text{ MeV})$$

$$\text{or:} \quad C^{12}(d,n)N^{13} \quad (Q = -0.29 \text{ MeV})$$

Burcham (B4) has discussed this problem and suggested the last reaction for use on the Ottawa equipment. He states that in order to obtain 1 gm Rn-Be equivalent, at 600 KV 30 microamp., and at 300 KV 900 microamp., of deuterons are required. Further, to get a neutron source of less than 20 KV inhomogeneity at 600 KV, (*) the deuteron beam must be homogeneous to about 1 KV.

Thus an ion beam of 1 mA of atomic ions and less than 1000 Volt spread is required.

(*) using a cone of semi-angle 30°, and a target of 10 keV equivalent thickness

(B) HISTORICAL --- LOW VOLTAGE SPREAD ION - SOURCES

Accounts of several ion-sources of low voltage spread have appeared in the literature. These are of six types and will be discussed in turn:

1. Low voltage arc with filament cathode

Such a source has been constructed by Crane and his co-workers (C2). The pressure is one to ten microns. With a voltage of 1000 Volts and a discharge current of 0.5 amps. an output of 0.2 mA is obtained.

Lamar and Luhr (L1) have obtained output currents consisting to 98% of atomic ions. The pressure is, however, high. The maximum output obtained is 0.5 mA at a current density of 3 mA/sq.cm.

Scott (S1) has described a source which operates at a very low pressure (o.3 microns). With 0.6 amp. passing through the discharge at 800 Volts, he obtains an output of 4 mA. Good focussing was, however, possible only up to outputs of 100 microamp.. The proton percentage is 60%.

2. Low voltage capillary arc with heated filament

A source in which a discharge was maintained through a constricted space (capillary) was first put into operation by Tuve and collaborators (T1). Ions are extracted from the region of intense ionization (plasma) which is set up in the capillary by a negative probe, or are simply allowed to diffuse out. Further modifications of this principle have been described by Lamar, Sampson, and Compton (L2) and by Zinn (Z1). The cathodes used in these sources are usually very robust and capable of emitting several amp. The ion output is very homogeneous in energy since the arcs run at voltages of the order of 100 V. The proton percentage is low (20%). Pressures are of order several microns. Total output currents of up to 4 mA were obtained.

3. Ionization by crossing an electron and a molecular beam

A source based on this principle has been built by Planiol (P2). Using an electron beam of 0.3 amp. and a few hundred Volts he obtained outputs of order 0.6 mA. The usefulness of this source is mainly in the field of mass spectroscopy.

4. Oscillating electron beam sources with heated filament

These sources depend on ionization by a stream of electrons oscillating between two cathodes situated at opposite ends of an anode. The anode may be in form of a rectangular box with open ends (Heil, H3; v.Ardenne, A2), or a ring (Finkelstein, F1). One, or both, of the cathodes are of the heated filament type. The electrons are kept from going immediately to the anode by a magnetic field of moderate strength along their direction of oscillation.

These sources operate at very low pressures (o.6 micron) and are capable of emitting well-focussed beams of order 1 mA. The power used is extremely low (1 Watt). The proton percentage is 50%.

This type of discharge was first described by Maxwell (M1). Further work was done by Penning who designed a vacuum gauge, now known as the Penning gauge or Philips gauge (P1), and an ion source (Penning, l.c.) based on an electron beam oscillating in a magnetic field. The ion-source used a cold cathode. Operating voltage was high (10 KV).

The sources described by by Heil and Finkelstein (l.c.) were the first of this type to be used in ion accelerators (v.Ardenne, A2,3).

5. Cold cathode oscillating electron beam sources

The main difficulty with the sources mentioned in the previous section is the short life of the filament cathodes when discharge currents corresponding to outputs of about o.5 mA are used. For this reason, much work has been done towards building a satisfactory ion-source along the lines of the hot-cathode oscillating electron beam source, but operated with a cold cathode (Burcham, l.c.; Ward, W1; Lorrain, L4). Burcham and Ward (l.c.) obtained some promising results with brass and steel electrodes but encountered difficulties such as variation of the source characteristics with pressure, existence of widely different modes of operation under the same conditions, and a low atomic ion percentage. Lorrain (l.c.) has shown recently that at output currents < 1 mA the voltage at which the discharge runs may be lowered, and the atomic ion percentage considerably improved, if magnesium electrodes are used and the source is fed with hydrogen plus 1 part in 10 of oxygen.

6. Ionization by an electrodeless discharge

Bayly and Ward (B1) have recently described a source in which ions are formed in a low pressure electrodeless discharge excited by a 15 Mcy. oscillator. With 50 KV available for focussing, these authors obtained a beam of 0.5 mA, 6 mm. in diameter, and containing 60% of atomic ions.

The characteristics of the sources enumerated above have been listed in Table II. Their merits will now be discussed for application to

TABLE II

Characteristics of low voltage spread ion sources.

	pressure (microns)	power (watts)	canal dxl mm^2	j_{max} (mA)	pos. atomic ion %age	energy spread (eV)	gas cons. ccxatm/min.	atomic ions / molecules (%)	filament
LOW VOLTAGE ARC									
1. Crane et al	1 - 10	500	3x20?	0.2	60?	1000?	0.20	6.8	yes
2. Lamar and Luhr	300	15	4x0	0.5	98	50	120	0.006	yes
3. Scott	0.3	500	?	(4.0)	60	800?	low	high	yes
CAPILLARY ARC									
4. Tuve et al	2	?	?	1.5	25	55	--	-	yes
5. Lamar et al (Pyrex)	≥20	135	0.8x0	1.5	60	30	0.4	3.1	yes
6. Zinn	30	235	1x6	4.3	15	10 [illegible]	0.16	5.4	yes
OSCILLATING ELECTRON BEAM									
7. Heil (v.Ardenne)	0.5	5	6.5x0	0.5	50?	100	0.84	0.4	yes
8. Finkelstein (v.Ardenne)	0.6	1	5.5x0	0.1	50	150	0.5	0.14	yes
R-F DISCHARGE									
9. Bayly and Ward	10	450	2x12	0.8	60	1200?	0.2	3.1	no
COLD CATH. OSC. ELECTRON BEAM									
10. Lorrain	>2	30	2x0	1	50	≅ 100	2.5	0.3	no
11. Present work:									
Low field (cyl.an.-symm.	3.5	30	5x0	5	50?	≅ 100	0.9	3.9	no
Low field (cyl.an.-asymm.	6	30	3x0	4	50?	≅ 100	1.8	2	no
High field (cyl.an.-symm.	6	30	3x0	1.5	50?	≅ 100	1.8	0.8	no
High field (cyl.an.-asymm.	9	30	6x0	10	50?	≅ 100	9.3	0.8	no

Note: typical figures are given; the gas consumption and the ratio of atomic ions/molecules are calculated in each case from the stated pressure, canal size, ion output, and atomic ion percentage.

Van de Graaff accelerators, High Tension sets of the type existing in Ottawa, and cyclotrons.

1. Van de Graaff accelerators

For the accelerator of this type in construction at the Chalk River Laboratories of the National Research Council, target currents of only a few microamp. are desired at present (private communication, Al). Almost any one of the types listed would therefore be suitable for this application. The R.F. discharge might offer some difficulties since the vacuum tubes used in the R.F. circuits would not stand up to the high pressures, and a separate low pressure case brings power and insulation problems. The Zinn type source is in use on the Van de Graaff accelerators at Los Alamos and Wisconsin; it is understood that the cathode life is reasonably satisfactory..

M.v.Ardenne has used the Finkelstein source in his 1 Million Volt generator. After one year's experience he describes it (l.c.) as being very satisfactory.

In this source the electrons, emitted by a heated oxide-coated Nichrome strip mounted edge-on, are subjected to an accelerating potential of 150 V and subsequently traverse the chamber into which the gas is fed, there producing ions. On the far side of the chamber they are stopped and turned back by a decelerating field. A large number of oscillations occur if a magnetic guiding field which may be supplied by a permanent magnet is employed. The ions are extracted by the same field which turns back the electrons.

In terms of all the requirements listed above (p.3), except high output and, possibly, cathode life, (cf. below), the source is seen to perform very well: The power consumption is low (1 Watt for a 100 microamp. output). The dimensions of the source proper are of order a cube of side 2.5 cm. The gas consumption is only 1 mg/hr of heavy hydrogen for a beam of 100 microamp. of deuterons. No differential pumping was required with an exit hole 5.5 mm in diameter and a source pressure of 0.6 microns. No data are available on pulsed operation. The life of the cathode, mounted in the manner described and at the stated running power, was many hundreds of hours. The energy spread is of order 1/100 that of a canal ray source. The proton content is 50%. The beam is well focussed by means of a disc-shaped steering electrode which provides a strong bunching action immediately in front of the emission region where the tendency for divergence is greatest due to the high space charge. With vacuum cast electrodes of great purity the ion beam intensity could be regulated by adjusting the gas flow.

This source, with an output of 100 microamp. of which 50% is in the form of atomic ions, appears to be well suited to the present needs of the Chalk River project. If it is desired to remove molecular ions at the source, a mass monochromator may be installed, provided space is available. Von Ardenne's monochromator is 60 cm in height. It is noticed, however, that v.Ardenne abandoned using his monochromator since, as he puts it, operation was much simpler without this feature. Trouble was in particular experienced due to the presence of organic vapors. When the amount of such vapors was reduced by replacing all rubber gaskets by Apiezon wax seals and by the addition of liquid air traps, the output was found to be increased by a large factor.

2. High Tension Sets of the Ottawa type

The sources qualifying from the point of view of output are Nos. 5, 6, 7(?), 8(?), 9, 10 (cf. Table I).

The high output of the Zinn source is due to the very efficient method of extraction used. This involves an extracting potential of up to 10 KV, 2 mm from the cathode. Probably, an energy spread of an order corresponding to this voltage is thereby imparted to the ion output since extraction is hardly likely to be space charge limited so that the extraction field penetrates into the region of ionization. While this is only a small percentage of the total acceleration of a 5 MeV Van de Graaff it becomes significant for the Ottawa 600 KV set, and inadmissible for the use of the Set as a neutron generator envisaged by Burcham (l.c.). In addition, the atomic ion percentage is low so that the useful output is only 0.5 mA.

The Finkelstein source is quoted in the original paper (11) as yielding 150 mA of ion output current. However, these outputs were measured with the electron oscillations extending almost to the collector. It is difficult to predict how much of this output current might be secured in the form of a beam. Further, no runs were made extending over more than 15 minutes in duration. For this length of time output currents of 70 mA could be obtained without damage to the cathode. At higher currents the cathode was damaged after 15 minutes.

Ward (l.c.) states that, using oxide coated cathodes in a source very like that of Finkelstein's, several emission failures and one heater failure was experienced in a short time.

In view of these facts it is difficult to predict whether a

Finkelstein source would be satisfactory as a source of 1 mA of atomic ions in form of a beam.

The Heil source has also been discussed by v.Ardenne (l.c.), but no data on its performance in actual use are available.

An account of some tests performed on this source by the author of this thesis is given below.

The Lamar capillary arc, using a Pyrex capillary is suitable (cf. Burcham, l.c.); but again no data on protracted performance are given.

3. The Cyclotron

For the cyclotron, the requirements listed above (p.3) must be modified. (1) and (8) are of minor importance here. For conventional cyclotrons (2) and (4) are also not stressed. For synchro-cyclotrons, however, these two requirements are critical. Due to the small radius of the first ion paths in the synchro-cyclotron (0.5 cm), no part of the ion source can be allowed to protrude into the median plane of the dees, or ions will hit this part of the source and be lost. Also, the source should operate satisfactorily under pulsing. Bohm and Foldy (22) have shown that ions can be picked up usefully only during a small fraction of the modulation cycle. Only ions picked up during this time can start in orbits which are phase stable and at the same time do not return to the origin. This acceptance time has been calculated as 0.6% for the McGill cyclotron. Thus, unnecessary loading of the dee is avoided and, possibly, spurts of ions of great intensity can be obtained from the source if it can be pulsed at a duty cycle corresponding to the acceptance time and in synchronism with appropriate frequencies of the modulation cycle.

Finally, a high ion output is very essential, since the extraction efficiency is low.

The conventional cyclotron ion source is a form of capillary arc source. This type of source uses a high current discharge maintained along the lines of force of the magnetic field by a steady hot-filament cathode. The discharge is confined along part of its length to a narrow region where it produces an intense ionization. A space charge plasma is formed in this region from which ions diffuse out or are extracted by an electrostatic field, into the dee. Target currents of 300-500 microamp. have been customary in U.S. conventional cyclotrons (Livingston, L3). Efficiency of extraction is low due to the space charge limitation. Other disadvantages of this source are; high running pressure (10^{-2} mm.), somewhat elaborate heating requirements of the filament (hundreds of amp., several KW), short life of the filament (60 hrs.), and a low atomic ion percentage (10-20%).

This type of source is in use in the Berkeley, Cal. frequency modulated cyclotrons. Lately, the Berkeley group have published some data on its performance in the 37" F.M. cyclotron (Richardson and collaborators, R1). A 100 mil tungsten filament was used and under pulsing (duty cycle 1/10) had a life of 600 hours, i.e. ten times that found in steady operation. It is noteworthy that the filament was simply D.C. heated.

No precise figures are available on the output obtained from this source. Probably, it is of the order of tens of milliamperes.

A cold cathode source of equal ion output would offer some advantages over the conventional source described above. In particular, extraction would not take place from a plasma. Rather, a beam consisting only of positive ions would be diverted into the dee. Extraction in this manner might be expected to be more efficient. Further, no heavy filament is required and the power requirements are small.

Some work toward modifying the "conventional" cold cathode source for use in the synchro-cyclotron has been done in cooperation with Mr. F.G.R. Warren of this Laboratory.

(D) Preliminary Considerations.

Previous to the announcement of P. Lorrain's results (later published in l.c.), it was thought (cf. Burcham, l.c., Ward, l.c.) that cold cathode sources were unsatisfactory on several counts, but especially on that of a too low atomic ion percentage. During this time (summer 1946) the author undertook the search for an ion-source for the Ottawa High Tension set. It was decided to turn attention in particular to the source described by Heil (l.c.). This is a hot-filament source which, at the time, appeared to be very promising.

Only three months were available for this work and it was possible only to try the source in the form in which v. Ardenne (l.c.) has described it.

On his return to McGill University in the fall of 1946 the author heard of Lorrain's results which showed that a satisfactory proton percentage could be obtained from a cold cathode source. Attention was therefore turned to the development of a cold cathode source which now seemed likely to be superior to a source using filaments.

(E) SOME TESTS ON THE HEIL SOURCE.

(This work was done during the summer of 1946 at the National Research Council Laboratories, Ottawa.)

I PRINCIPLE OF THE SOURCE

Apart from details of construction, the von Ardenne modification was adopted. The anode consists of a flat box 2 cm. long, 1.5 cm wide and 0.5 cm deep (Fig. 5) with two opposite ends left open. In front of each of these openings was mounted a filament cathode (annealed non-sag tungsten wire) and a cylindrically bent reflecting shield kept at a potential negative with respect to the filament. These reflectors help to focus the electrons emitted from the filament, thus reducing considerably the magnetic field strength required. The small size of the source permits the use of a pole gap of 32 mm. so that a permanent magnet giving 1500 oersted could be used.

Electrons leave the cathode and acquire the full energy corresponding to the anode potential soon after entering the anode-box. On reaching the far end of the box they are slowed down and finally turned back either by the space charge surrounding the filament (if it is heated) or by the reflector. The magnetic and electrostatic focussing cause the electrons to oscillate a large number of times before going to the anode. To furnish the current flowing to the anode, the emission of a simple tungsten wire cathode is adequate. Normally the emission of only one filament is sufficient, so that the second filament can serve as a reserve cathode. The gas enters through a tube into the top of the anode box. The ions formed are extracted through a hole in the bottom of the box. As the ions are formed by electron collision in a field-free space they have both extremely small velocity and velocity-spread, so that a fine mesh probe at a few hundred volts negative with respect to the anode, and mounted a few mm. below it, is sufficient to extract a practically parallel beam.

II CONSTRUCTION OF THE SOURCE

The overall construction of the source is shown in Fig.43. The dimensions of the source elements proper are the same as those used by v. Ardenne (A2). Kovar terminals and porcelain insulators were used for conducting and insulating supports respectively. Brass rods, copper, nickel, or tungsten wires were silver soldered to these supports to carry the source elements (Fig45,47). A brass anode was used throughout. Tantalum was tried and also found to be satisfactory, but it did not appear better. The filaments were spot-welded on to tungsten wire supports with nickel sleeves, and were easily replaceable. Various types of probe were used. These are described below. The sylphon bellows permitted the directing of the beam to the centre of the target or to the entrance-hole of the analyzer.

A leak of the type described by Fowler (F2) proved fairly satisfactory. Tank hydrogen was used throughout.

III THE TESTING EQUIPMENT

The equipment described by Burcham (B4) was used. The power supply (Fig.48) consisted of a small insulated power supply operated at a frequency of 2000 cps for running the ion source itself, and a 50 KV DC transformer-rectifier set for the final acceleration of the ions.

The insulated power supply was fed by means of a step-up transformer from a small aircraft generator at ground potential via the condenser of the 50 KV set and supplied a few hundred watts at 80 V at whatever potential above ground the 50 KV set was operated. This 80 V in turn fed a transformer and rectifier set giving several thousand volts. Pumping speed of the MC 275 diffusion pump, backed directly by a Welsh Duoseal rotary pump, was about 200 litres/sec.

In principle batteries can be used with advantage to supply all the power required for operation of the source. As the insulated power supply referred to in the previous paragraph was available it was used for the probe and intermediate accelerating voltages V_p, V_{acc}, whereas V_A, V_s were supplied by dry cells (Fig.49). The filaments were heated by a 6 V storage cell.

IV MEASUREMENTS

1. General Remarks: Preliminary measurements of output were made with a Faraday cup 2 cm. from the mesh probe. These give information about the output of the source proper. The cup currents thus obtained are denoted by i_c. For the final measurements the accelerating potential of 10-30 KV was employed, and the ion output (i_o) was read at a distance of about 25" from the source. The ions were collected on a brass plate, 3.5" in diameter, replacing the analyzer shown in Figs. 44 and 46. The beam at this point was circular in cross-section and about 3" in diameter.

It will be seen (Fig. 56) that i_c is determined by i_A for given voltages and pressure. The current i_A in turn depends on i_f, a change of 0.1 amp. in the latter producing an appreciable change in the former. As i_f is of the order of several amperes it is not possible to regulate it with an accuracy adequate for taking repeatable readings. Therefore other variables are referred to i_A throughout.

2. Pressure: Pressures were measured with a Distillation Products Inc. ionization gauge. Pressure readings in the portion of the thesis in which work on the Heil source is reported, are given in microamperes. The reason for this is that no definite statement can be made about the actual pressure without re-calibration of the gauge for an air-hydrogen mixture. A good idea of the approximate pressure may, however, be gained from Fig50 where the factory calibration is given as well as a line based on a paper by Dushman and Young (D1) in which it is shown that for mixtures of air and hydrogen the sensitivity of an ionization gauge is decreased at most 3.5-fold. The actual pressure lies between the two lines of the figure for any given reading of i_g.

For all readings the system was pumped down to $6\mu A$ (air) and then hydrogen was let in to bring the pressure up to the desired value. The source started to run at about $8\mu A$ (i.e. $2\mu A$ partial pressure of hydrogen) and ran increasingly well as the pressure was increased. A good running value was $18\mu A$.

It should be noted that the ionization-gauge was mounted a considerable distance from the source (Fig.44). Although the rated speed of the diffusion pump was 200 litres/sec., the pumping speed of the aperture directly below the source, calculated in the conventional manner, including end effects, was only about 7 litres/sec. While this can serve only as a rough guide, it seems likely that the pressure in the source was higher than that measured at the ionization gauge by more than a factor of ten. The linear increase of ion output with pressure reported by v. Ardenne (l.c.) was confirmed with a flattening off at higher pressures (Fig. 51).

3. Magnetic Field: The effectiveness of the field in keeping the oscillating electron beam off the anode, i.e. keeping the ratio i_A/i_f low, increases with field strength up to about 1100 oersted. Higher field values do not decrease this ratio much further. This is plausible in view of the extreme effectiveness (97%) of the 1500 oersted field, shown in Fig. 52. Heil (33) obtained an increase in effectiveness up to 6000 oersted. This is due, presumably, to his use of several filaments in parallel and the different geometry of his source. However, v. Ardenne's estimate (l.c.), that higher field values should increase i_0 by a factor of 2-4 times does not seem to be substantiated for the source in its present form.

4. Reflecting Shields: A typical plot of i_A vs. V_s is given in Fig.53.

5. Anode Voltage: The variation of output with V_A is shown in Fig. 54. The optimum value of V_A depends on the variation of the atomic ion output percentage with V_A. As the output was not analyzed this aspect of the source was not investigated.

6. Filament Emission: It is seen from Fig.55 that most of i_A is made up by electrons produced in the discharge. The dotted curve was obtained with only one filament heated, the full curve with both filaments heated. Thus, for the same

emission, the output is only slightly altered by using the second filament. However, with both filaments, the same diode emission as with one may be obtained farther from the flare-up point (cf. #9. of this section). This is sometimes advantageous. Tungsten filaments, approximately 2 cm long and 0.005-0.010" in diameter, were used. They are reasonably long lived (1 day). The 0.01" wire takes about 7A at 6V for a good discharge.

7. A typical output curve: A typical output curve is shown in Fig. 14, together with the corresponding curve given by von Ardenne (l.c.)

8. Probe Potential: Higher probe potentials than 200 V did not sufficiently increase the output to make their use practical. Fig.59 shows some curves obtained for comparison. Figs. 55,56 (both obtained from Fig. 10) are also informative in this connection.

Fig.47 shows that the output depends considerably on the nature of the probe. The full curves were obtained with a probe consisting of a washer (o.d. 10 mm., i.d. 5 mm.) with coarse copper mesh spot-welded to the under side. The dotted curves were obtained using eight equidistant strips of 0.002" diameter tungsten wire spot-welded across the washer.

The ratio of probe to output current was usually between 1:1 and 2:1.

9. Stability of the discharge: As soon as hydrogen was admitted to the evacuated system a bluish discharge (referred to as *the* discharge) appeared throughout the anode box. This increased in brightness with increasing i_F or with increasing pressure; i_A and i_O increased correspondingly. As i_F was further

increased a point was usually reached where the discharge suddenly jumped to an extreme brightness. At this point i_A increased also to several times its former value, with no appreciable increase in i_O. If only one filament was heated, the discharge on "flare-up" was intense enough to heat the other filament to a dull red. The flare-up point was shifted toward higher i_A for higher pressure or heavier filaments.

10. Contamination: After running the source for a few hours the discharge sometimes went out and the source ceased to function. The higher the discharge intensity, the sooner did this occur. The anode was then found to be covered with a thin bluish layer, presumably of tungsten evaporated from the filaments. Upon cleaning off this layer with sandpaper the source ran normally again.

11. Repeatability: It has been noted throughout this work that the behaviour of the source was in certain respects rather unpredictable. For instance at times a probe voltage of only 500 V interfered with the functioning of the discharge considerably, whereas at other times no effect on the discharge was observed for probe voltages three times this value. Similarly, flare-up occurred once for a discharge current of only 5 mA while at other times no flare-up occurred up to i_A = 150 mA.

V DISCUSSION AND CONCLUSIONS

It has been shown that an output of 2 mA of ions may be obtained from this source. 25% of this was focussed to a distance

25" from the source. This output can probably be increased by the use of heavier filaments and a stronger magnetic field. It seems probable that oxide-coated filaments, mounted edge-on as described by Finkelstein (F1) and successfully used by v.Ardenne (A3) would have a longer life than those used by Heil (l.c.) and in this work. The use of sturdier filaments of a different material might well reduce the tendency toward instability and contamination.

It appears likely that, with some further development along these lines, the Heil source could be made into an efficient ion-source.

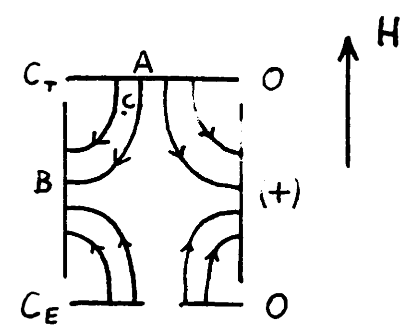
Heil (l.c.) estimates the proton percentage given by his source to be 50% on the basis of the performance of the Scott (l.c.) source. This estimate has since been substantiated further by v.Ardenne's analysis of the output from the Finkelstein wource which is very similar in operation to the Heil source. The figure obtained was 50%.

(F) THE COLD CATHODE SOURCE

(This work was done at the Radiation Laboratory, McGill University, during the years 1946-8)

(i) description of the construction and operation of the source

The cold cathode oscillating electron beam source consists of an anode in the form of a box with open ends. Usually, a cylinder or ring anode is used. The cathodes are simply metal discs placed opposite the open ends of the anode. The course of the electrostatic lines of force is shown qualitatively in the following sketch:



The arrows indicate the direction in which electrons are accelerated. One of the cathodes is provided with a hole through which positive ions may pass, and the source is placed in an axial magnetic field.

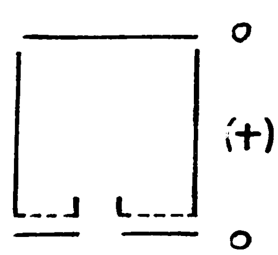
The following commonly accepted explanation of the manner in which this source operates is given to fix ideas:

Electrons at the point C are accelerated along a line of force such as AB. The effect of the magnetic field is to change this motion into a spiral along the magnetic lines of force. The radius of such a spiral for an electron of a few tens of Volts in a field of a few hundred oersted is of the order 0.5 mm. Electrons from C travel thus essentially toward the cathode C_E. They traverse the central region of the source which is a space free from electrostatic fields, except that due to space-charge, and are slowed down and turned back upon approaching the cathode C_E. An electron may perform a large number of oscillations before the combination of space charge and sideways velocity components gained in collisions finally drives it into the anode (Heil, l.c.). Thus, its effective path is longer than in electron beam sources where no oscillations take place, and the number of ions produced per electron reaching the anode is increased. Ions produced near the hole in the extracting cathode find themselves in a field which causes them to leave the source via the extracting hole. Since ions formed by low voltage electrons such as in this source are practically at rest, a parallel beam of ions is obtained.

(ii) modifications of the symmetric cylinder type source introduced in the course of this research

It was thought that positive ion output might be favored if the lower cathode (extracting cathode) were run at a few Volts negative with repect to the upper. This type of operation is called "asymmetric" in this thesis and is discussed at length below.

Another modification, used with both symmetric and asymmetric operation, is the "ejector anode". This type of anode is shown in Plate III,k. It consists of an ordinary cylinder anode to which is added a coaxial cylinder, 1/16" high and of internal diameter 5/64", flush with the lower end of the main anode cylinder. The wall of the small cylinder is 1/64" thick and it is supported by a narrow ridge. The whole ejector anode is machined out of one piece of Magnesium. Such an anode construction creates a high voltage gradient favoring positive ion emission, near the extracting hole.

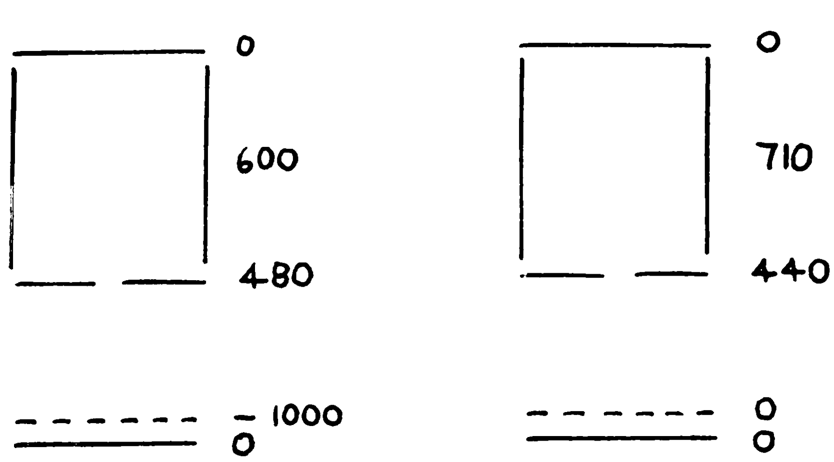


(not to scale)

A discussion of asymmetric operation follows. Some other, minor modifications are also discussed. The performance of the ejector anode may be judged from Table I, p. 2 .

Asymmetric operation: A first attempt in the high field, using storage cells to provide voltage differences up to ±36 Volts, gave the results shown in Fig.34. In order to obtain a larger positive voltage on the lower cathode, a resistor was inserted between it and the upper cathode (ground, cf. Fig.42). This was found to increase the output current by a factor of nearly forty. Later work showed that the asymmetric mode of running improved the low field output also, though only by a factor of two. Thus, the output maximum of 5 mA shown in one of the curves of Fig.2, was somewhat exceptional for symmetric running; but with asymmetric operation such outputs were quite consistently obtained.

A noteworthy feature of asymmetric operation is that a shallow pit is formed, as the result of ion bombardment, in the top cathode (and in the collector). The area of these pits is always equal to the area of the extracting hole. Thus, whereas in symmetric running the discharge covers the whole cathode area uniformly, in asymmetric running the discharge takes place largely across an area equal to that of the extracting hole. The explanation appears to be that the discharge electrons pass through the extracting hole, i.e. the discharge extends into the low pressure region outside the source. The "beam" observed through the window is, in fact, part of the discharge. If the electrode voltages are considered, this interpretation becomes plausible:



The electrical circuit for asymmetric running was always such that $V > V_L$. Thus an electron formed in the upper half of the source might well have enough energy ($E < V > V_L$) to pass through the lower cathode. Such an electron would be stopped and turned back before reaching the grid in case A. In case B it might proceed to the collector. Higher output currents were obtained, the more negative V_g was made. It was not possible to observe visually in case A whether a change in intensity of the "beam" occurred slightly above, or at, the grid.

The higher output currents obtained in asymmetric operation might be expected to result, if this interpretation is correct, since collection takes place closer to the discharge. It is pointed out above that Finkelstein (l.c.) measured his ion current under similar conditions.

Further experimentation will be required to determine to what extent extraction of ions in form of a beam can take place from a discharge which has thus spread into the low pressure region outside the source.

From the point of view of a cyclotron source it is interesting to observe that operation in this manner is equivalent to the manner of operation of the conventional low voltage arc where also a discharge is maintained outside the source proper. In the present case, however, emission from a heated filament is not required to maintain the discharge.

Improvement of electrostatic field An attempt was made to improve the ratio $\frac{\text{output current}}{\text{discharge current}}$ by changing the source geometry in such a way as to make the electrostatic lines of force in the source run more nearly parallel to the magnetic field in the region of maximum potential gradient, i.e. away from the centre. It was hoped that the discharge electrons would in consequence stay longer in the discharge and cause more ionization per unit discharge current. A ring anode and a cylindrical anode with ends tapering inwards were tried. No significant improvement resulted.

Changes in cathode geometry It was thought at one time that the "drop-off" in output (Fig.2) observed at the higher discharge currents might be due to a sideways spreading due to mutual repulsion, of the positive ions inside the source. To test this, extraction through a peripheral aperture (Plate III, top, 6) was tried. No change in the i_0 vs. i_T curve resulted.

Cathodes resembling more closely those used by Lorrain (l.c.) and shown in Plate III, top, 7, also gave no improvement in output.

(iii) Experimental work - General

Source constructions used:

A construction in which the anode was cylindrical and the cathodes were discs held at small distances from the open ends of the anode has been used by Ward, Burcham, and Lorrain (l.c.), and in some of the present work. Magnesium metal is used throughout, except for a few runs with an all-Calcium source.

In the early part of this work the electrodes were separated and supported by glass spacers so that the appearance of the discharge could be observed. The magnesium-glass joints were sealed with Apiezon-W.

This construction was later replaced by a sturdier one in which the cathodes were inserted at the two open ends of a brass cylinder or else threaded into a closed cylindrical brass box ("enclosed model"), the anode being supported axially inside, on some form of insulating support. A source of this type which was used extensively is shown in Fig.40 and Plate III, top. This source incorporates the following features:

1. water-cooled anode
2. water-cooled cathodes
3. Lavite insulators
4. glass insulator in the anode lead

The glass insulator in the anode lead was installed because a discharge had occurred across the bakelite spacer marked C in Fig.40.

This source was retained for the early work in the cyclotron magnet; here, however, it was mounted on the 4" square chamber shown, associated with the "spacer source", in Fig. 41. A grid which could be biased to suppress secondary electrons was mounted on a Kovar seal approximately 1 cm above the chamber floor which served as the collecting electrode.

At the start of pulsed operation a brass disc 1.5" in diameter was mounted on a Kovar seal just above the floor of the chamber to act as a separate shielded collector, the chamber and brass tube being grounded. The grid was moved to a position about 1 cm above the collector disc. The purpose of the change was to prevent electrical pickup due to the capacitance associated with the bulky chamber and tube.

For asymmetric operation a source (Fig.41 and Plate III, bottom) in which the two cathodes were electrically insulated was used. This source also has the following features:

1. separate and more efficient cooling of the cathodes
2. efficient anode cooling
3. the anode is held by a set screw and is easily removable
4. the source is easy to dismantle and reassemble

The cooling leads, shown only in part in the diagram, are $\frac{1}{4}$" brass tubes which slide through the inner hollow conductor of $\frac{1}{4}$" Stupakoff Type GA Kovar-glass seals, soft soldered into the top cathode holder (a, Plate III). The brass tubes were soft soldered to the Kovar terminals. It is realized that Kovar metal has a relatively high magnetic permeability in low fields. It is hoped that this interfered little with the operation of the source since the seals were located well out of the source, and symmetrically.

It should be noted that provision is made in this source for measuring accurately the pressure actually existing inside the source.

Vacuum system

In the early part of the work the small vacuum chamber (Fig.40) was used: in this case a Distillation Products Inc. Type GF 25A all-Pyrex diffusion pump, backed by a Welsh Duoseal #1405 pump provided the vacuum. The rated speed for air of this pump is 25 litres/sec. Octoil was used in the diffusion pump.

The GF 25A was later (large vacuum chamber, Fig. 11) replaced by a Distillation Products MF-250 pump for greater pumping speed. This pump is rated at 240 l/sec for air. The brass tube shown in Plate I (length $3\frac{1}{2}$'; i.d. 9.5 cm.; pumping speed 80 litres/sec) was inserted between this pump and the source so that the mechanical pump would be situated well out of the magnetic field. This tube reduces the total pumping speed to 60 l/sec (calculated).

Insertion of a three section optical baffle (cf. below) lowered the pumping speed further. With a $\frac{1}{4}$" extracting hole in the lower cathode of the source (pumping speed 3 l/sec) a 5:1 ratio of (source pressure)/(chamber pressure) was measured. In most of the runs a 1/8" hole was used. It may be inferred that the pressure ratio in this case was 20:1.

<u>leak-testing</u>

The following method of leak-testing was found to be effective: a glass tube was inserted between two sections of rubber tubing in the lead into the mechanical pump. A strip of tin foil was wrapped tightly round part of this tube. A few turns of #20 wire were wound over the foil. An electrodeless discharge could be set up by applying a spark-coil (commercial: "Tnergex") to the end of the wire. At pressures down to a few tens of microns a glow fills the glass tube. If acetone is now applied by means of a dropper to a point where a leak exists, the discharge will change towards blue in color, or be extinguished.

Pressure measurement

An air-pressure operated McLeod gauge was constructed. The volume of the large bulb is 67.10 cc. From it, a rather wide capillary leads into a bulb of 0.62 cc volume which provides a cushioning for the fine capillary (0.00052 cc/cm; 5.20 cm long) following it. On the fine scale, the length of capillary between the points corresponding to 1 and 10 microns was 1 5/8". This scale reads to 140 microns. Two further scales read to 0.14 mm and 2.3 mm respectively.

The leads to the McLeod gauge are shown in Plate II, top.

It will be observed (Fig.40) that the gas from the source has to pass through the narrow space between the anode and the Lavite insulators on its way to the McLeod, whereas the gas which enters from the Fowler leak can reach the McLeod without going through the source at all. It was feared that our pressure readings taken with this model might be on the high side, for this reason. However, the range of pressures for which the source runs well, was substantially the same as before, when measured in the later design (Fig.41) which allowed an accurate determination of the pressure inside the source. It is thus not considered likely that the earlier pressure readings were greatly in error.

Insulating layer due to the diffusion pump oil

Shortly after the MF-250 pump was first used (with Narcoil, supplied by National Research Corporation, Boston, Mass., U.S.A., the presence of a circular layer black in color, about $\frac{1}{2}$" in diameter, and several thousands of an inch thick was discovered on the floor of the chamber. This layer had been formed around the spot where the ion beam hits the collector but exceeded the beam in area. At the point where the beam actually hits the brass the layer was raised to a platform about 1/64" high and 1/16" in diameter. No electrical continuity could be established through the layer by means of a #13 copper wire probe pressed on it. This insulating property persisted to a high degree out to a radius of order 3/4" where the layer was so thin that it was no longer black in color.

It was thought that the layer might consist of Narcoil, which has not an extremely low vapor pressure, reduced by the ion beam. A two section baffle did not prevent formation of a new layer within a few hours of running.

At Professor Foster's suggestion a section of the brass tube about 1 foot long was then cooled with dry ice (Plate I). Also, another section was added to the baffle which remained inside the tube making good thermal contact with the dry-ice cooled wall. This combination of baffle and dry ice was found completely effective. Values of output current quoted in this thesis all date from after the dry-ice cooling was used, except for some early values obtained with the all-glass diffusion pump using octoil, where there was never any sign of an insulating layer.

The formation of films due to reduction of organic oils by ion beams is discussed in a paper by R.L.Stewart (50).

<u>gas supply</u>

An electrolyzer, mounted behind the McLeod gauge and not visible in Plate I was used to generate the gas for supplying the source. It had a storage bulb of volume 100 cc. Hydrogen and oxygen in the ratio 9:1 were collected over the dilute phosphoric acid used as the electrolyte and fed into the storage bulb until the pressure in the bulb was nearly atmospheric. A few feet of pressure tubing led from the storage bulb to the Fowler leak (l.c.) shown in Plate II. This leak has proved very satisfactory. One revolution corresponded to about 1 micron change in pressure at low pressures. It is thought that the leak gave reproducible values of the source pressure, but no attempt was made to check this carefully.

anode cooling

For cooling, the anode was surrounded by a tightly fitting thin-walled copper jacket fitted with a threaded collar for insertion of the cooling lead (length 2", cross-section 5/16" with two canals of i.d. 1/16" drilled through lengthwise) shown in place in Fig.40 and Plate III, top, h, i. The threads are such that the drill-holes in the lead coincide with the holes in the collar when the lead is screwed in tight. For vacuum-tightness the threads were heated and covered with a thin layer of Apiezon W before insertion. In later work soft solder was used instead of the Apiezon as leaks had developed occasionally which were very troublesome. Unidirectional flow of the cooling water around the jacket is ensured by a piece of copper wire soldered lengthwise into the copper jacket between the two holes in the base of the collar.

Water was used commonly for both the anode and the cathode cooling. For low output oscillograph photographs, oil was substituted in the anode to prevent display of a conduction current through the water. The oil is circulated by a small pump visible on the low platform of the "wagon" (Plate I).

circuits and electrical measurements

For high-power D.C. operation the power supply consisted of a 330 Volt motor generator capable of supplying several amperes in series with the 220 Volt D.C. mains.

For pulsing and low power D.C. the circuit used is shown in Fig.42. Power leads are indicated by heavy lines. A small aircraft generator capable of supplying 100 mA at 1000 V was used. The wide, heavy rectangle (Fig.42) indicates the series circuit for D.C. operation (switch down). The current through the (constant voltage) discharge was regulated by adjusting the 5600 ohms series resistor. From this resistor the current flows through the i_m meter into the anode. The cathodes are shown connected by a resistor R_c, as in asymmetric operation. In symmetric operation R_c is made zero. From the cathode of the source the return path leads through the 50 ohms current-viewing resistor back to the generator.

For pulsed operation a number of triode-connected 6L6 tubes in parallel are connected in series with the source (switch up). The pulse generator is a phantastron circuit, kindly designed for this work by Mr.J.S. Fraser of this Laboratory. It furnishes pulses 150 V in magnitude (Plate IV). The frequency range is 400-1850 cycles/sec. and the pulse lengths are continuously variable from 4-90 microseconds. The two controls are independent. Both fixed and cathode bias (shown) have been used at various times on the 6L6 tubes. With fixed bias the tubes may be biased beyond cutoff. Current will then flow through the circuit only while a pulse makes the tubes conduct. Alternately, the tubes may be biased so that a small continuous current flows on which the high current values during pulses are superposed. With cathode bias this is always the case.

If the source has not been in operation for some time it may have to be started on D.C., possibly with the induction coil (cf. p.45). The procedure in this case has been to turn on the generator, open S to put the high blocking inductance into the circuit, and apply the induction coil at the point marked A. The source will ignite instantly, as indicated by the voltmeter V dropping from 1200 Volts (generator voltage) to about 700 Volts (initial discharge voltage). S is now closed. The discharge voltage drops rapidly to the usual running value of about 300 V. Pulsed operation can then be started by putting the double pole switch in the "up" position.

The output current is received on the brass collector disc and flows to ground through a 300 ohm current-viewing resistor and a meter.

Errors due to secondary emission from the collector could be minimized by biasing the suppressor grid suitably. A negative voltage with respect to the collector of about 30 V is usually considered sufficient for this purpose (cf. Handbuch der Experimentalphysik, H1) and was found to be sufficient in this case. The effect of secondary electron emission on the output current was never more than 10%.

All cables wwre shielded, except the anode lead, since shielding it would introduce undesirable capacitance effects, the anode being far from ground.

It is noticed that the pulsing circuit is far from ground. This introduced no difficulty as shown by the steep rise of the discharge current pulse when observed on the C.R.O.

Circuits different from that described were also considered, in particular thyratron arrangements. The circuit described was chosen for this experimental work as it was thought that a hard tube pulsing arrangement would be easier to control and would allow of a greater degree of mismatch, than a thyratron circuit (cf. Glasoe and Lebacqz, G1).

In D.C. operation the currents were read on the meters i_T, i_L, i_c, the discharge voltage on V and the potential of the extracting cathode on the meter V_L.

All these meters were shunted by 1 microfarad condensers to read average values during pulsing.

A #241 DuMont C.R.O. was used to view the current and voltage traces. The current traces were viewed across 50 and 500 ohm non-inductive resistors and led to the C.R.O. through 30 feet of 50 ohm shielded cable. The discharge current cable was perfectly matched at the input end. It is easily shown that the 500 ohm resistor across which the output current was read introduces a mismatch leading to a retardation of the

C.R.O. rise which is quite negligible compared to the pulse lengths used ($>$ 20 microseconds).

The voltage trace was viewed through a cathode follower across the 15 K resistor forming part of the compensated attenuator shown in Fig.42. A 6AC7 tube was used. The amplification of the cathode follower was 0.85.

For calibration of the C.R.O. a 60 cy/sec sinusoidal voltage of known amplitude was measured or photographed for the same vertical gains setting as used for the trace examined.

Lavite insulators

After the readings of Fig.2 were taken, a typical bluish "bombardment deposit" was noticed on those parts of the cathode enclosure (enclosed source, Fig.40 - without Lavite insulators) on which ended electrostatic lines of force having a component along the lines of force of the magnetic field, but <u>not</u> on those parts where presumably they are perpendicular to the magnetic field. This seemed to point to the occurrence of parasitic discharges outside the source. It was thought that some of the troubles experienced due to instability of the discharge might be associated with these parasitic phenomena. An attempt was made to surround the anode with polystirene insulators in order to suppress the discharges outside the source, but this material could not stand up to the higher current densities in the source. At the suggestion of Prof. Foster, Lavite insulators of the shape shown (in place) in Fig.40 were next machined and baked.

These insulators stood up to the highest discharge intensities used and have been retained in one form or another throughout the remainder of this work. The insulators improved the stability of the discharge greatly but did not change the i_C vs. i_T characteristic.

(iv) Symmetric Operation

output current vs. discharge current - symmetric

The curves of the output current vs. the discharge current of Fig.2 are representative of a large number of similar ones for which data were obtained. These curves exhibit a striking similarity. At first an approximately linear rise occurs to a maximum value which may be as high as 6 mA or as low as 0.02 mA depending on the extraction potential, the magnetic field strength, and the pressure. No collector potentials more negative than -100 V were used in the curves shown in Fig.2. The maximum point referred to occurs at a discharge current value between 90 and 220 mA. From the maximum there is a steep drop to a much lower value of i_o, accompanied by a rise in pressure and a drop in voltage across the source. If i_T is increased further by decreasing the series resistance, i_o may increase again while the pressure in the source resumes its normal value and the voltage increases. In some cases there occurred oscillations between a high and a low voltage mode of operation (Fig.11)

The output current may actually become negative as shown in some of the curves of Fig.2 This occurred only when the collector was at the same potential as the cathodes ($V_c = 0$), and not when $V_c = -100$ (cf.Fig2) Only once was a negative output obtained in spite of the presence of a negative electrode below the source. This is shown in the curve of Fig.5. The ejector anode was used in this run, however, which makes interpretation rather difficult.

In general there was a definite trend for the value of the discharge current at which the maximum occurred to increase with increasing pressure and decreasing field strength (Fig.10).

In the high field ($V_c = 0$) the symmetric operation always gave very low outputs for the cylinder anode (cf. Fig.29). Even with grid voltages on the suppressor of -1000 V, the output current never exceeded 0.08 mA. With both the grid and the collector disc at -330 V an output of 1 mA (no secondary electron correction made) was obtained.

At high fields the ejector anode gave a reliable output of order 1 mA. The curve (top) of Fig.1 shows an output of 1.6 mA at "optimum" grid bias (-330 V) and $V_c = 0$ which is better by almost a factor of ten than any high field outputs obtained with the cylinder anode ($V_c = 0$).

At low fields on the other hand, the ejector anode is inferior to the cylinder type. No output higher than 0.09 mA was obtained from it at magnetic field strengths up to 2700 oersted and with the suppressor grid voltage as low as - 1000 V, the collector being always at zero voltage. The drop from the maximum is less steep for this type of anode (Fig.27).

Dependence of output on pressure

The curves of Fig.7 show that the output for the cylinder source does not vary greatly with the source pressure under normal running conditions.
The curve of Fig.6, taken in the 16,000 oersted field indicates a pronounced variation of output with pressure for the ejector type anode.

The bulk of this work was done at pressures between 2 and 10 microns since below 2 microns the proton percentage decreases rapidly (Lorrain, l.c.) and pressures > 10 microns are undesirable for most applications.

dependence of output on magnetic field strength

It was found in general that the output decreased as the magnetic field strength was increased. The falling curve of Fig. 29 shows this effect.

dependence of output on hole size

This was determined for a discharge in air. The comparison was made between a 5/32" and a 7/32" hole, both bevelled at 30 degrees in the usual manner. The ratio of areas is closely 1:2. Two sets of readings were taken for each hole size: one with $V_c = 0$, the other with $V_c = -81$ V. All readings were taken at the same pressure and magnetic field strength. An increase in output by a factor somewhat less than two resulted (Fig.8)

the discharge voltage

The discharge voltage in symmetric operation is between 280 and 310 V except under extreme conditions such as low pressure (< 1 micron) or high discharge current (> 250 mA), when it is higher. No regular variation with magnetic field strength could be established, (cylinder anode)

For the ejector anode the discharge voltage has generally been somewhat lower: between 250 and 280 Volts.

The discharge voltage depends on the state of the cathode surfaces. Thus, after the source had been exposed to the air it usually started running at a voltage sometimes as high as 1000 V. This high starting voltage would decrease within a few minutes, to the usual running value. Before the source is thus aged, a strong dependence of voltage on pressure, not otherwise observed, exists. A curve typical of several which have been recorded is shown in Fig.9 for a calcium and a magnesium source.

extracting voltage and focussing

The output depends very markedly on the magnitude of the negative potential employed for extraction, acceleration, or even suppression of secondary electrons (suppressor grid) below the source. Curves of Fig.4 are chosen to illustrate this. The curve of Fig.5 shows the variation with the suppressor grid bias of an output current which was negative for zero bias. Assuming that the negative output is due to a preponderance of electron emission from the source (cf.p.57) this curve may be accounted for as follows: as the grid is made a few Volts negative it starts inhibiting secondary electron emission, thus making i_c more negative (emission of secondary electrons from the collector corresponding to a positive current), but does not have sufficient effect on the source to increase the output of positive ions to the same extent. At more negative voltages, all secondary electrons from the collector and the slower electrons from the source are suppressed. The number of positive ions extracted from the source may start to increase significantly here. At about -200 V an equal number of electrons and protons reach the collector (zero output). At more negative grid voltages the positive ion output becomes predominant.

Curves similar to that of Fig.5 were also obtained for output currents positive at $V_g = 0$. The explanation here is similar.

Fig.1 shows the output current plotted against the discharge current for three sets of values of the grid potential:

1. $V_g = 0$

2. V_g = value giving minimum output) for a given value of i_T

3. V_g = value giving maximum output)

Burcham, and Ward (l.c.) have observed a similar dependence of output on extracting voltage. Ward states that there is an optimum extracting potential for any given value of discharge current. He explains this as a consequence of the aberration in the first lens present when the focussing field extends into the source, i.e. of the plasma being pushed back into the source. It follows that if maximum output is to be secured, any energy further than that due to the optimum extracting potential must come from succeeding lenses.

It is felt that there will be no great difficulty in focussing a beam of 1 mA and 1 mA/cm^2 which may be obtained from the cold cathode source. More experimental work is required to show whether the higher outputs obtainable can also be focussed without too elaborate means (cf. e.g. Smith et al., 54). The work of Burcham and Lorrain shows that beams of order 1 mA can be focussed if a few KV can be used. This is the case in all accelerators except the cyclotron (extraction along the magnetic field). In the cyclotron a well focussed beam is not essential.

(v) Asymmetric Operation

output current vs. discharge current

cylinder anode: representative curves are shown in Fig. 13 for the 16,000 oersted field and in Fig. 12 for a 2700 and a 5500 oersted field. In general, the high field curves exhibited an initial rise, followed by a flattening off at $i_o = 4$-5 mA for a discharge current somewhat over 100 mA. The low field curves rise almost linearly from $i_T \cong 50$ mA on, the output current exceeding 3 mA at $i_t \cong 130$ mA, $p = 6$ microns.

ejector anode: satisfactory output currents were obtained with this anode in low fields (Fig. 17). In the high field no output greater than 0.5 mA was obtained, and this at a pressure of 11 microns (Fig. 19). This type of anode has on occasion given i_o vs. i_T curves of negative slope (Fig.17).

No high discharge current runs (>150 mA) were made using the asymmetric mode of operation. It is thus not known whether a drop-off comparable to that in symmetric running, occurs here.

dependence of output current on magnetic field strength

Fig.29 shows a plot of output current vs. magnetic field strength (rising curve). It is seen that the output rises considerably, up to about 5000 oersted. The point at 16,000 oersted is also made part of this curve although it is not known whether any points of inflexion occur between the values 5000 and 16,000 oersted.

As this curve contains points obtained on different occasions, and as some interpolation was necessary in order to obtain four points for it, this curve cannot be considered final. In fact, on switching off the magnet after the run shown in Fig.35 (asymmetric) the following readings were obtained:

H (oersted)	i_o (mA)
2700	6.6
2300	8.0
1250	9.5
1000	12.5
< 1000 *	13.5

(cylinder anode, $\frac{1}{4}$" hole, asymmetric, $p = 9$ microns, $V_g = V_c$)

These readings indicate that as the field was decreased from 16,000 oersted, the output current decreased to a minimum value and then rose again to a high value.

dependence of output current on pressure

Figs. 14,20 show the variation of the output current with the source pressure for the cylindrical Mg source under various conditions of asymmetric running. The output increases with increasing pressure with some indication of a flattening off. Fig.19 shows three sets of two points each which were obtained with the ejector source in the 16,000 field under identical conditions, except pressure.

No asymmetric runs were made at a pressure lower than 5 microns, with the exception of one run at 3.3 microns which gave a constant output of -0.05 mA for a discharge current up to 80 mA. Some results obtained at a pressure of 5 microns are shown in Fig. 12.

discharge voltages in asymmetric running

Table II illustrates the great variety of values of

---

*value not known

V, V_L, and $(V-V_L)$ obtained under various running conditions.

Table II

Source type	Field (oersted)	Pressure (microns)	discharge current (mA)	V (Volts)	V_L (Volts)	$V-V_L$ (Volts)
cyl. anode, magnesium, 1/8" hole	16,000	11.0	47	650	400	250
	16,000	2.5	48	980	315	565
	2700	4.5	55	640	455	185
	2700	7.6	82	1080	860	220
	410	7.9	69	858	735	120
	410	7.9	77	1220	920	300
ejector, magnes. 1/8" hole	2700	9.8	54	980	920	60
	2700	9.8	98	510	435	75
	16,000	10.5	85	420	360	60
	16,000	3.3	68	840	660	180
cyl. anode, calcium, 3/16"	16,000	8.9	37	840	460	380
	16,000	8.9	100	840	485	365

The following trends were observed:

1. An increase in i_T from $\cong 30$ to $\cong 150$ mA is accompanied by increases in V, V_L at such relative rates that $V-V_L$ increases by up to 50% of its value at 30 mA. Occasionally $V-V_L$ decreased (Figs.21,22).

2. An increase in pressure by a factor of 2 to 5 is accompanied by a decrease in V and an increase in V_L, $V-V_L$ decreasing by up to 60% (Figs.23, 24, 25).

3. An increase in magnetic field strength by 5 times is accompanied by a decrease in V, V_L such that $V-V_L$ may increase to twice its original value (Fig.26).

4. Neither V nor V_L is dependent on V_g. For this reason values of V_g are not given in the above Table.

dependence of output on extracting voltage

The curves of Fig.18 are representative. It should be noted that in all cases recorded in this Figure, the collector was at zero ($V_c = 0$), i.e. at a negative potential with respect to the lower cathode ($V_L > 0$). In Fig.33 curves are given for which the collector was at the same potential as the extracting cathode ($V_c = V_L$). To eliminate the possibility of a discharge occurring between the collector and the floor of the square chamber the latter was also kept at the potential V_L in this run. The fact that under these circumstances a large negative output was obtained illustrates the necessity for a negative extracting potential if a positive output is to be obtained in asymmetric operation. An interpretation of these and other observations concerning asymmetric operation cannot at present be given to any degree of completeness. Some suggestions and cautions are, however, given in the following paragraph.

a note on asymmetric operation

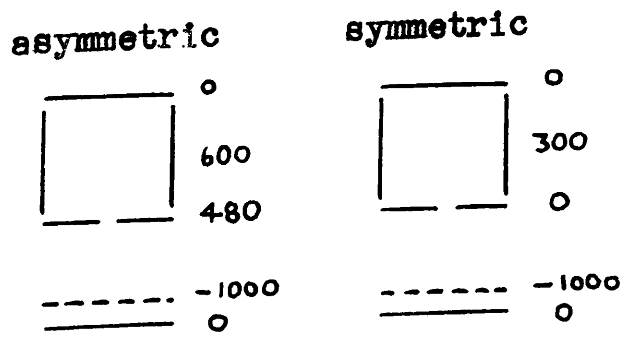
As has been pointed out (p.29) it appears likely that in this type of operation the oscillating electron beam reaches out of the source and towards the grid and collector. In fact the grid, if it is negative with respect to the collector, acts not only as a suppressor of secondary electrons but also as an accelerator or extractor, of ions. In the above, the potential on the grid has for this reason occasionally been referred to as an "extraction potential". The action of the grid as an accelerator of ions appears in many cases to outweigh its action in suppressing secondary electrons as far as output current is concerned.

If the assumption of electrons and ions emerging from the source simultaneously at the higher discharge currents is valid, a somewhat similar action must take place in symmetric operation.

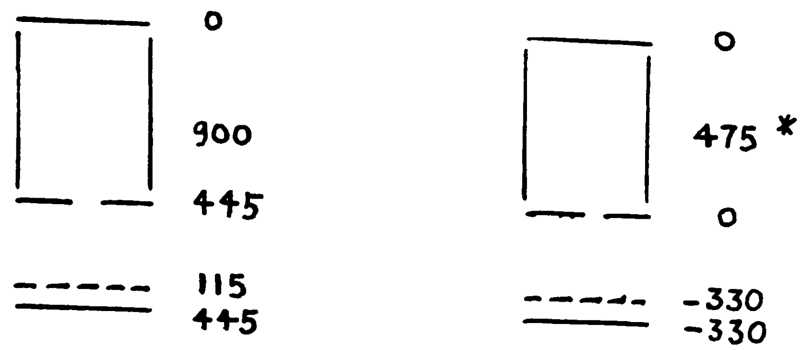
Further experimental work will be needed to determine how much of the output currents quoted for asymmetric operation can be made available in the form of a beam to the first electrode of an accelerator. In the meantime only the output currents obtained as part of the initial rising portion of the symmetric runs can be considered as, very probably, focussable to a large extent.

The interesting possibility of using this extension of the discharge into the low pressure region outside the source, in the cyclotron has been mentioned above.

Caution is necessary in making comparisons of the relative merits of the asymmetric and symmetric modes of operation. It has been pointed out that in the asymmetric runs the collector disc is usually at a fairly high negative potential with respect to the extracting cathode whereas in the symmetric runs these two electrodes are usually at the same potential. Typical values are shown in the following sketch:



To test the effect of the collector disc on the output the source was run asymetrically with $V_c = V_L$ and $(V_g - V_L) = -330$ V and for comparison, symmetrically with $V_c = V_g = -330$ V:



This represents, in the first case, an asymmetric run without "acceleration" due to the collector and in the second a symmetric run with acceleration due to the collector (but without any safeguards against secondary emission). The results (Figs.30,31) show that the collector potential has a vital bearing on the output current. For, the symmetric run with collector acceleration gave a positive output higher than any ever obtained in the high field and the asymmetric run without acceleration gave a negative output of a magnitude never previously obtained in the high field. The error due to secondary electron emission in the symmetric case is probably small.

It may be inferred from Fig. 30, however, that if a moderate negative potential -equal for the two cases- is provided, the asymmetric mode is superior, at least in the high field.

---

* 475 Volts is an exceptionally high value for the discharge voltage in symmetric running (cf. above); it is possible that an error was made in reading or recording this value. If the reading is correct the high output current obtained may have to be attributed wholly, or in part, to the high discharge voltage; for, it was observed in general that the output was increased by a large factor, when the discharge ran at an abnormally high voltage (e.g. before being "aged"); Lorrain (l.c.) describes a similar observation.

(vi) Pulsed Operation

The source was run under pulsed operation for many weeks and always performed satisfactorily. When "run in" it could be started up on pulsed operation; it could be left to run on pulsed operation for hours without interference from the operator. During this time the C.R.O. traces would not change or drift. This applies to all pulse lengths ($>$20 microseconds) used and frequencies from 400 to 1850 cycles/sec. Plate IV shows typical traces obtained with the cathode bias circuit shown in Fig.42. Fig.39 shows sketches of pulse shapes obtained with a fixed bias arrangement and asymmetric operation. Each horizontal set of traces corresponds to one setting of the fixed bias; successive sets are the result of decreasing the bias (i.e. increasing the pulsed discharge current). At the lower bias values the tubes passed a continuous current on which the pulsed values were superposed.

The initial exponential rise on the voltage trace and the accompanying steep rise and exponential drop of the discharge current trace (e.g. first line of Fig.39) are interpreted as being due to charging up the capacity of the circuit (capacity of source and leads at 1000 cy/sec was 600$\mu\mu$f). These portions of the pulse remained if the pressure was lowered so that the source would not ignite. The fact that these portions of the pulse shapes shorten with increasing discharge current may possibly be attributed to a corresponding increase in the deionization time of the source. It is known that in thyratrons the deionization time is longer the higher the current carried. Thus the source would strike at a lower voltage if more ions and electrons are left from the previous pulse. No explanation can be suggested for the change in shape of the voltage pulse in going from line 1 to line 3. This may be a connected phenomenon but seems rather to suggest that the true explanation is different from that just given. An intermediate stage of the voltage shape is shown in line 2 where both modes co-exist. It is noteworthy that the change in shape of the voltage trace is accompanied by the output current going from positive to negative.

Curves of output current vs. discharge current in pulsed operation are shown in Figs.36-8. In each case the average-meter readings are plotted. The equivalent peak values assuming square pulses, calculated from the average values and a knowledge of the duty cycle, are given on a parallel axis. The average meter readings were corrected for the presence of a continuous current in the following manner: (1) fixed bias: the phantastron was switched off after each "pulsed" reading and the D.C. value remaining (if any) subtracted; (2) cathode bias: the biasing voltage was recorded for each reading. After conclusion of a pulsed run, a run was made with the phantastron switched off. Again the biasing voltages were recorded. In this manner a curve of D.C. output and discharge current vs. bias was obtained and D.C. values could be subtracted from the (pulsed plus D.C.) values.

Under pulsing, the various combinations of anodes and modes of operation give instantaneous outputs equal to those they would be expected to give under D.C. operation for the corresponding value of the discharge current. The drop-off is also observed in pulsed operation. As in D.C. operation, the ejector anode in a low field performs poorly under symmetric operation (Fig.36) but gives a high output in asymmetric operation (Fig.38). Again, the output increases considerably when V_g is made negative (Fig.37)

The output values calculated on the assumption of a square pulse are gratifyingly high for the ejector anode and asymmetric operation: 90 mA were obtained in the high field for a discharge current pulse of 500 mA. Similarly, in a 2700 oersted field, 60 mA pulsed output were obtained.

Assuming 1 part in 10,000 of the 90 mA pulse could be extracted and accelerated in a synchro-cyclotron, a target current of 9 microamperes would be obtained. With no comparison intended, as no data are known to the author concerning the extraction efficiency of synchro-cyclotrons, it may be stated that target currents of only a fraction of a microampere are obtained at present on the large Berkeley cyclotron.

(G) THE "DROP-OFF" PHENOMENON

In an interpretation of the form of the curves of Fig. 2 and the large number of similar curves obtained but not shown, the following facts must be accounted for:

1. At the zero output point (i.e. where the curve crosses the axis after reaching the maximum) the beam emerging from the source was observed to be sometimes very intense (corresponding in brightness to a positive ion beam of several mA)

2. A considerably smaller drop was obtained when there was present, below the source, an electrode such as the suppressor grid at a negative potential with respect to the extracting cathode.

3. The value of the discharge current at which the drop occurs increases with decreasing magnetic field strength and with increasing pressure (Fig.10),

4. The discharge voltage decreases steeply while the output current drops.

Observation 1. shows that the source must be emitting positive ions and electrons simultaneously. Secondary electrons travelling into the source from the collector cannot be responsible for the beam since both positive ions reaching the collector, and secondary electrons leaving it, are positive currents and thus cannot add up to zero meter reading. An explanation in terms of equal numbers of electrons from the source and photoelectrons from the collector is hardly plausible in view of the great brightness of the beam observed.

Observation 4. shows that the drop is probably not due to a change from the normal to the abnormal discharge since, when a glow discharge changes from normal to abnormal, the discharge voltage rises.

Observation 2 finally, indicates that the electrons in the beam must be at least in part, slow enough to be turned back by a moderate decelerating potential.

The following considerations lead to a simplified picture of the processes in the extracting half of the source:

1. The electric lines of force may be considered as being axial since the presence of the axial magnetic field inhibits sideways motion of electrons and ions.

2. A virtual anode may be thought of as existing at the centre of the source since electrons and protons are acted upon by forces toward and away from the centre respectively.

3. The combined effect of the magnetic field and the presence of electron oscillations is an effective lengthening of the path of electrons in the discharge. Thus enough ions can be produced per electron to maintain what is effectively a glow discharge at a pressure of only a few microns.

Thus, from the point of view of extraction, the discharge may be thought of as taking place between the cathode and an anode in presence of an electric field perpendicular to both.

The magnetic field may be taken into account by allowing for a bunching action on the ion beam and the plasma, toward the axis of the discharge.

The above argument must be considered tentative until checked by quantitative work. Reference should be made to a paper by Compton, Turner, and McCurdy (C1) in which the importance for a theory of the glow discharge of diffusion of electrons and ions due to a partial pressure gradient is pointed out. This diffusion may take place against an opposing electrid field. It is hoped that it may be possible to substantiate, in terms of such a diffusion process, the assumption of ions and electrons simultaneously emerging from the source, as well as account for the variation in their relative numbers with discharge current, magnetic field strength, and pressure.

(H) THE QUESTION OF ATOMIC ION PERCENTAGE

A careful investigation of the proton percentage of an all magnesium source of the type used in this work (cylindrical anode; symmetric operation) has been made by Lorrain (l.c.). He finds that the proton percentage can be raised by feeding the source with a 9:1 mixture of hydrogen and oxygen. Under optimum conditions ($p = 2$ microns, $H = 2000$ oersted, $i_A = 90$ mA) proton percentages up to 50 could be obtained. In a field of 700 oersted and for a discharge current of 30 mA the proton percentage had its maximum value at a pressure of 2 microns and was decreased to about 3/4 of the maximum value by raising the pressure to 6 microns. The variation with the discharge current consists of an initial rise, with a complete flattening off at 90 mA. A linear increase of the proton percentage with the logarithm of the magnetic field strength was also observed ($p = 2$ microns, $i_A = 30$ mA). No fields higher than 2300 oersted were available. Up to this field strength, there was no evidence of any flattening off.

No mass analyses were made of the output from the sources used in the present work. The beam was generally pinkish blue in color and showed a strong H_α and H_β and a weak H_γ line when viewed through a 1 mm slit cut into a sheet of black paper and pasted over the window, and a large prism.

In pulsed operation the beam color changed to a medium red; the spectrum did not appear to be appreciably changed.

The Calcium source gave a spectrum which did not appear to be different, when viewed in the above manner, from that of the magnesium source.

No consistent data were recorded of the appearance of the spectrum for the various source geometries employed.

It would be interesting to follow up Lorrain's (l.c.) investigations to the high field strengths available in a cyclotron magnet. These high fields themselves would, even with longitudinal extraction, provide the means of obtaining a mass spectrum, if a magnetron principle is employed.

A plane or cylindrical magnetron may be used. In the plane magnetron (Hemwell, p. 283-4, H2) an electric field is maintained between two parallel plates perpendicular to the magnetic field. The path of an ion in such a configuration of fields is cycloydal if the initial velocity components perpendicular to the magnetic field are zero. The ion returns to a point in the plane parallel to that of the plates and passing through its point of origin, at a distance from its point of origin depending on the mass. In its course, a molecular ion of hydrogen goes a maximum distance perpendicular to the plane of the plates, equal to twice that traversed in this direction by an atomic ion. For a field of 10 KV/cm these distances are 0.72 and 1.44 cm respectively. The distances traversed in the direction perpendicular to this, i.e. in a plane parallel to that of the plates are larger, viz. 2.24 and 4.48 cm. respectively. For an electric field of 5 KV/cm these values are reduced by a factor of two.

The distence travelled along the magnetic lines of force, i.e. vertically in the cyclotron magnet, while traversing the full cycloidal path of 4.40 cm is $2.74 \times \frac{V}{100}$ cm for the molecular ion, where V is the voltage with which it emerges vertically from the source.

Thus if one plate of an arrangement such as that suggested is mounted near the extracting hole of the source, and the other at a distance away such as to give a suitable voltage gradient, the analysis may be performed in two ways: either by moving the far plate towards the near plate until successively, first the molecular and then the atomic ions are intercepted; or, by keeping the plates a fixed, suitable distance apart and intercepting the ions near the end of one cycloidal path by means of a probe maintained at an appropriate potential such that the field distribution at the point of collection is not disturbed by the presence of the probe.

In the cylindrical magnetron the paths traversed for a given available voltage are somewhat longer. While this would tend to increase the accuracy of the analyses two difficulties arise. First, a radial electrostatic field would have to be obtained by some means such as surrounding the beam by an axial cylinder from which a small section is cut out in the form of a low cylindrical window, and which is maintained at the positive voltage. Second, the vertical distances traversed by ions of the same V (cf. above) are greater in this case than in the case of the plane magnetron. Since the distance available between the poles of the magnet is only $7\frac{1}{2}$" and the source would have to be at least 1" in height, this might lead to a loss of the faster ions unless some decelerating electrode is added.

(I) CONCLUSION

The conventional cold cathode ion source is capable of yielding reliably an output of over 2 mA of ions in low fields. Modified forms of this source yield steady output currents of several mA in both low and high fields, and pulsed currents of equivalent square pulse height 50 - 100 mA.

Either the conventional or the modified form is suitable for installation in the Ottawa H.T. set or a Van de Graaff accelerator in which high ion output is desired. The modified form is suitable as an ion source for synchro-cyclotrons.

Some remarks concerning the curves following:

Due to the large number of variables involved in the work on the cold cathode source it has, unfortunately, not been possible to obtain an equally satisfactory number of points for each curve. In a few cases, only two points are available for comparison. Where the discussion necessitated their inclusion, they are shown connected by a dotted line.

For some curves the points obtained were so numerous that the shape of the curves is well established. In such cases, and in cases of curves obtained by calculation, no points are shown.

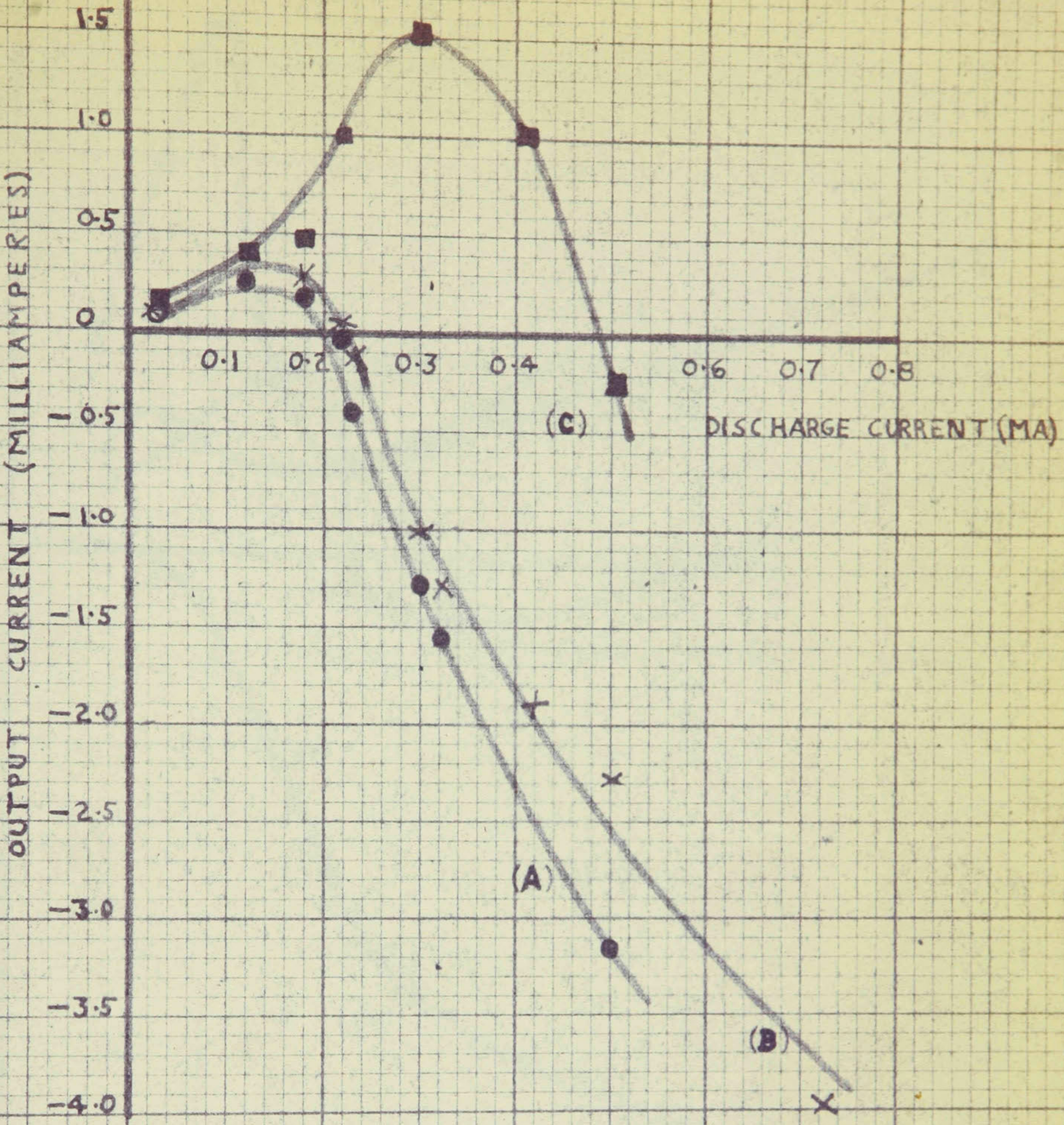


FIG. 1

OUTPUT CURRENT vs DISCHARGE CURRENT

for various suppressor grid voltages - symmetric, ejector anode, 1/8" hole, $H = 16,000$ oersted, $p = 6$ microns, $V_c = 0$

A: V_g = value giving minimum i_o for given value of i_T

B: $V_g = 0$

C: V_g = value ($\geq$ -260 V) giving maximum i_o for given value of i_T. Unless otherwise indicated, V_g = -260 V, the upper limit of the power pack

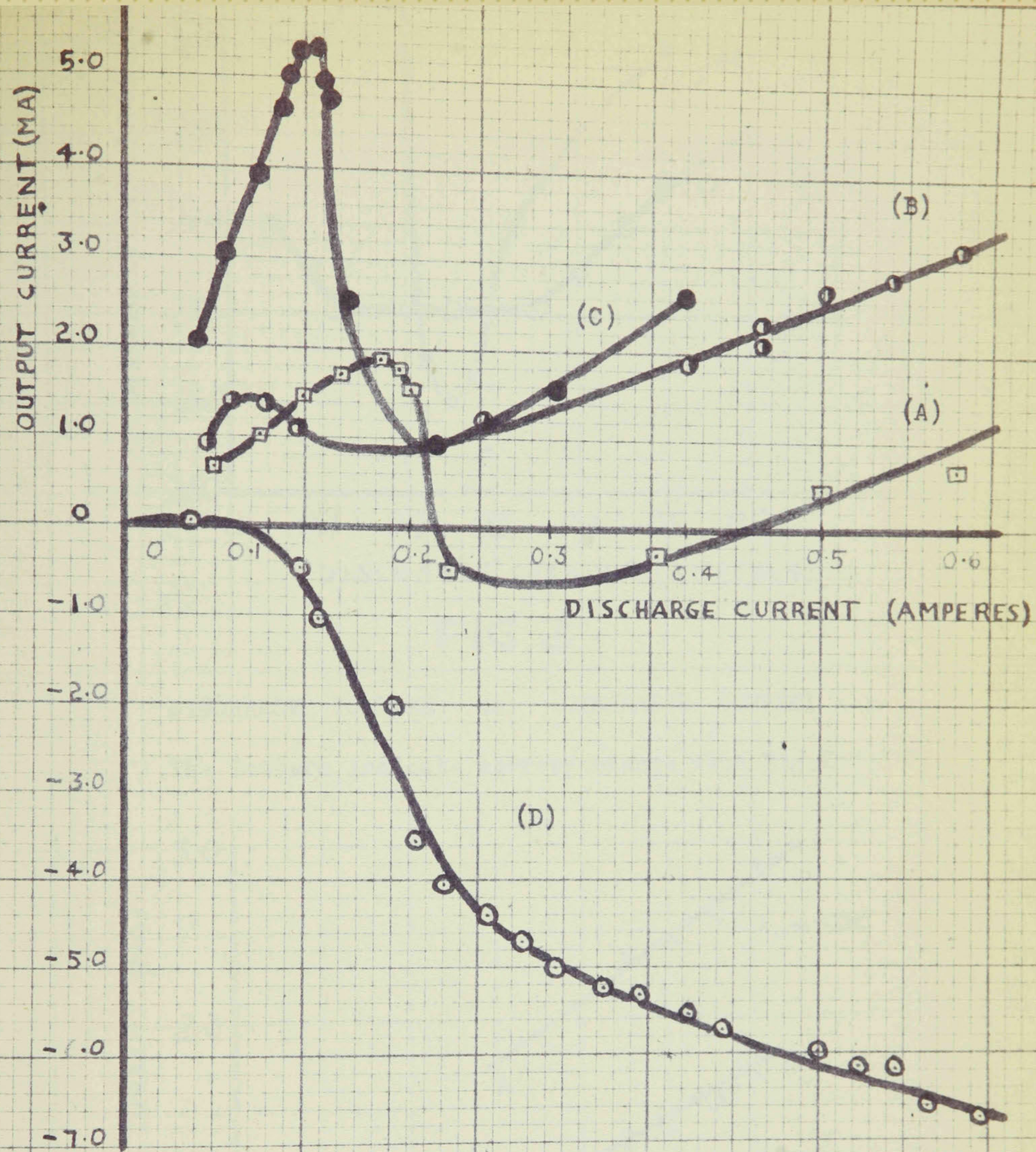


FIG. 2

VARIATION OF i_o vs. i_T TO HIGH DISCHARGE CURRENTS

cylinder anode, symmetric

	A	B	C	D
H (oersted)	400	1870	1870	16,000
p (microns)	3.5	4.4	3.0	4.2
V_c (Volts)	0	-100	-100	0
hole size	1/8"	5/32"	5/32"	1/8"

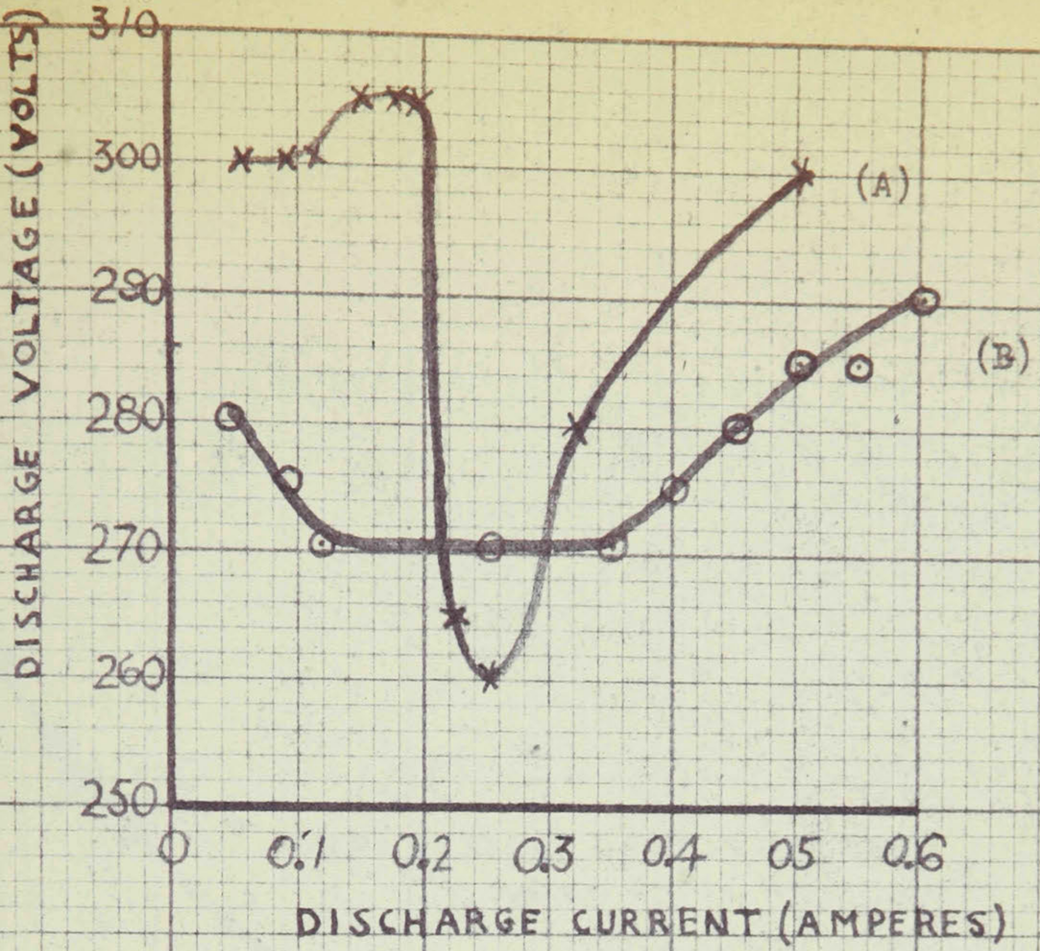


FIG.3

DISCHARGE VOLTAGE vs. DISCHARGE CURRENT

The letters indicate correspondence with Fig.2.

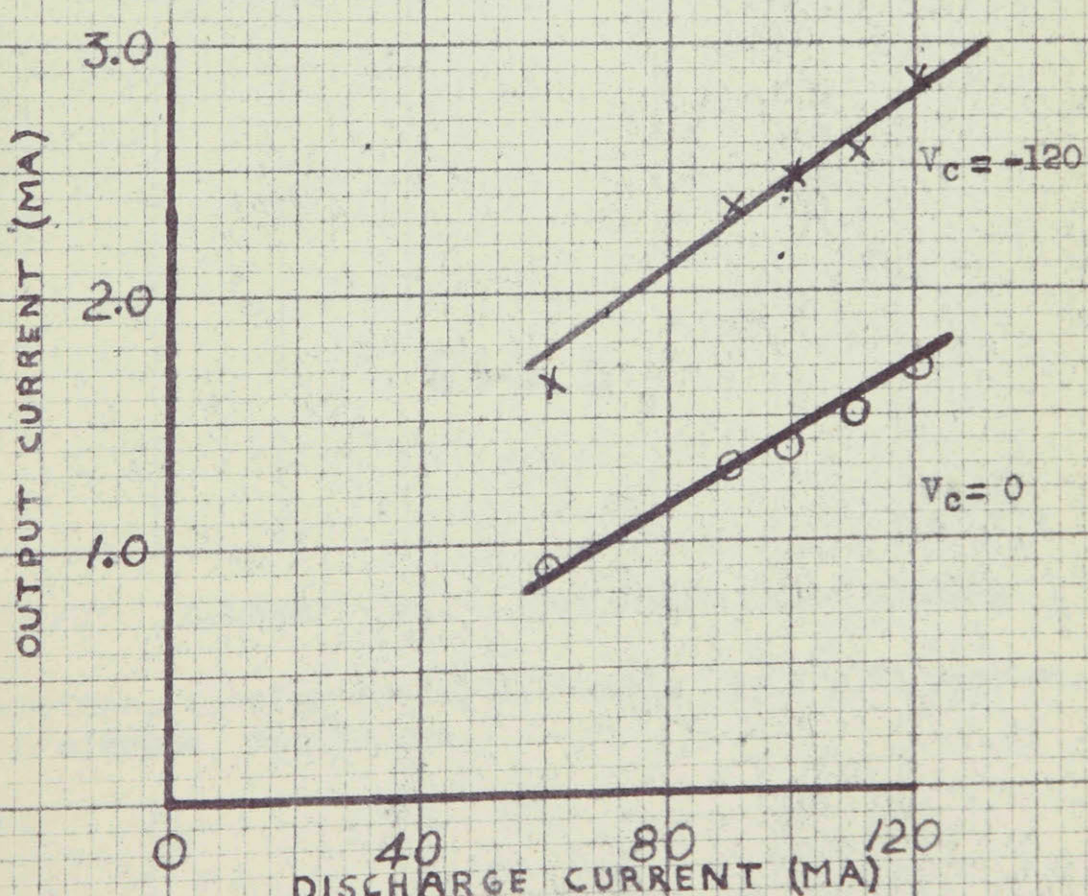


FIG.4

OUTPUT vs. DISCHARGE CURRENT

for two collector voltages -
symmetric, cylindrical anode,
5/32" hole, H = 1870, p = 1.2 microns

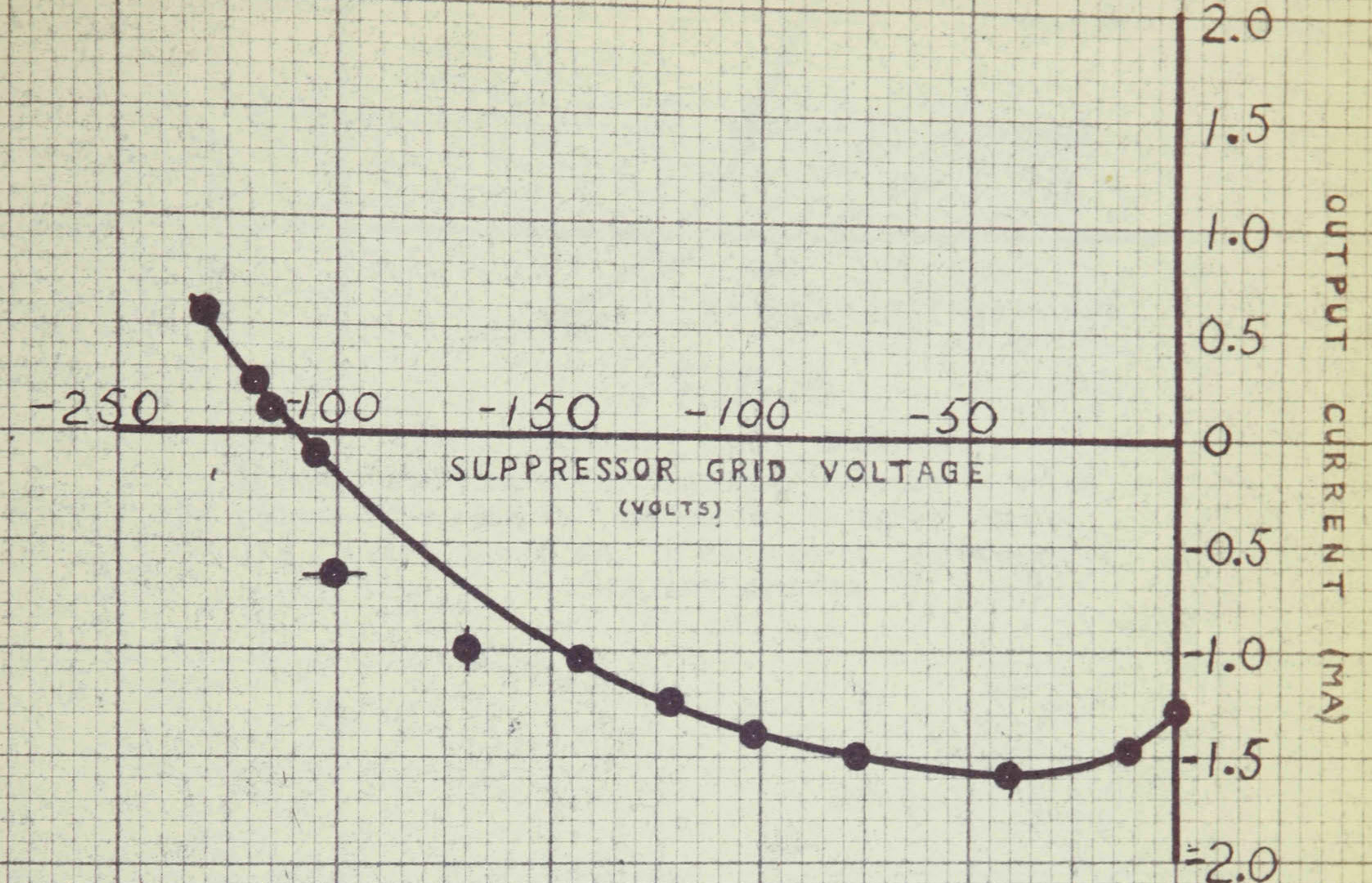


FIG.5

OUTPUT CURRENT vs. SUPPRESSOR GRID VOLTAGE -

symmetric, ejector anode, 1/8" hole, H = 17,000 oersted, p = 6 microns, i_T = 320 mA

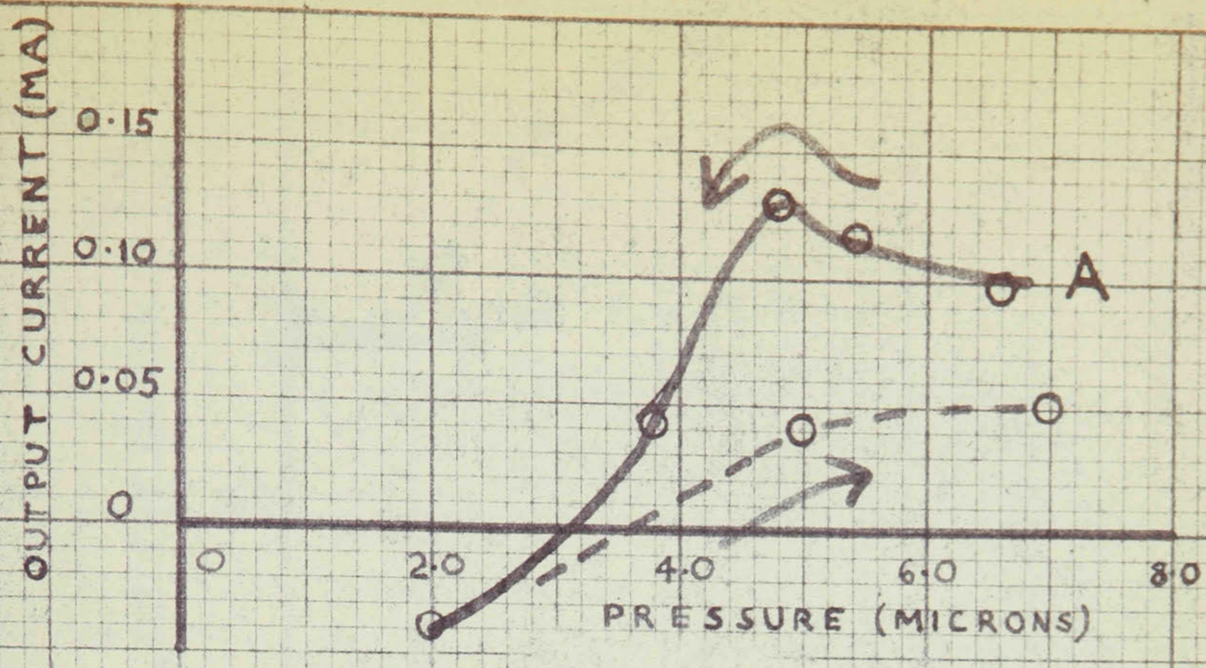


FIG. 6

OUTPUT CURRENT vs. PRESSURE
Arrows, starting at A, indicate sequence in which points were read - symmetric, ejector anode, 1/8 " hole, i_T = 85 mA, in absence of suppressor.
H = 16000 OERSTED

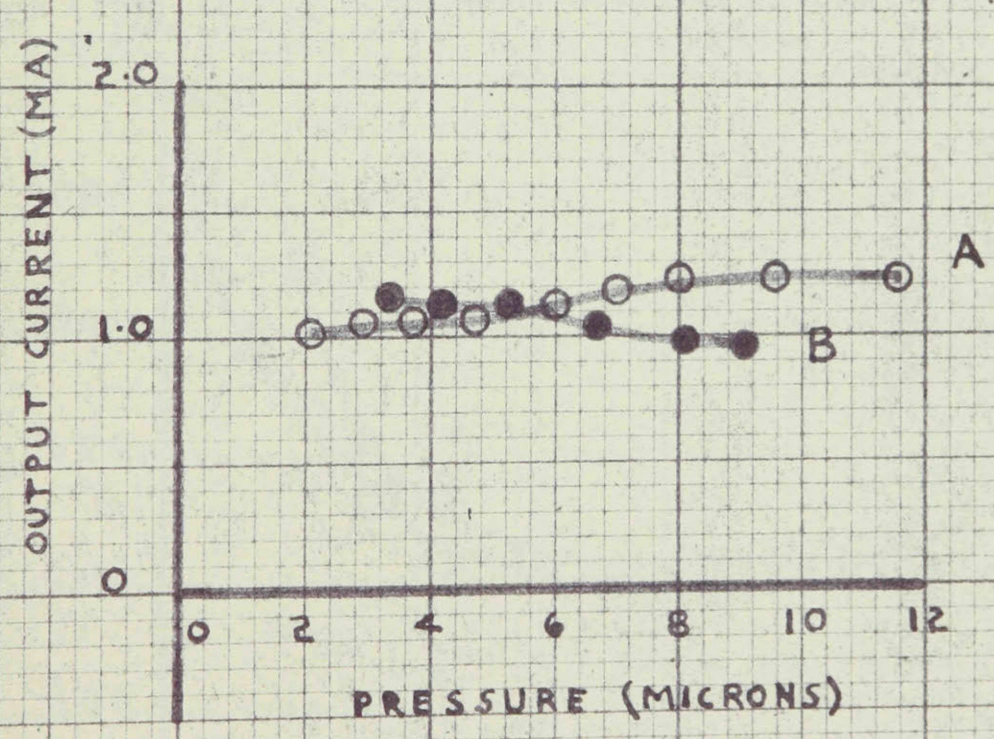


FIG. 7

OUTPUT CURRENT vs. PRESSURE

symmetric, cylinder anode, 5/32" hole,
H = 1900 oersteds, i_T = 60 mA
A: $V_c = 0$ B: $V_c = -120V$

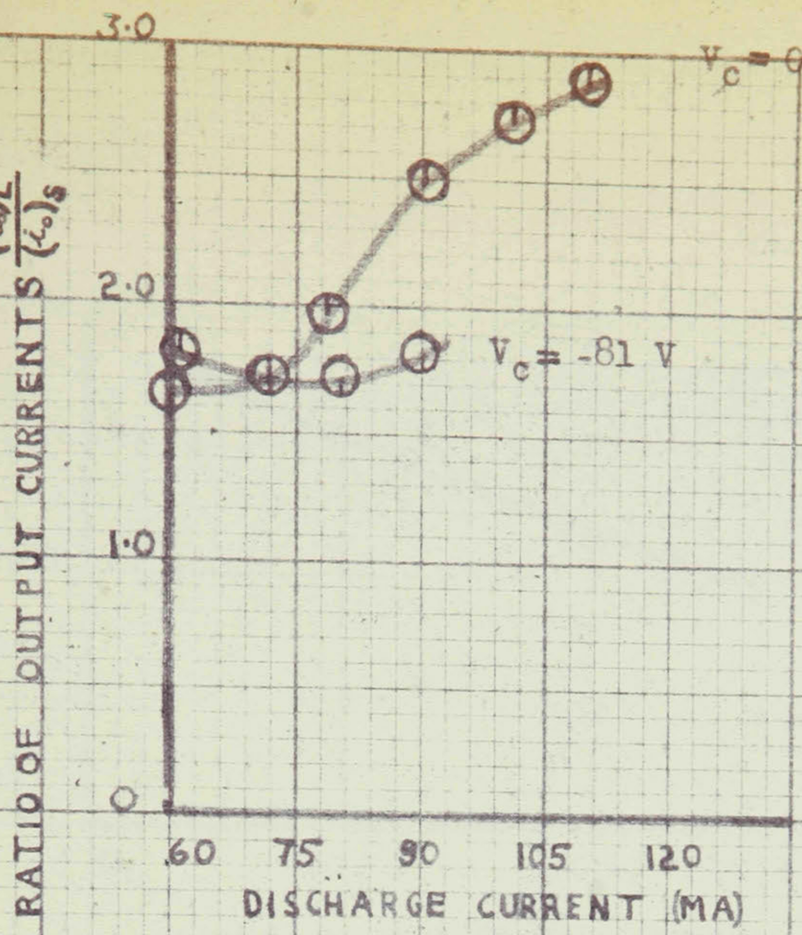


FIG.8

EFFECT OF HOLE SIZE (AIR)

cylinder anode, symmetric, H = 1700 oersted, $(i_0)_1$, $(i_0)_s$ represent output currents for the 7/32" and 5/32" hole respectively

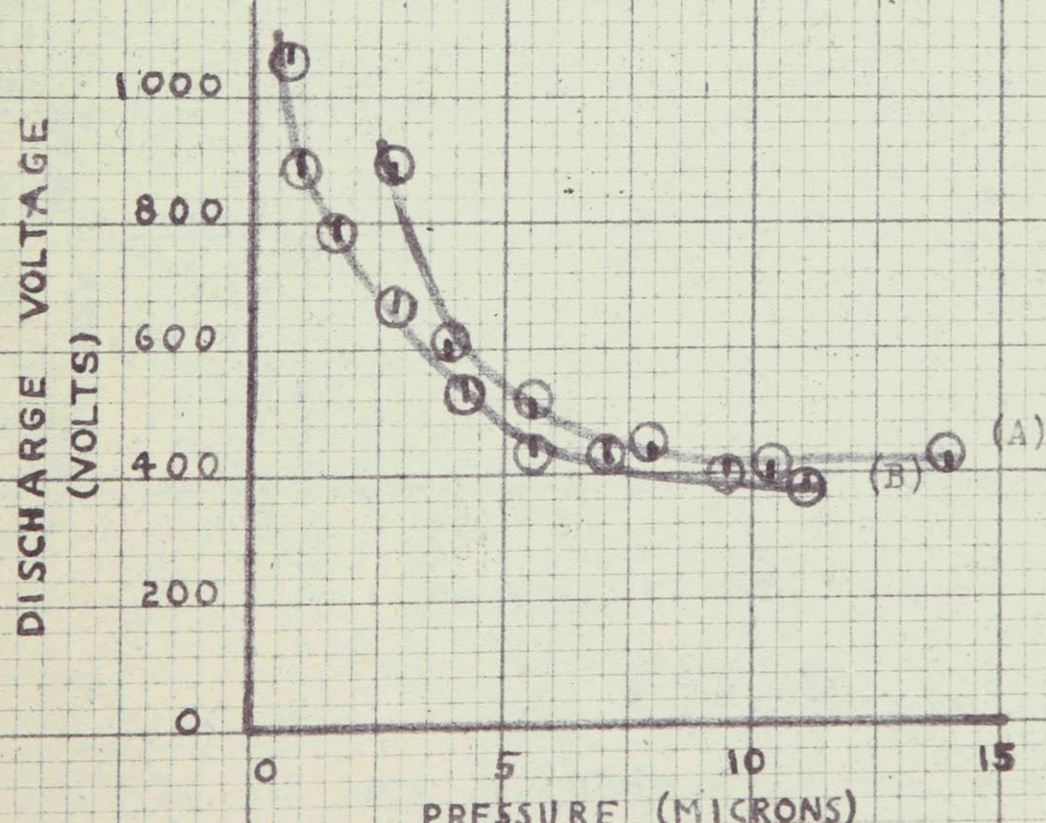


FIG.9

DISCHARGE VOLTAGE vs. PRESSURE of non-aged sources: symmetric, cylinder anode, A: Calcium source, 3/16" hole; B: Magnesium source, 1/8" hole, H = 16,000

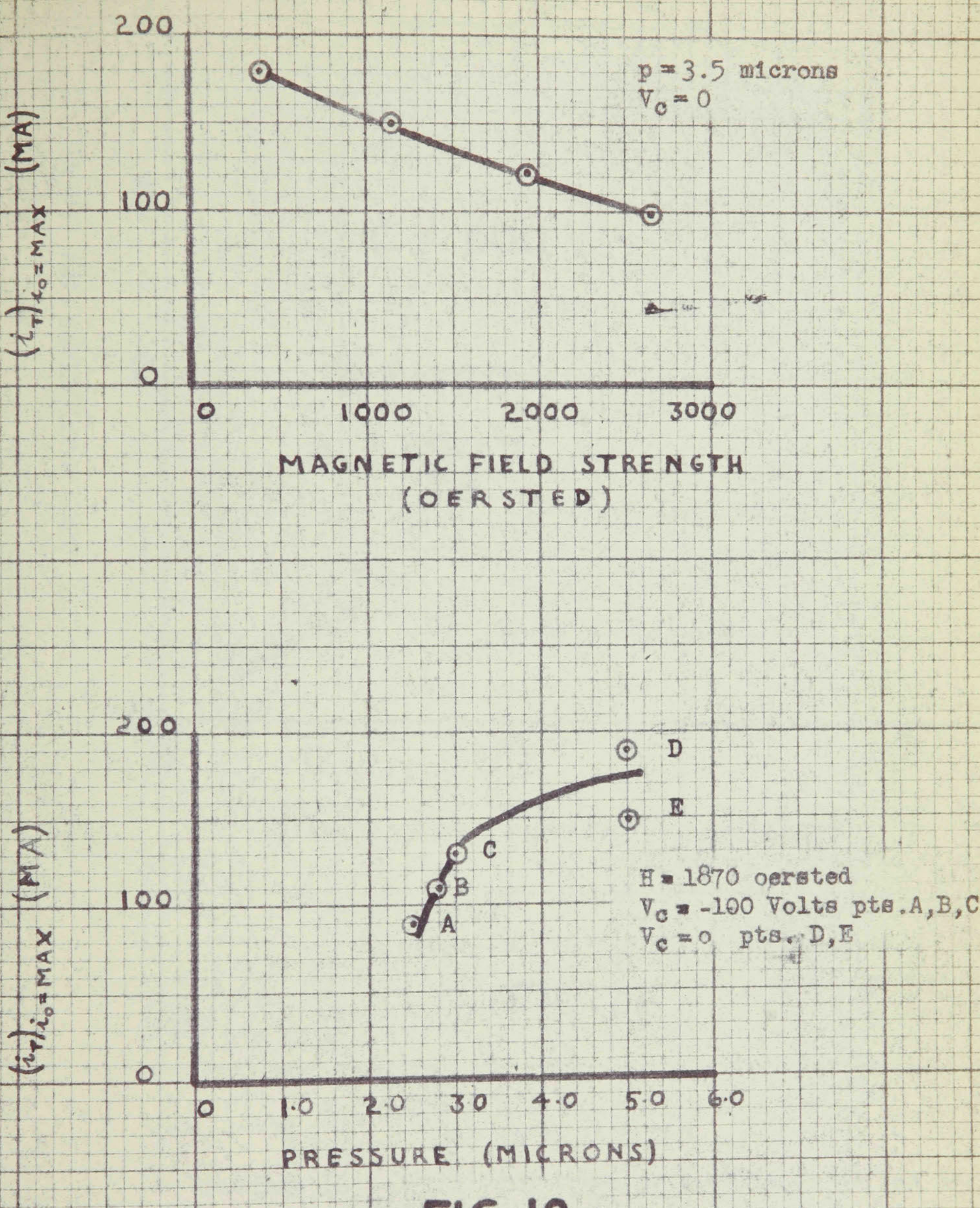


FIG. 10

POINT OF MAXIMUM OUTPUT vs. H and P

cylinder anode, symmetric

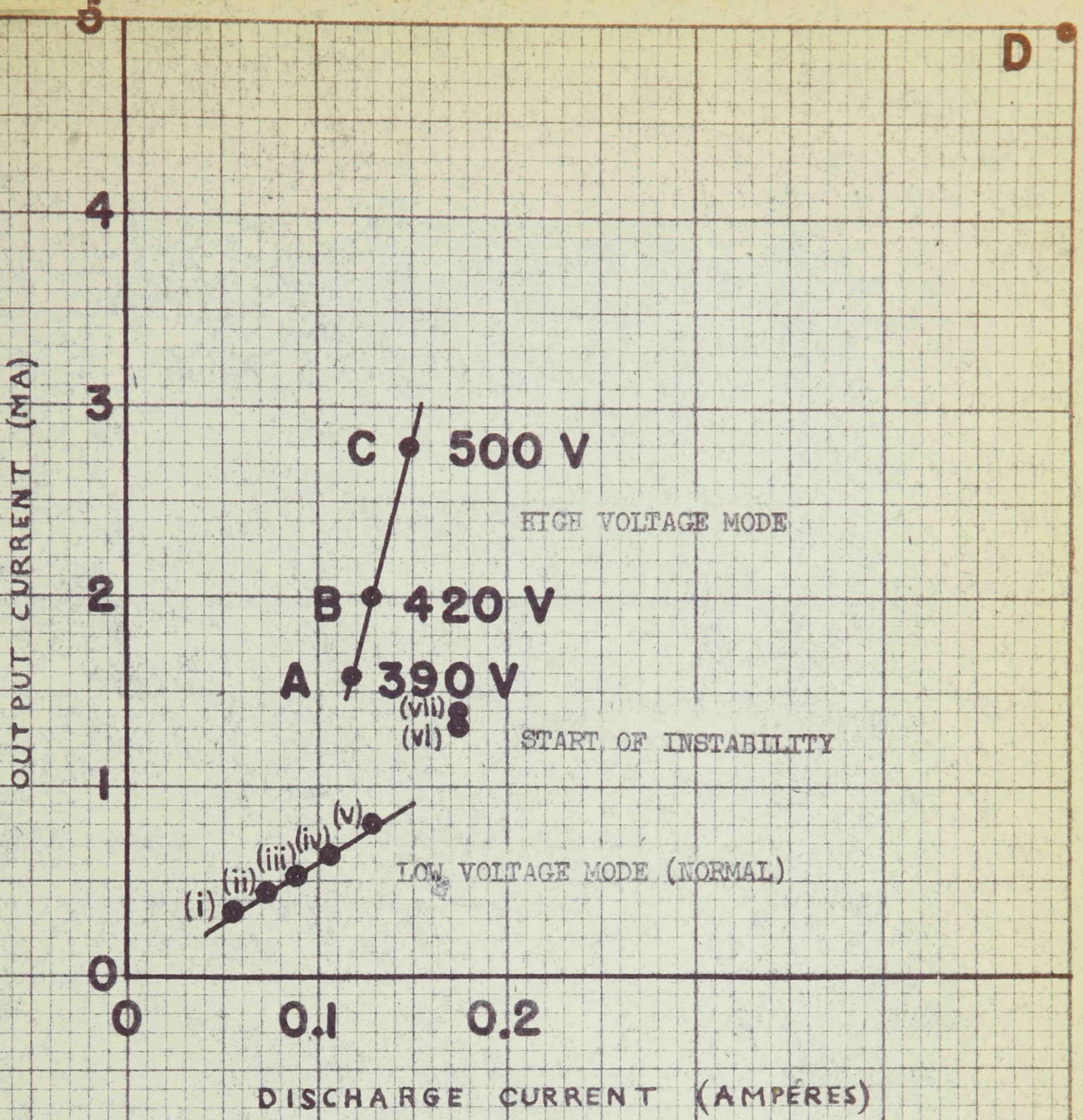
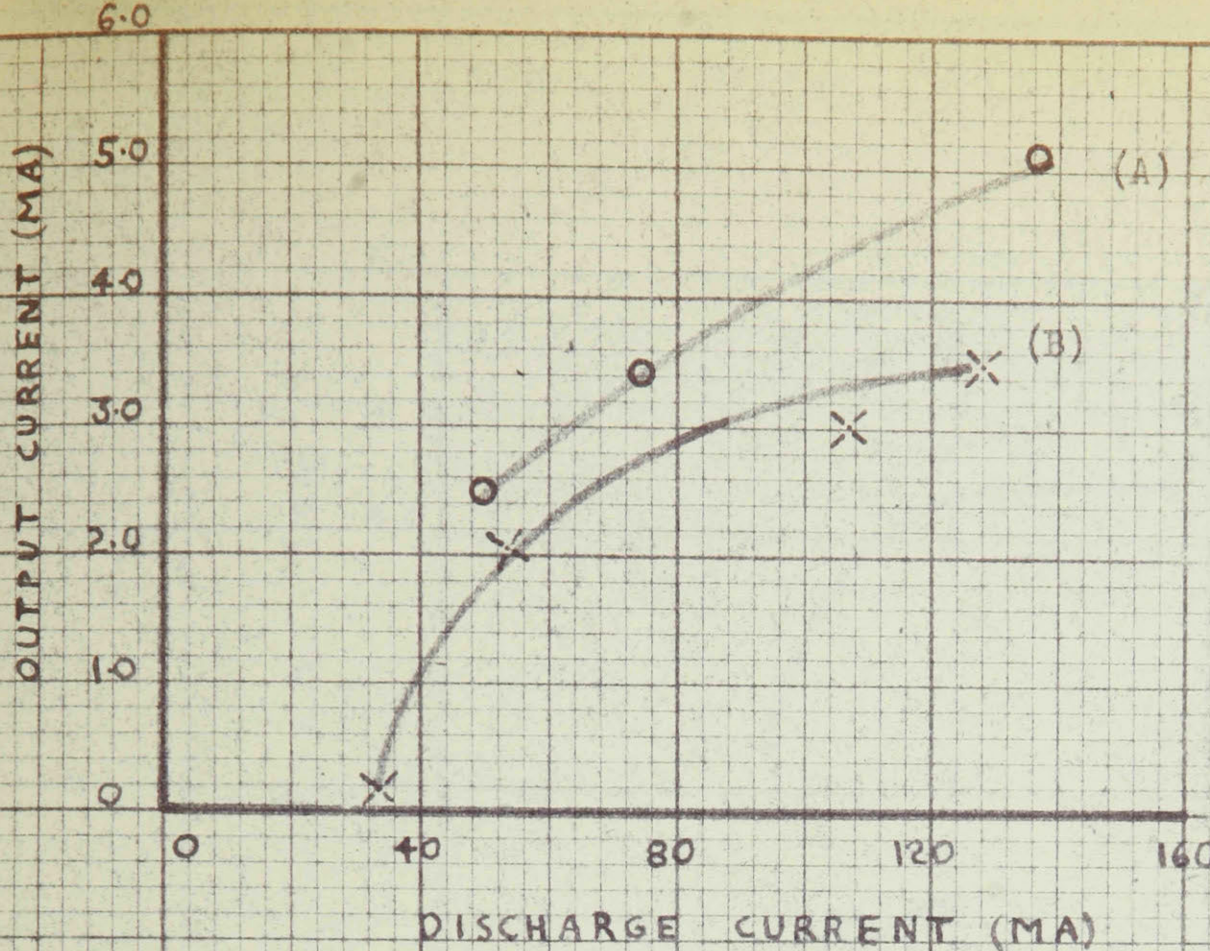


FIG. 11

UNSTABLE OPERATION

H = 1700 OERSTED

Readings (i) - (vii) are taken successively, as the series resistance R is decreased. Points A, B, and C are obtained on decreasing R further. From points A, B, and C frequent "kicks" to the point D (normal) occur.



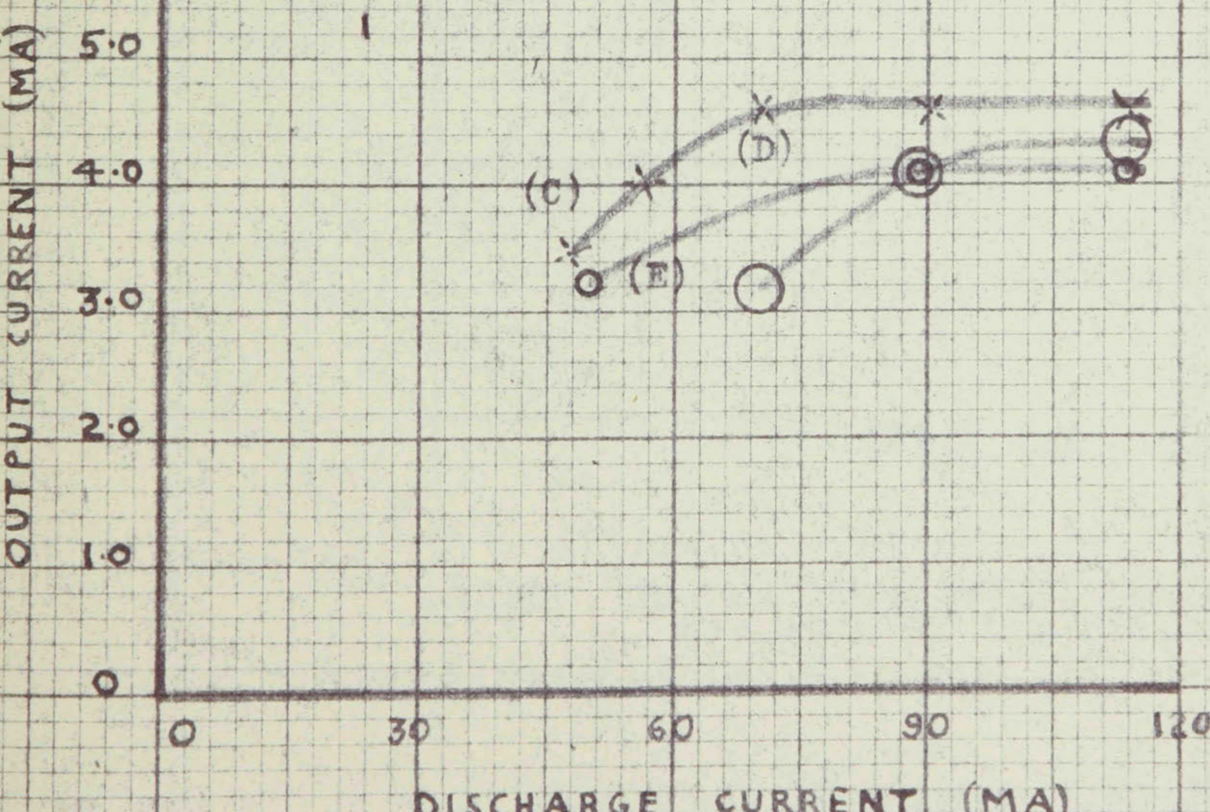
(A) H = 5500 oersted
p = 5 microns
$V_g = -340$ V
$V_a = 0$

(B) H = 2700 oersted
p = 6.2 microns
$V_g = 0$
$V_a = V_L$

FIG. 12

OUTPUT CURRENT vs. DISCHARGE CURRENT

cylinder anode, asymmetric, low fields



(C) p = 11 microns
$V_g = 0$
V_a see (*)

(D) p = 11 microns
$V_g = -50$ V
$V_a = V_L$

(E) p = 10 microns
$V_g = 0$
$V_a = 0$

FIG. 13

OUTPUT CURRENT vs. DISCHARGE CURRENT

Cylinder anode, asymmetric, H = 17,000 oersted

(*) positive self-bias through 0.3 megohms

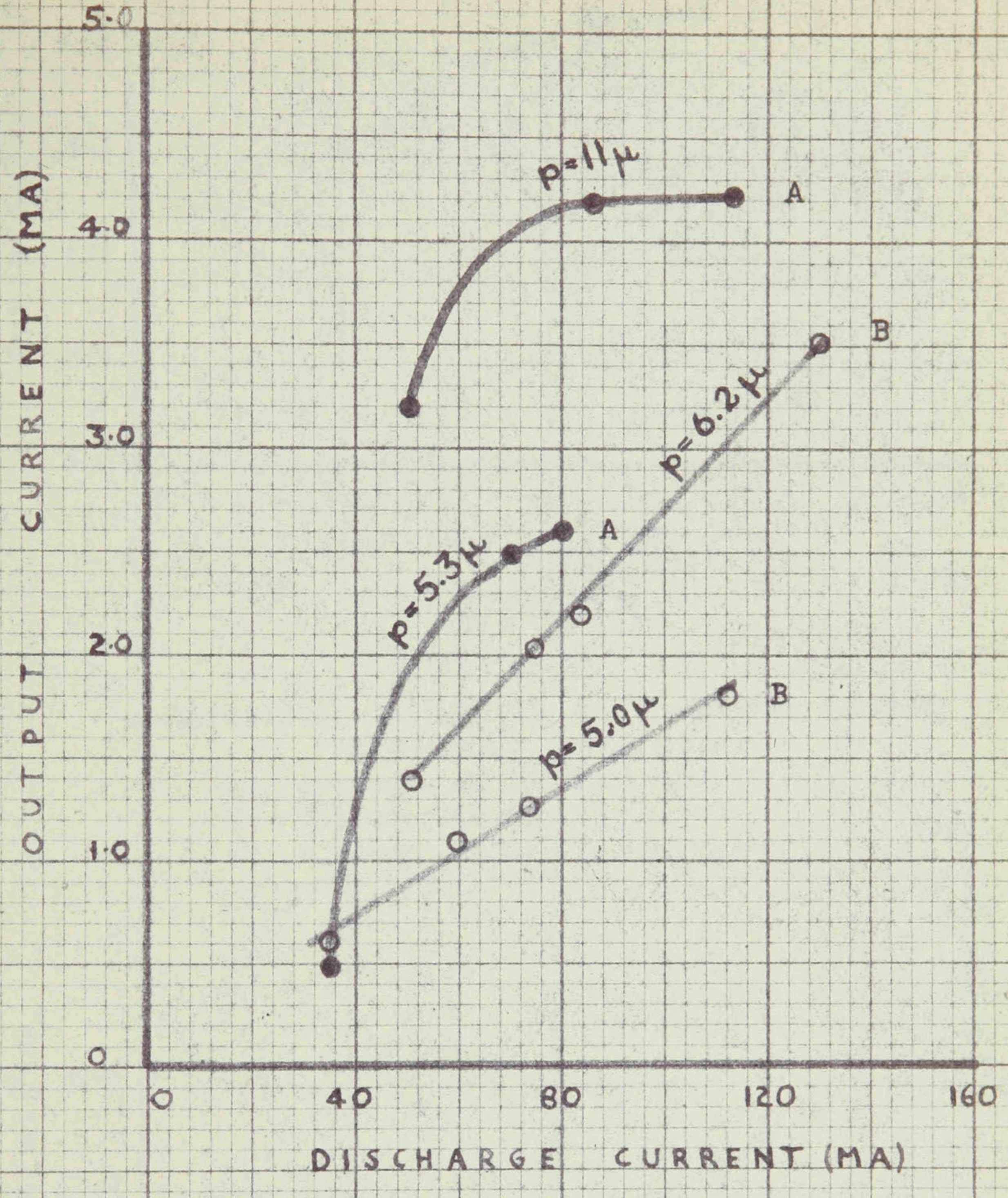


FIG.14

OUTPUT VS. DISCHARGE CURRENT FOR TWO PRESSURES
for each of two fields
cylinder anode, asymmetric, 1/8" hole, $V_a = V_L$

A: H = 16,000 oersted, $V_g = -50$ V
B: H = 2,700 oersted, $V_g = -330$ V

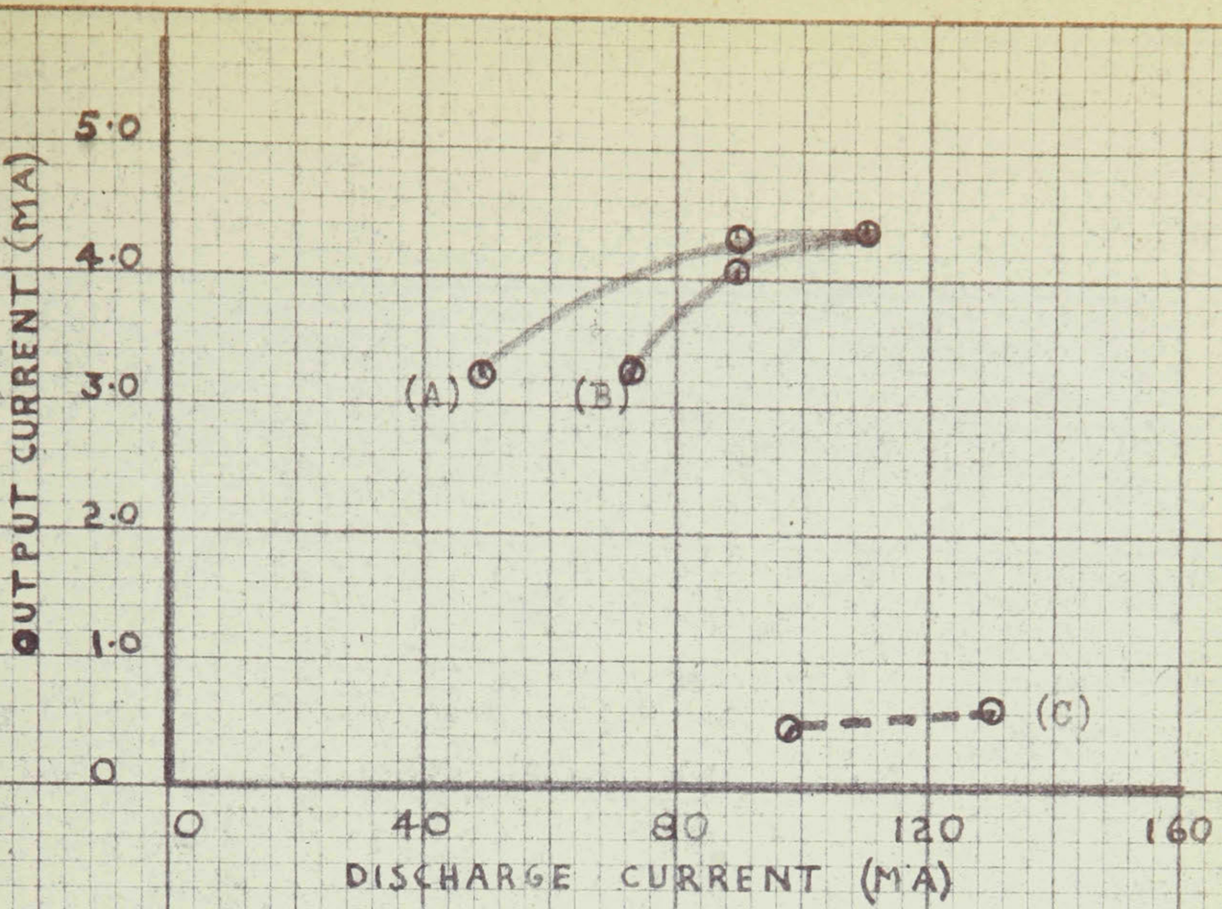


FIG. 15

COMPARISON OF ANODES AT H = 16,000 OERSTED
ASYMMETRIC, p = 11 microns
A: cylinder anode, V_g = -50, $V_a = V_L$
B: cylinder anode, $V_g = V_a = 0$
C: ejector anode, $V_g = 0$, $V_a = V_L$

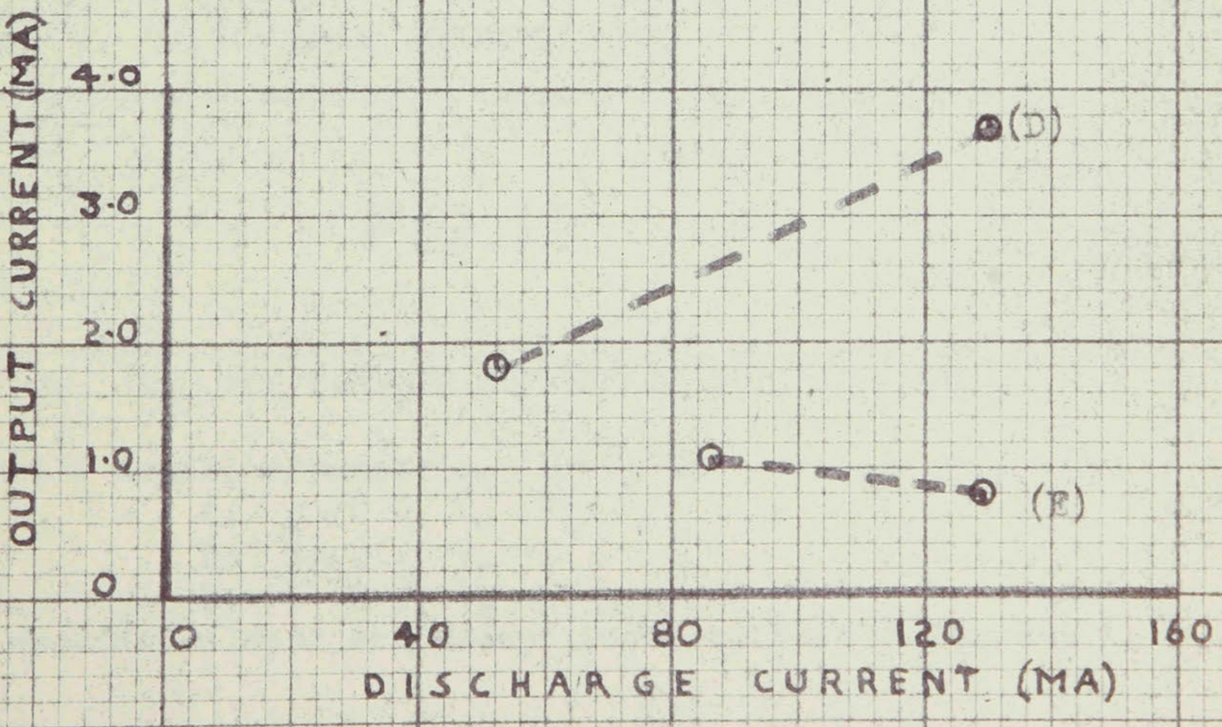


FIG. 16

COMPARISON OF SOURCES AT H = 2,700 OERSTED
asymmetric, p = 6.2 microns, V_g = -330 V
D: cylinder anode, $V_a = V_L$
E: ejector anode, $V_a = 0$

HUGHES OWENS 315-C 10×10

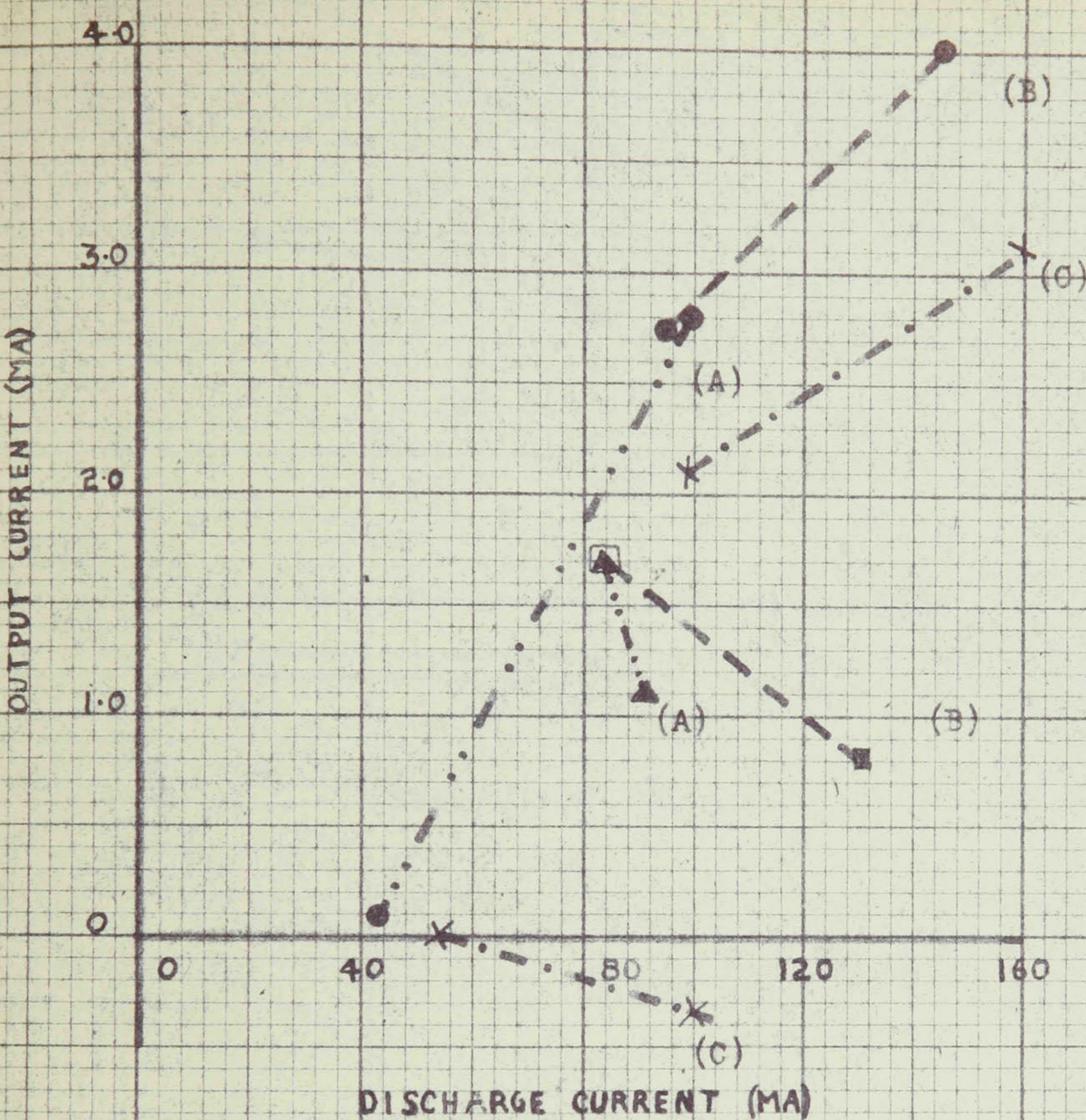


FIG. 17

i_o vs. i_T FOR VARIOUS SUPPRESSOR GRID VOLTAGES

ejector anode, asymmetric, H = 2,700 oersted

A: $p = 8.2$, $V_a = V_L$

B: $p = 6.2$, $V_a = 0$

C: $p = 9.8$, $V_a = 0$

(The negative slopes are exceptional; cf. Figs 12, 13 and 14.)

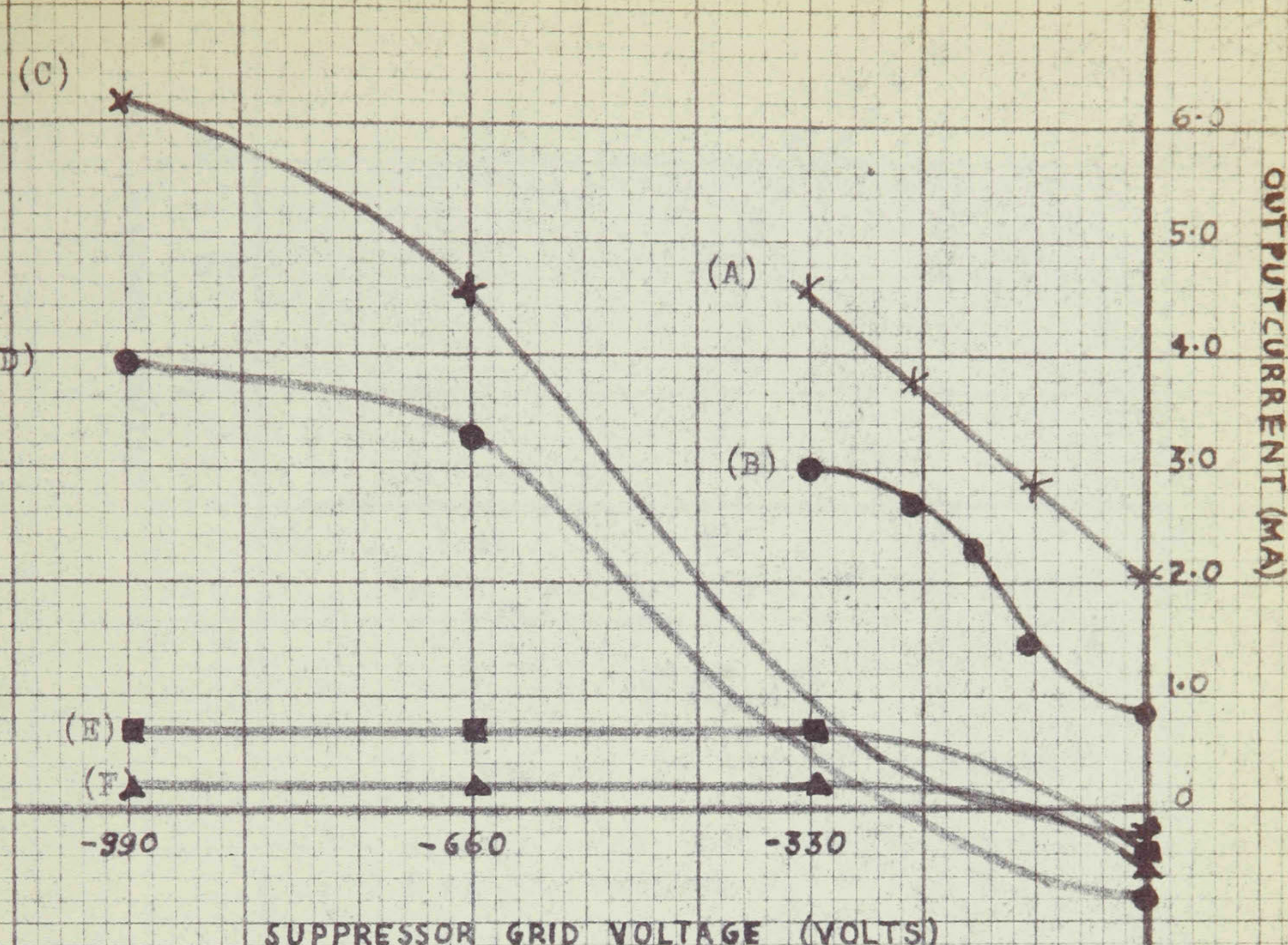


FIG. 18

OUTPUT CURRENT vs. SUPPRESSOR VOLTAGE (*)

ASYMMETRIC, $V_c = 0$

	A	B	C	D	E	F
i_T (mA)	67	49	89	137	80	60
H (oersted)	5500	5500	16000	2700	410	1140
V_a (Volts)	$\approx V_L$	$\approx V_L$	$\approx V_L$	0	0	V_L
anode type	--cylinder-		-------ejector--------			

(*) some of the points are obtained by interpolation in i_o vs. i_T curves

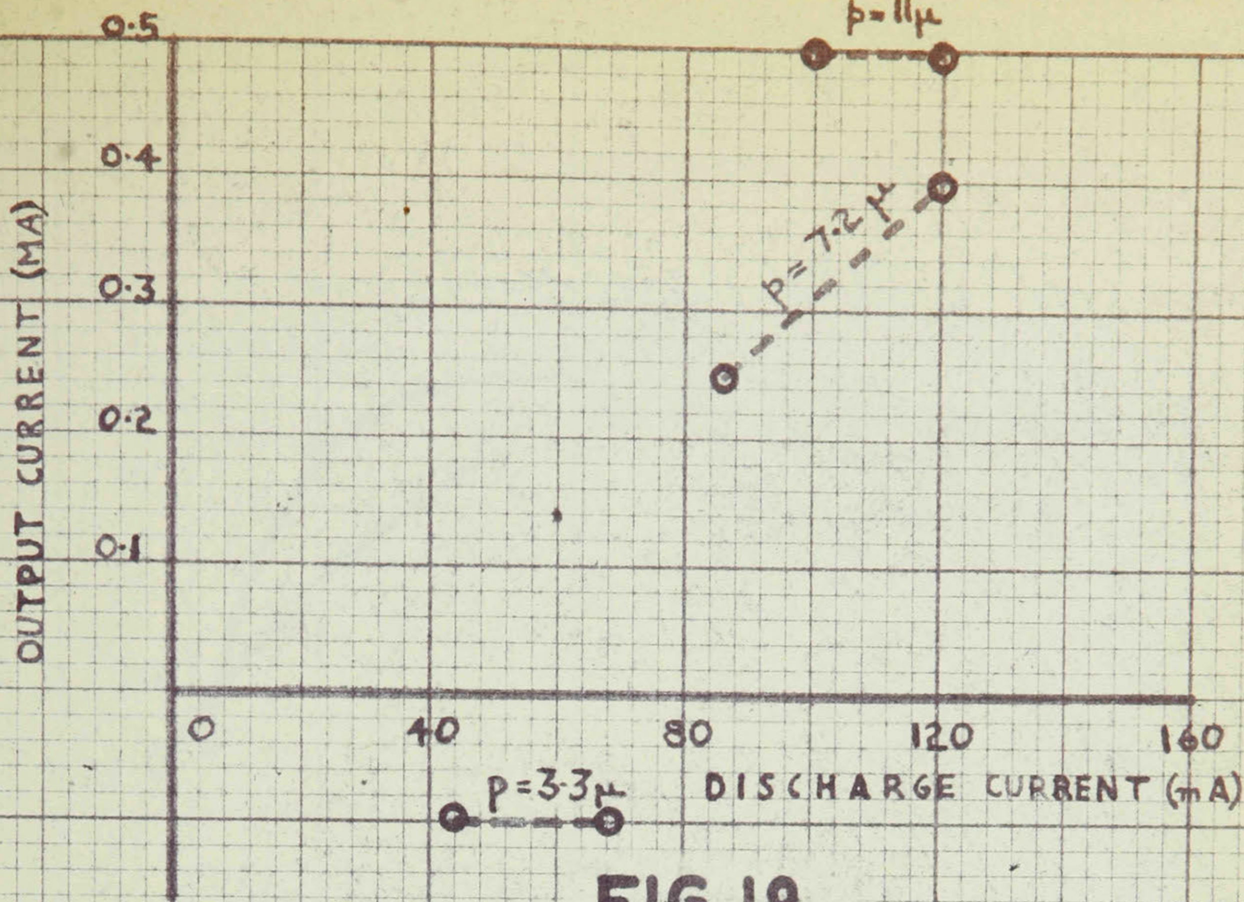


FIG. 19

i_o vs. i_T AT VARIOUS PRESSURES

ejector anode, 1/8" hole, asymmetric, H = 16,000 oersted, $V_g = 0$, $V_a = V_L$

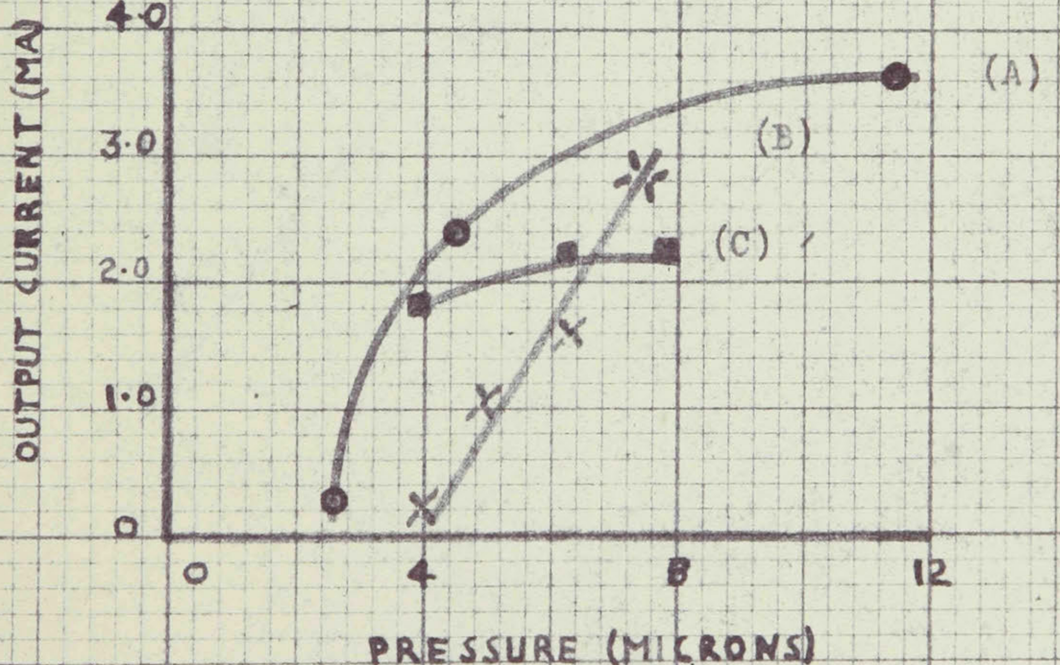
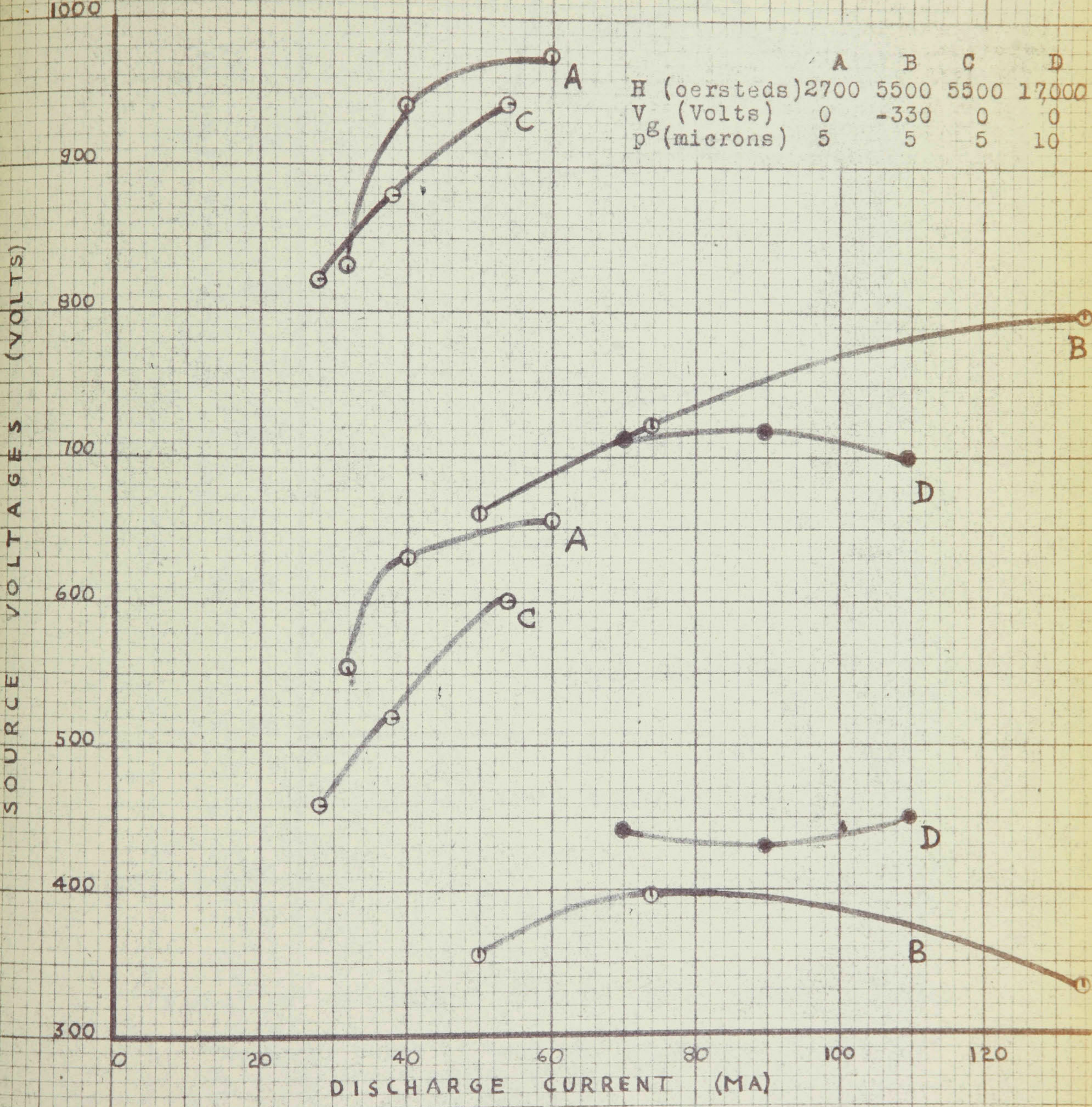


FIG. 20

OUTPUT CURRENT vs. PRESSURE
CYLINDER ANODE, ASYMMETRIC

	A	B	C
H (oersted)	16,000	2,700	2,700
i_T (mA)	70	61	112
V_g (Volts)	+50	+330	+330
V_a (")	= V_L	= V_L	0



VARIATION OF SOURCE VOLTAGES WITH DISCHARGE CURRENT

The upper curve of each pair represents V, the lower V_L - cylinder anode, 1/8" hole, asymmetric, $V_a = 0$

FIG. 21

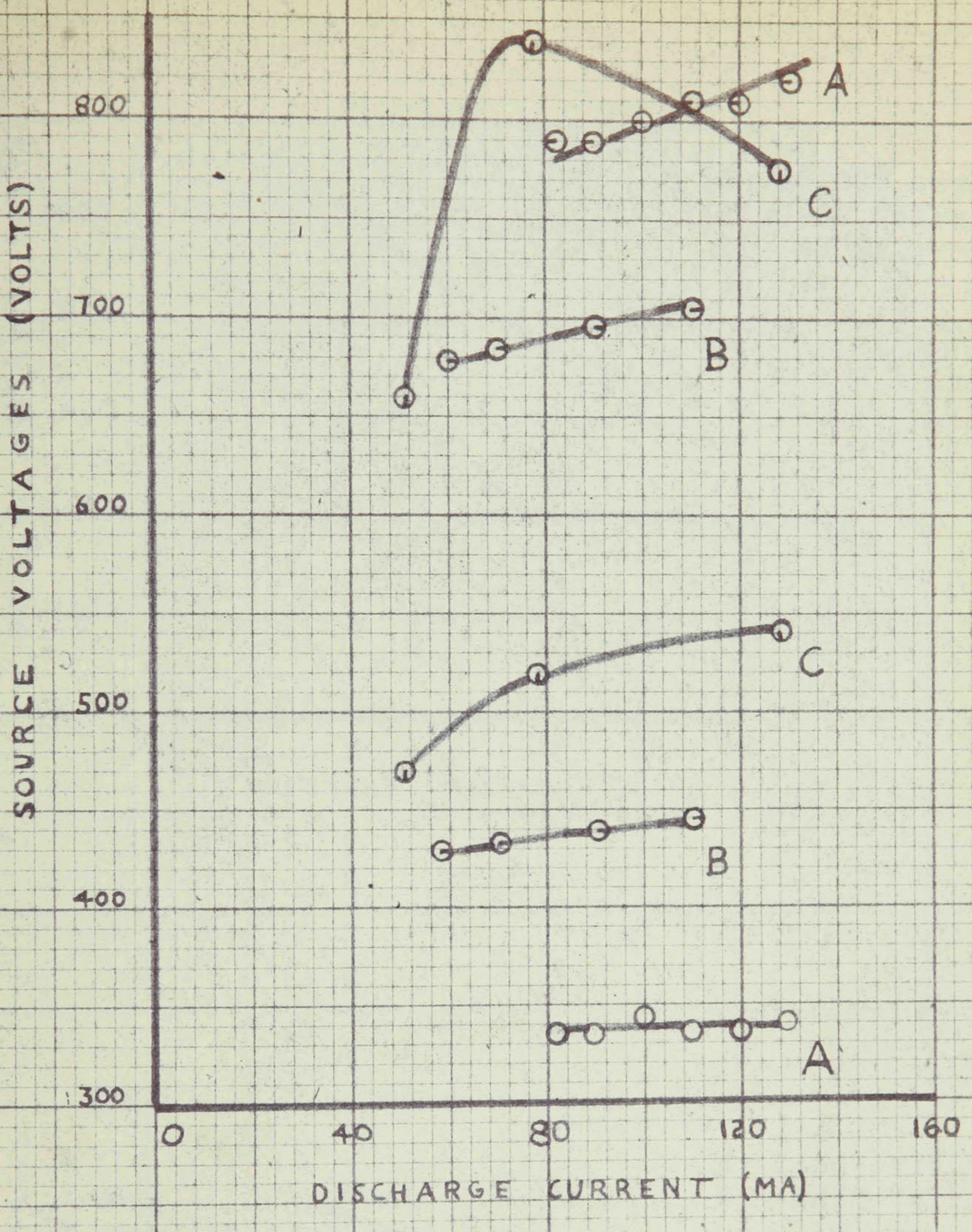


FIG. 22

VARIATION OF SOURCE VOLTAGES WITH DISCHARGE CURRENT

The upper curve of each pair represents V, the lower V_L - cylinder anode, asymmetric, $V_a = V_L$

	A	B	C
H (oersted)	17,000	17,000	2700
V_g (Volts)	-330	-50	-330

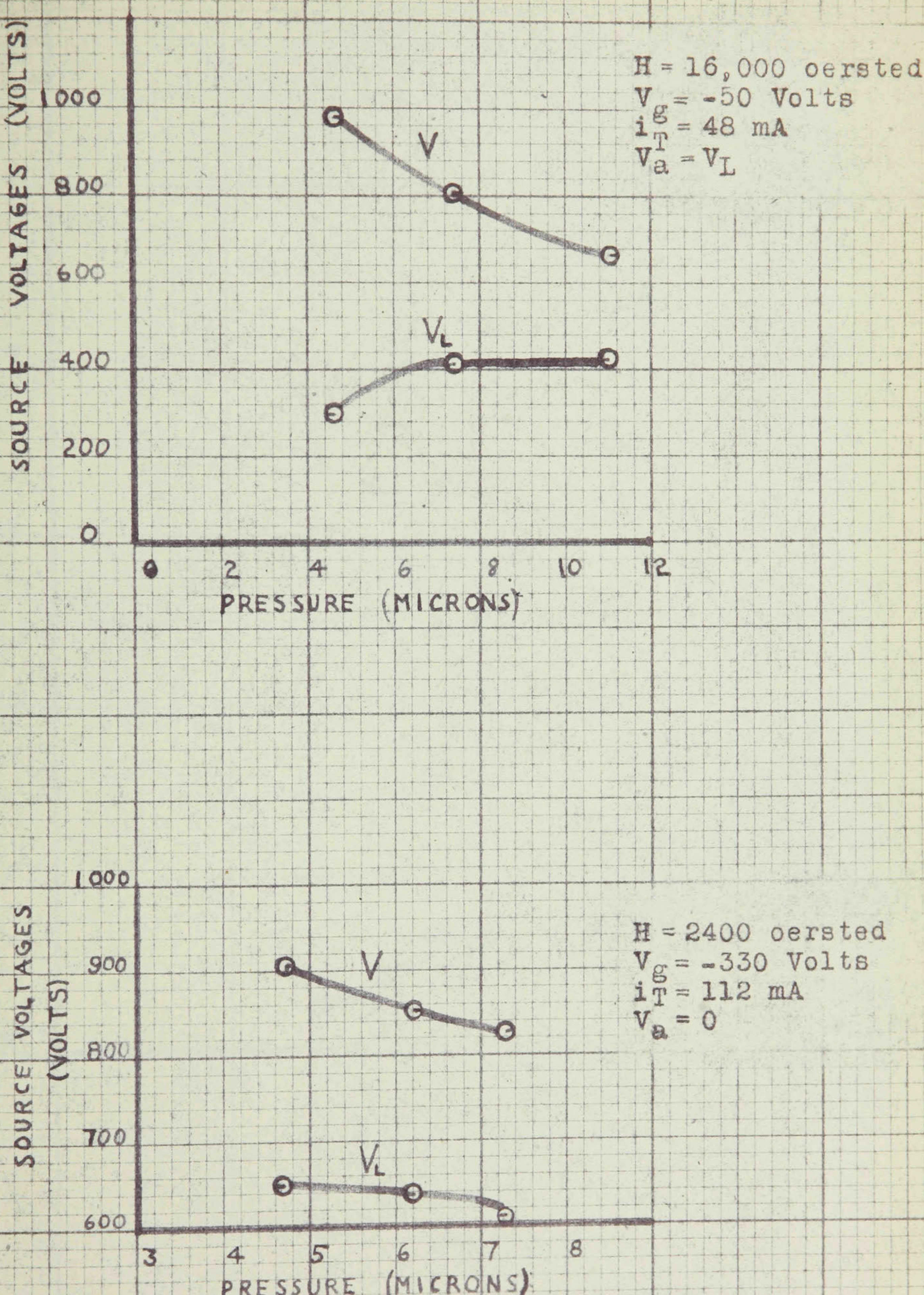


FIG. 23

VARIATION OF SOURCE VOLTAGES WITH PRESSURE
ASYMMETRIC, CYLINDER ANODE

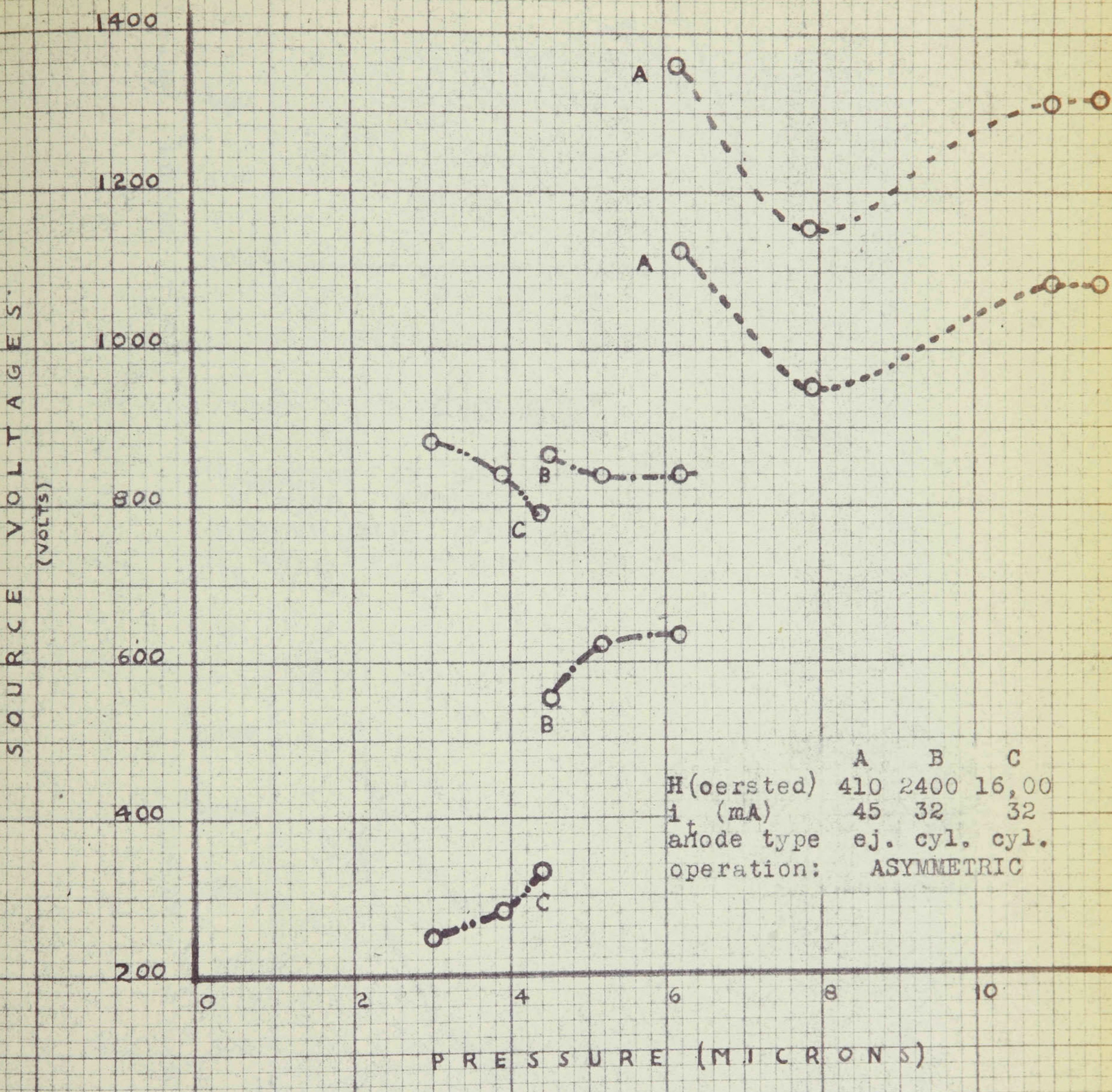


FIG. 24

VARIATION OF SOURCE VOLTAGES WITH PRESSURE

The upper curve of each pair represents V, the lower V_L. - $V_g = 0$ for all points

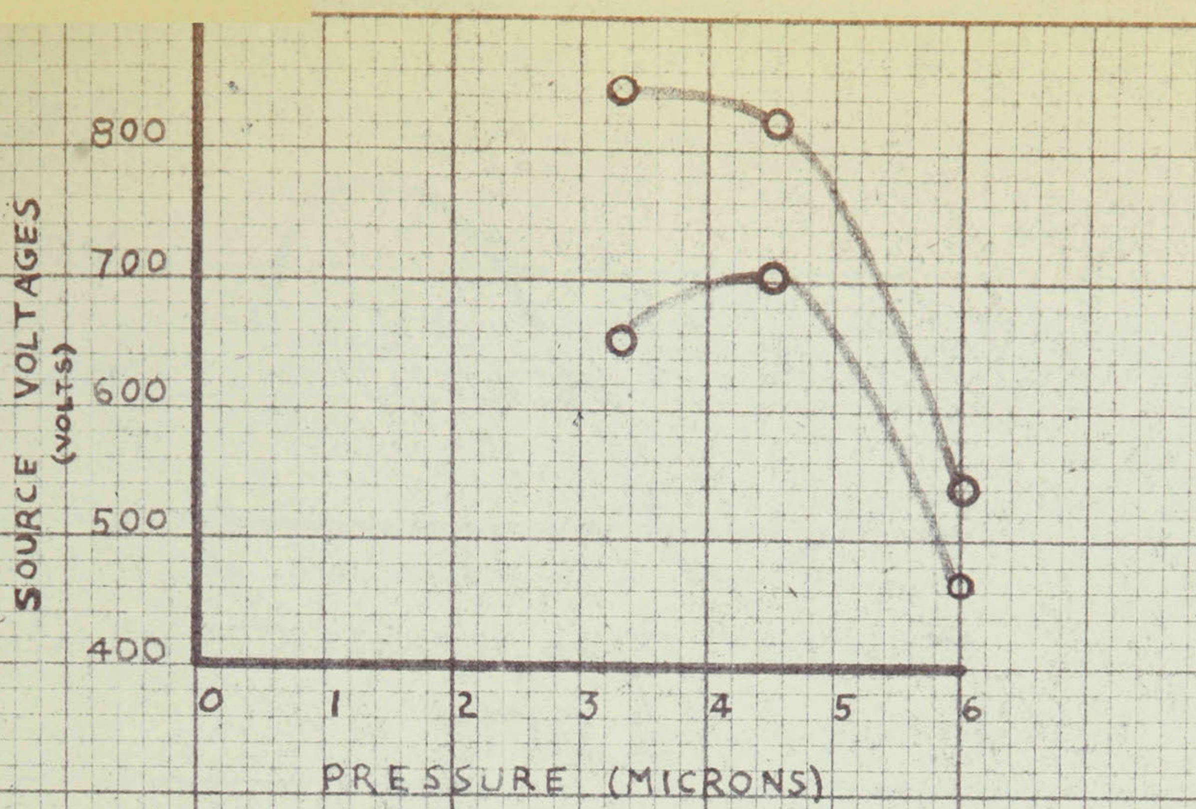


FIG. 25

VARIATION OF SOURCE VOLTAGES WITH PRESSURE
EJECTOR ANODE, asymmetric, $V_g = 0$, $V_a = V_L$, $H = 16,000$ oersted, $i_T = 74$ mA

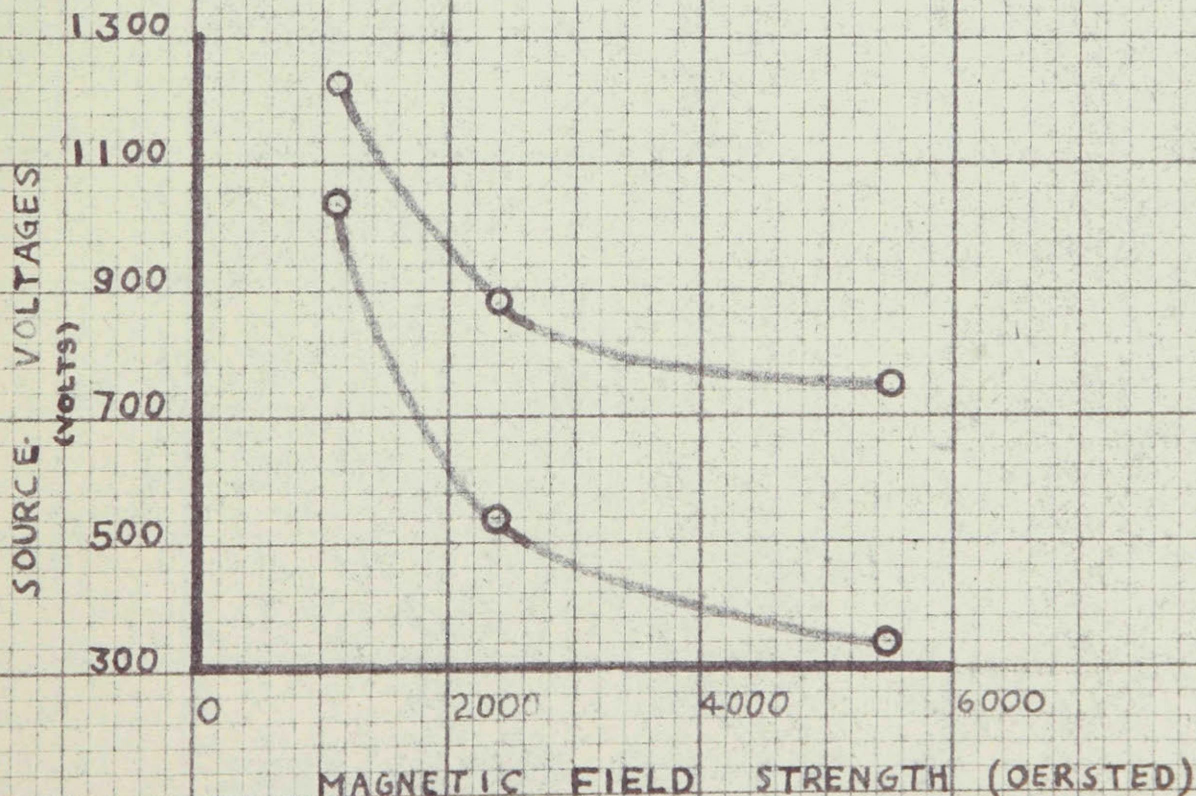


FIG. 26

VARIATION OF SOURCE VOLTAGES WITH MAGNETIC FIELD STRENGTH
cylinder anode, asymmetric, $V_g = 0$, $V_a = V_L$, $p = 6$ microns, $i_T = 40$ mA

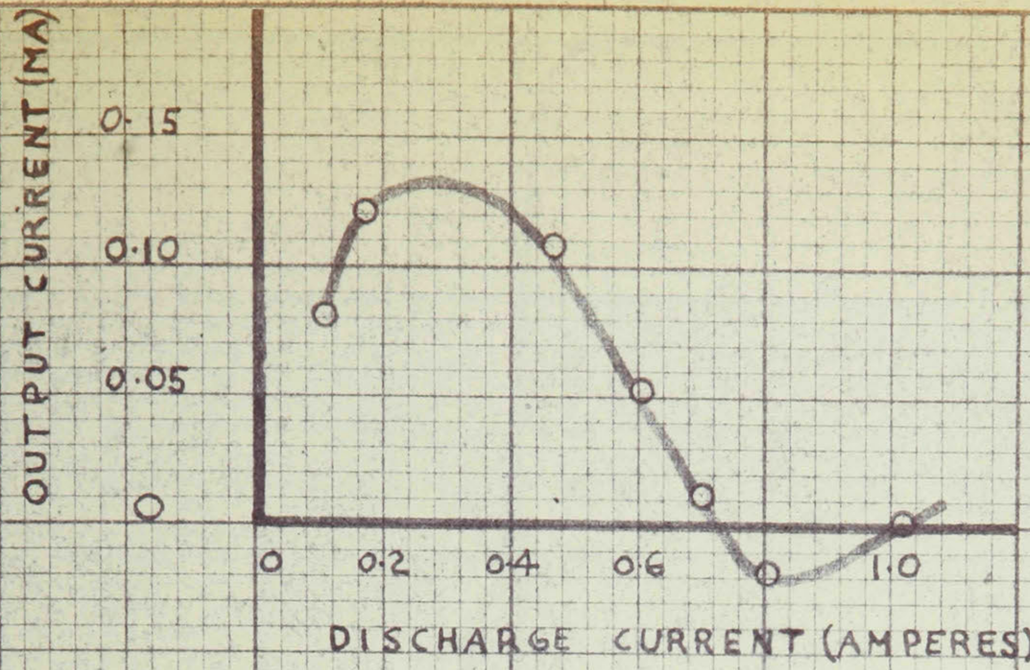


FIG. 27

OUTPUT CURRENT vs. DISCHARGE CURRENT

ejector anode, symmetric, p = 10 microns
H = 1130 oersted, V = 250-280 Volts, 1/8"

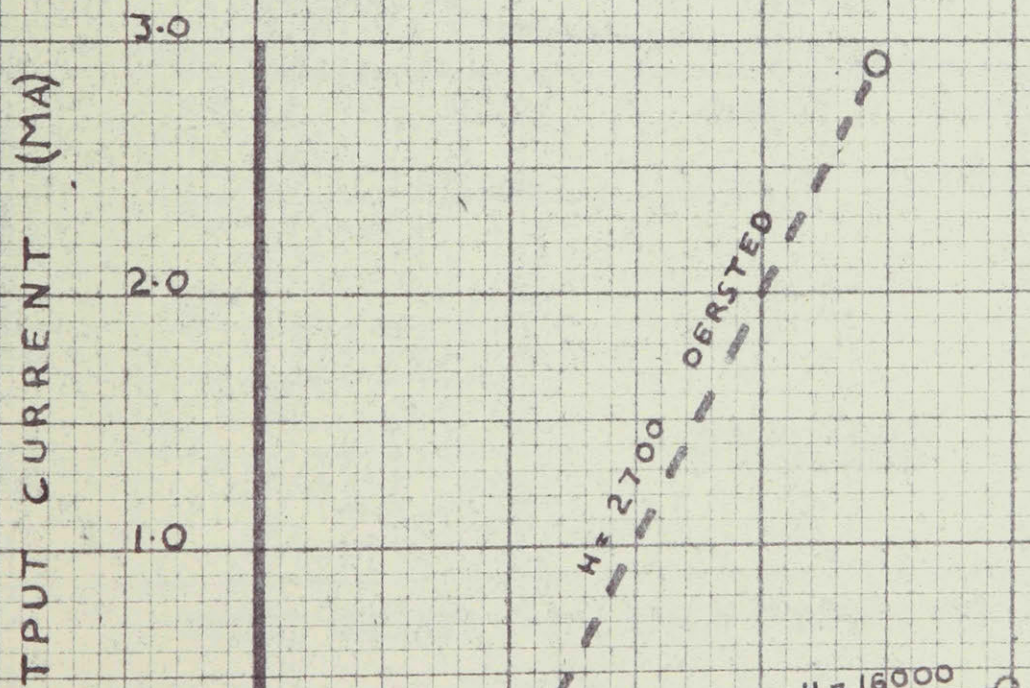


FIG. 28

OUTPUT CURRENT vs. DISCHARGE CURRENT
EJECTOR ANODE, ASYMMETRIC, P = 8.2 microns
H = 2,700, 16,000 oersted resp., $V_g = 0$, $V_a = V_L$

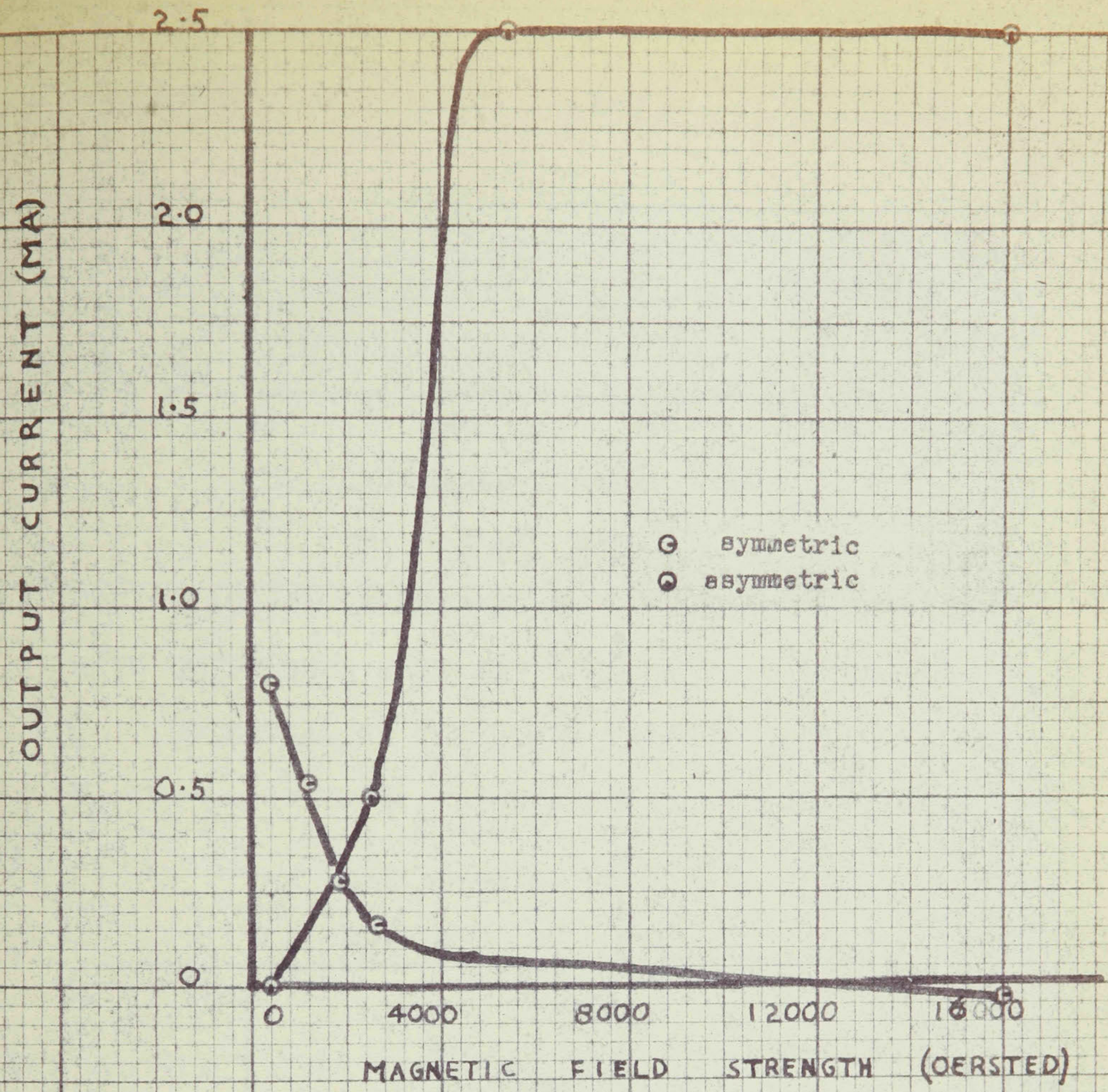


FIG. 29

OUTPUT CURRENT vs. FIELD STRENGTH FOR THE TWO MODES OF OPERATION

(cylinder anode)

rising curve: asymmetric, $p = 5.2$ microns (*), $i_T = 70 \pm 4$ mA, $V_a - V_L$, $V_c = 0$

falling curve: symmetric, $p = 3.5$ microns, $i_T = 70$ mA, in absence of accelerator

(*) the pressure is 7 microns for the point at 410 oersted

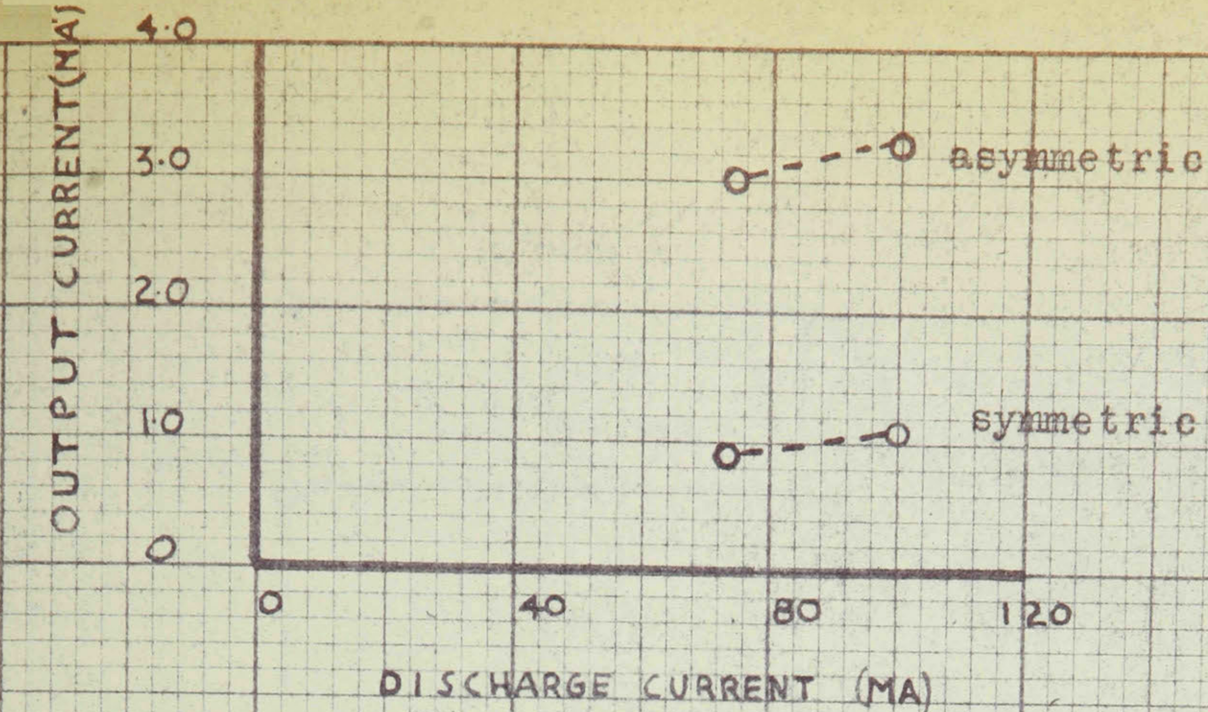


FIG. 30 (*)

COMPARISON OF ASYMMETRIC AND SYMMETRIC OPERATION WITH SUPPRESSOR GRID AND COLLECTOR AT THE SAME POTENTIAL RE THE LOWER CATHODE $[V_L = 0]$

$V_g = V_c = -330$ Volts, $p = 9$ microns, cylinder anode, ¼" hole, $H = 16{,}000$ oersted

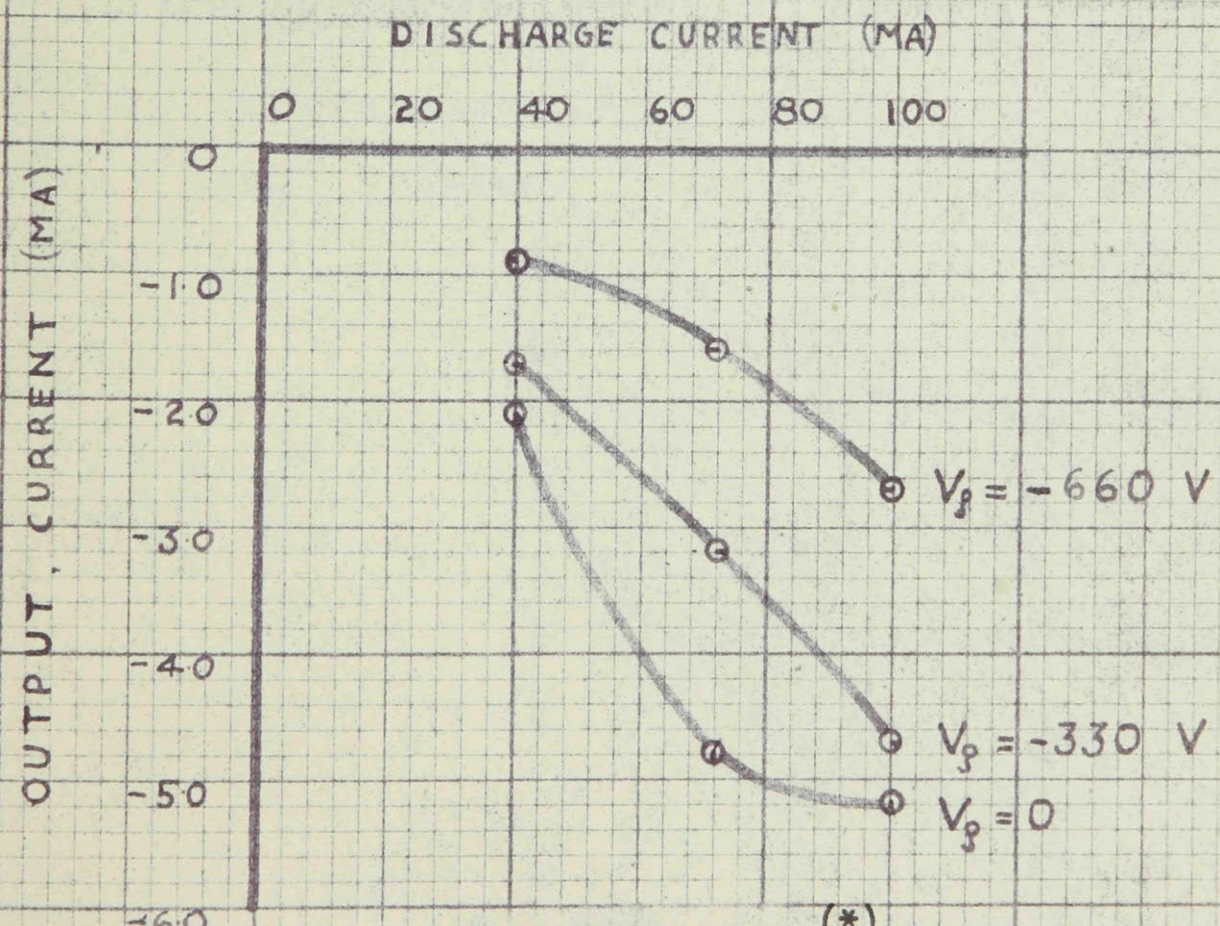


FIG. 31 (*)

ASYMMETRIC OPERATION WITH COLLECTOR AT SAME POTENTIAL AS THE LOWER CATHODE AND VARIOUS GRID VOLTAGES -

cylinder anode, ¼" hole, $V_c = V_L = 0$, $H = 16{,}000$

(*) Voltages are measured with respect to $V_L = 0$ in this Figure.

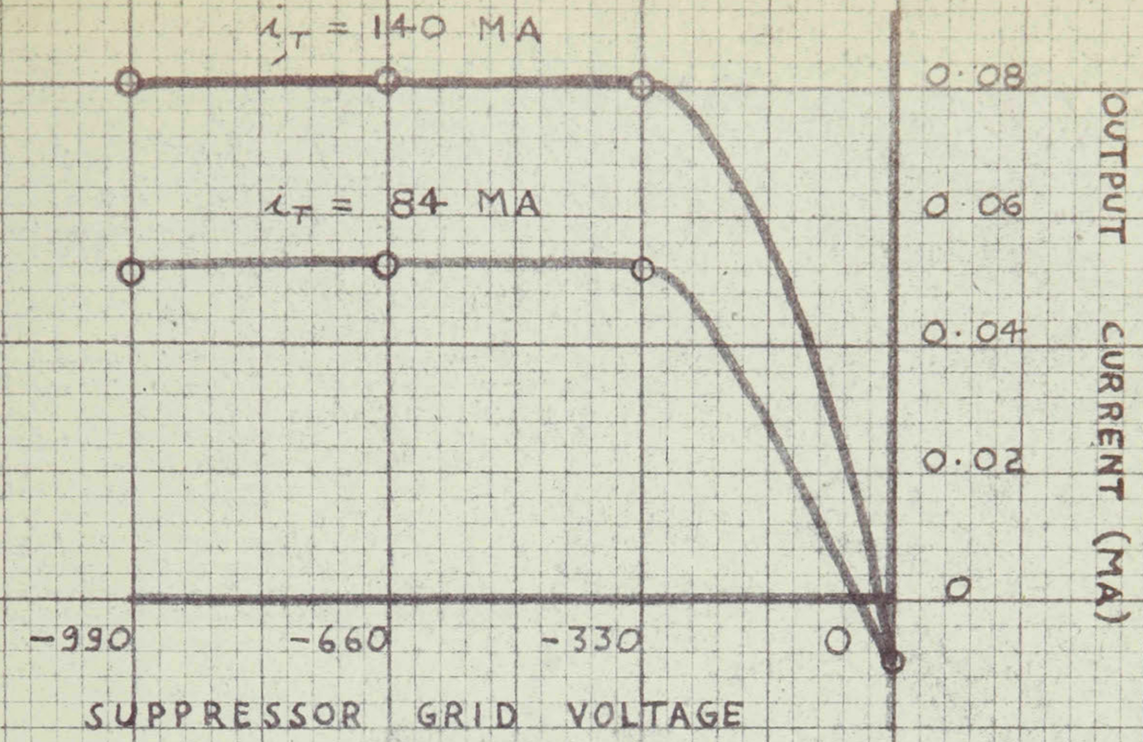


FIG.32

OUTPUT CURRENT vs. GRID VOLTAGE
ejector anode, symmetric, p = 5.2μ
H = 2400 oe., $V_a = V_L = V_c = 0$, 1/8" hole

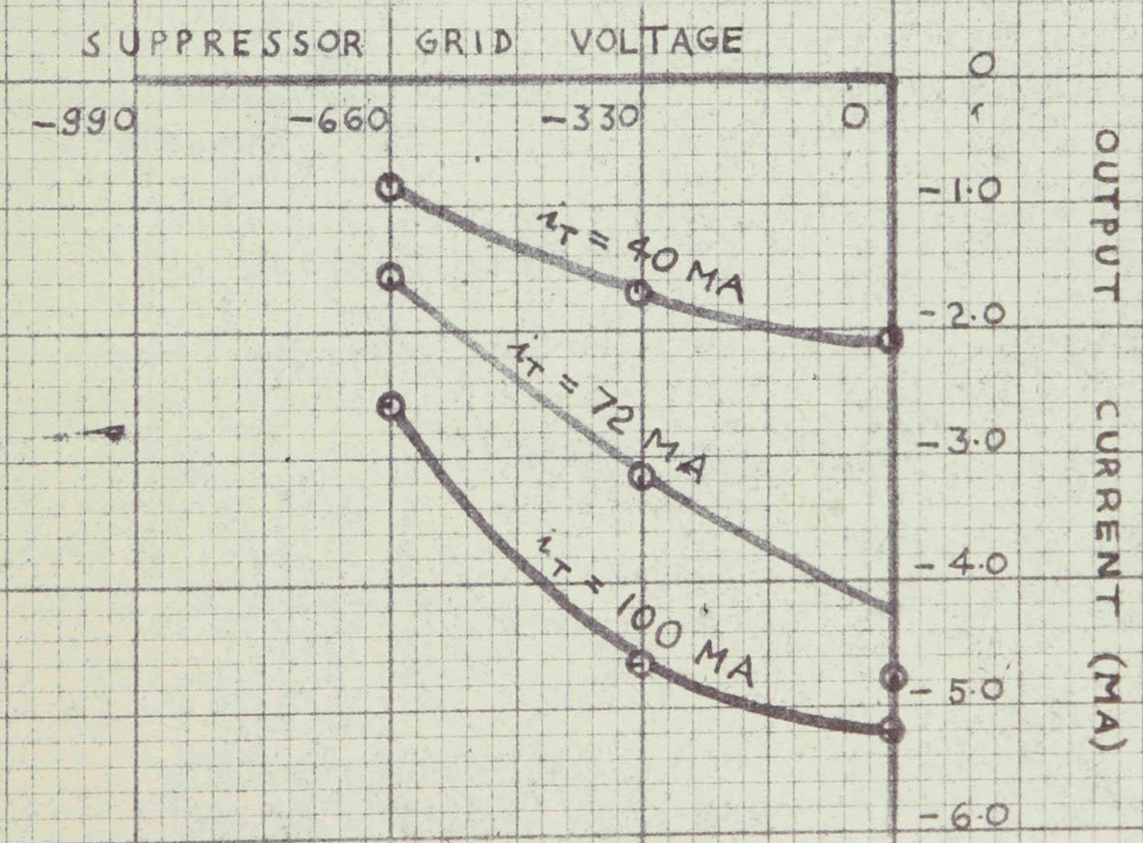


FIG.33

OUTPUT CURRENT vs. GRID VOLTAGE
WITH COLLECTOR AT POTENTIAL OF
LOWER CATHODE
$V_c = V_L$, p = 9 microns, $V_a = V_L$,
cylindrical anode, ⅛" hole, asym-
metric

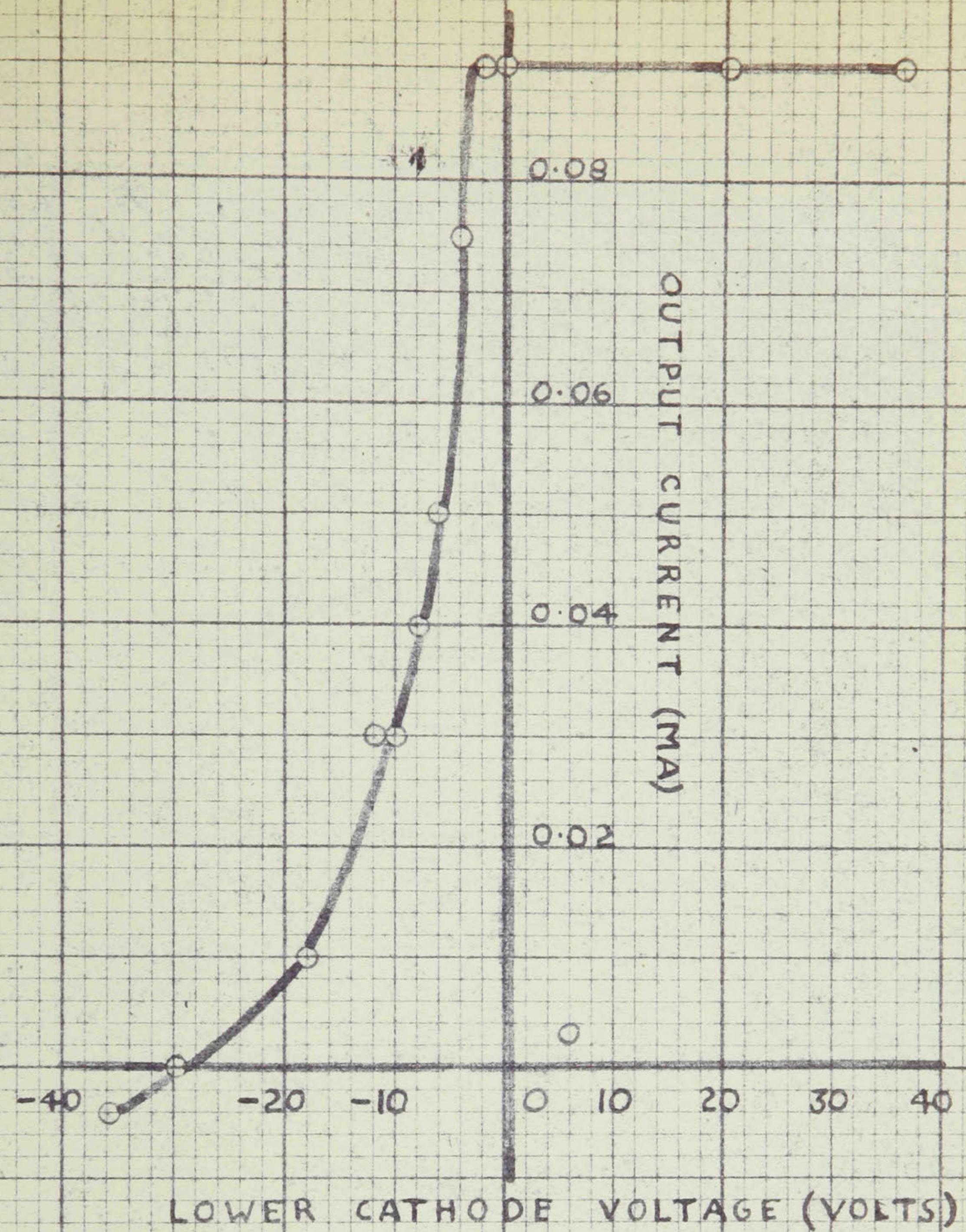


FIG.34

OUTPUT CURRENT vs. LOWER CATHODE VOLTAGE
(V_L IS OBTAINED FROM STORAGE BATTERIES) -

cylinder source, 1/8" hole, asymmetric,
p = 9.5 microns, H = 16,000 oersted, V_a=V_g=0

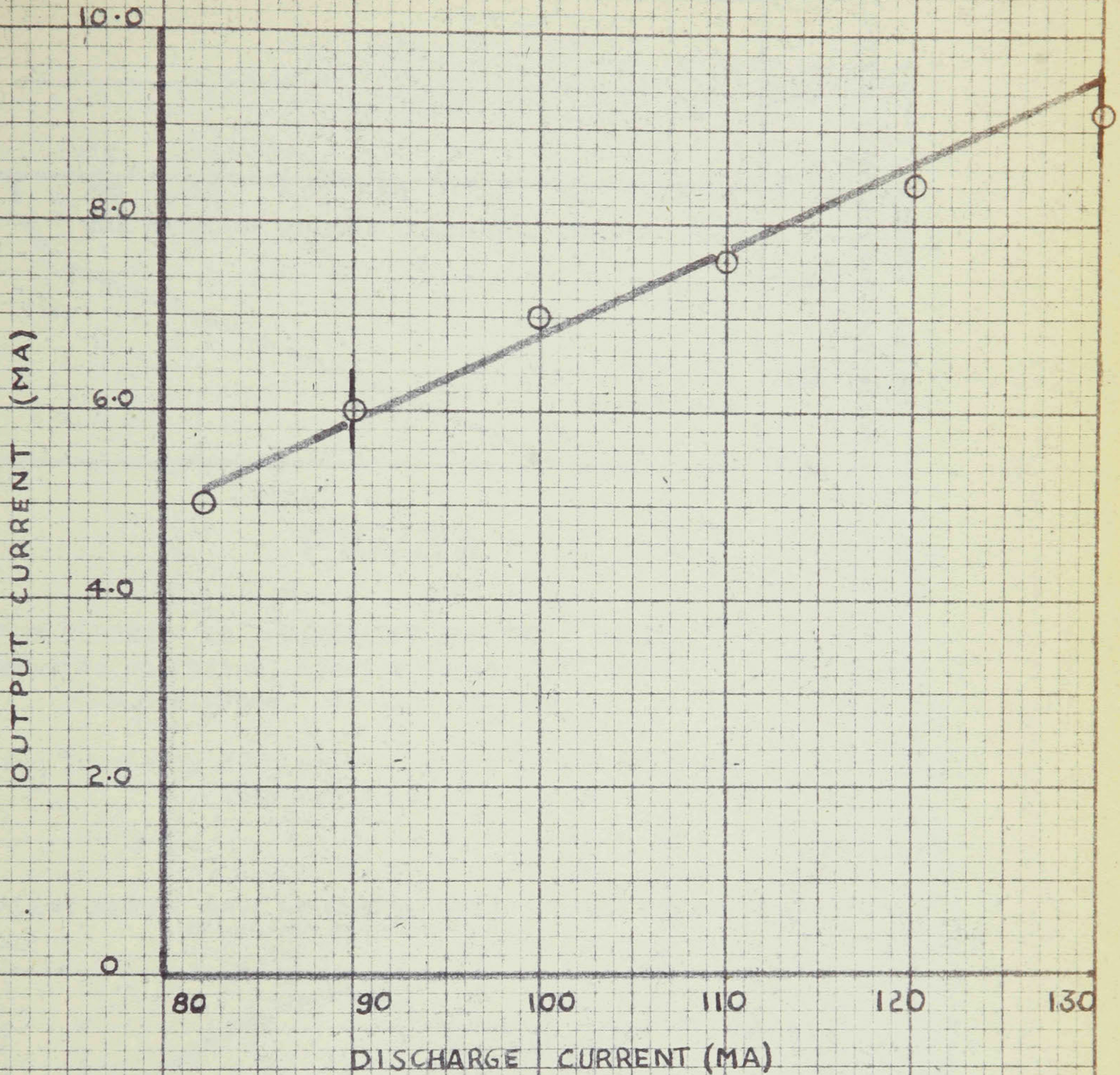


FIG. 35

OUTPUT CURRENT vs. DISCHARGE CURRENT

(cylinder anode, $\frac{1}{4}$" hole, asymmetric, H = 16,000 oersted, p=9 microns, $V_g - V_c = -330V$)

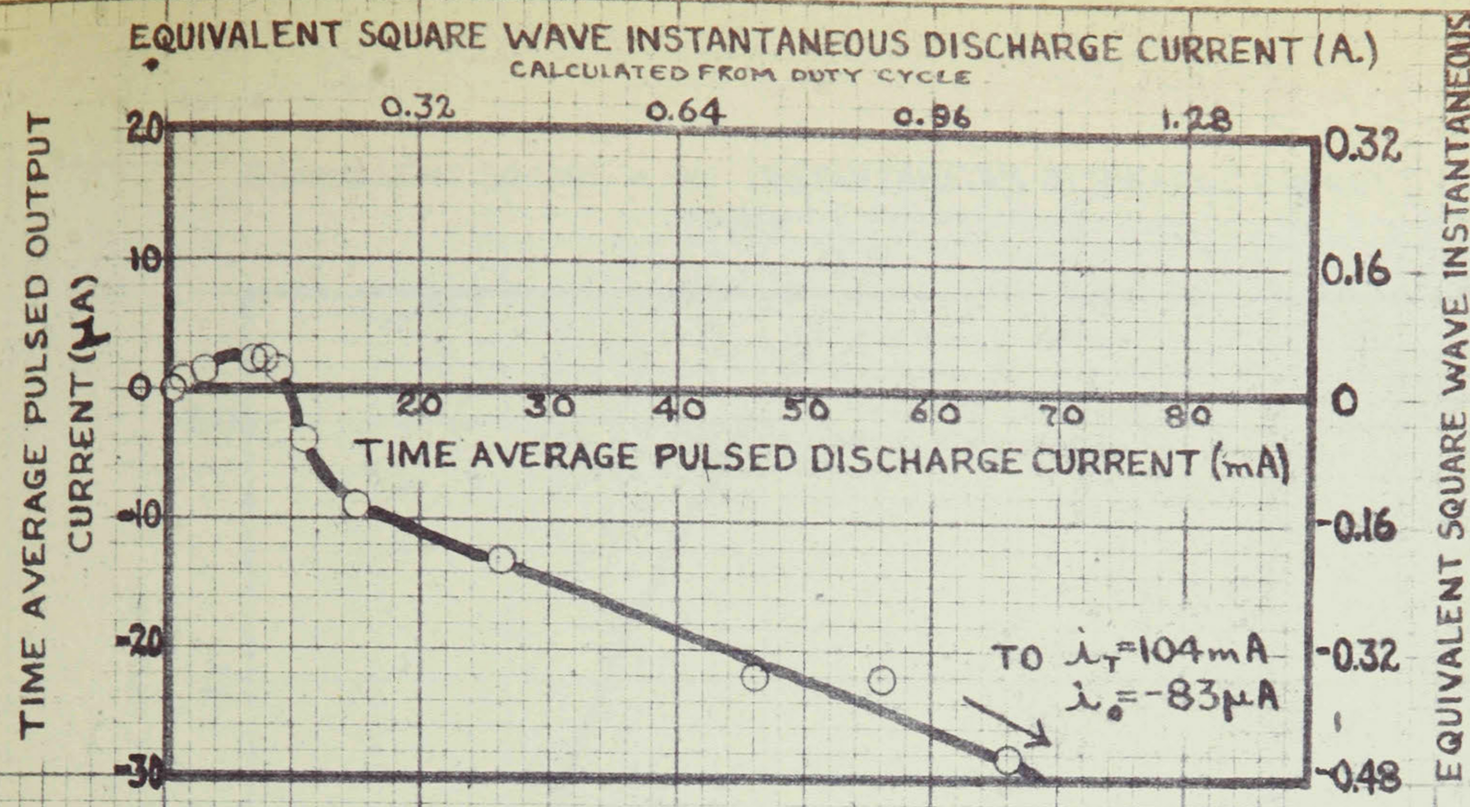


FIG. 36

OUTPUT CURRENT vs. DISCHARGE CURRENT; PULSED symmetric operation, ejector anode, 1/8" hole
p = 6.5 microns, H = 1130 oersted

repetition frequency = 850 cy/sec, pulse length = 75 μ sec
duty cycle = 1/16

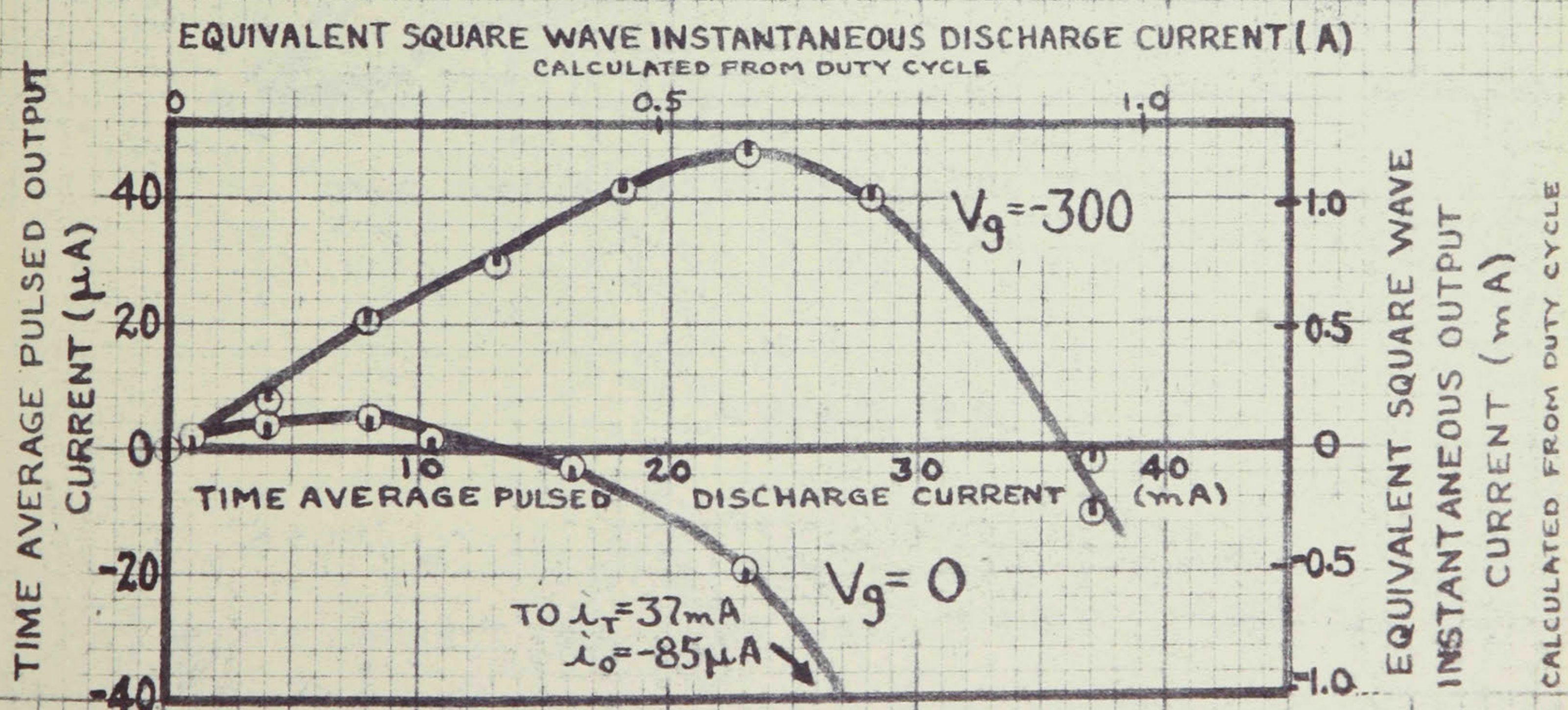


FIG. 37

OUTPUT CURRENT vs. DISCHARGE CURRENT; PULSED SYMMETRIC OPERATION, EJECTOR ANODE, 1/8" hole
p = 5 microns, H = 16,000 oersted
repetition frequency = 796 cy/sec, pulse length = 47 sec
duty cycle = 1/27

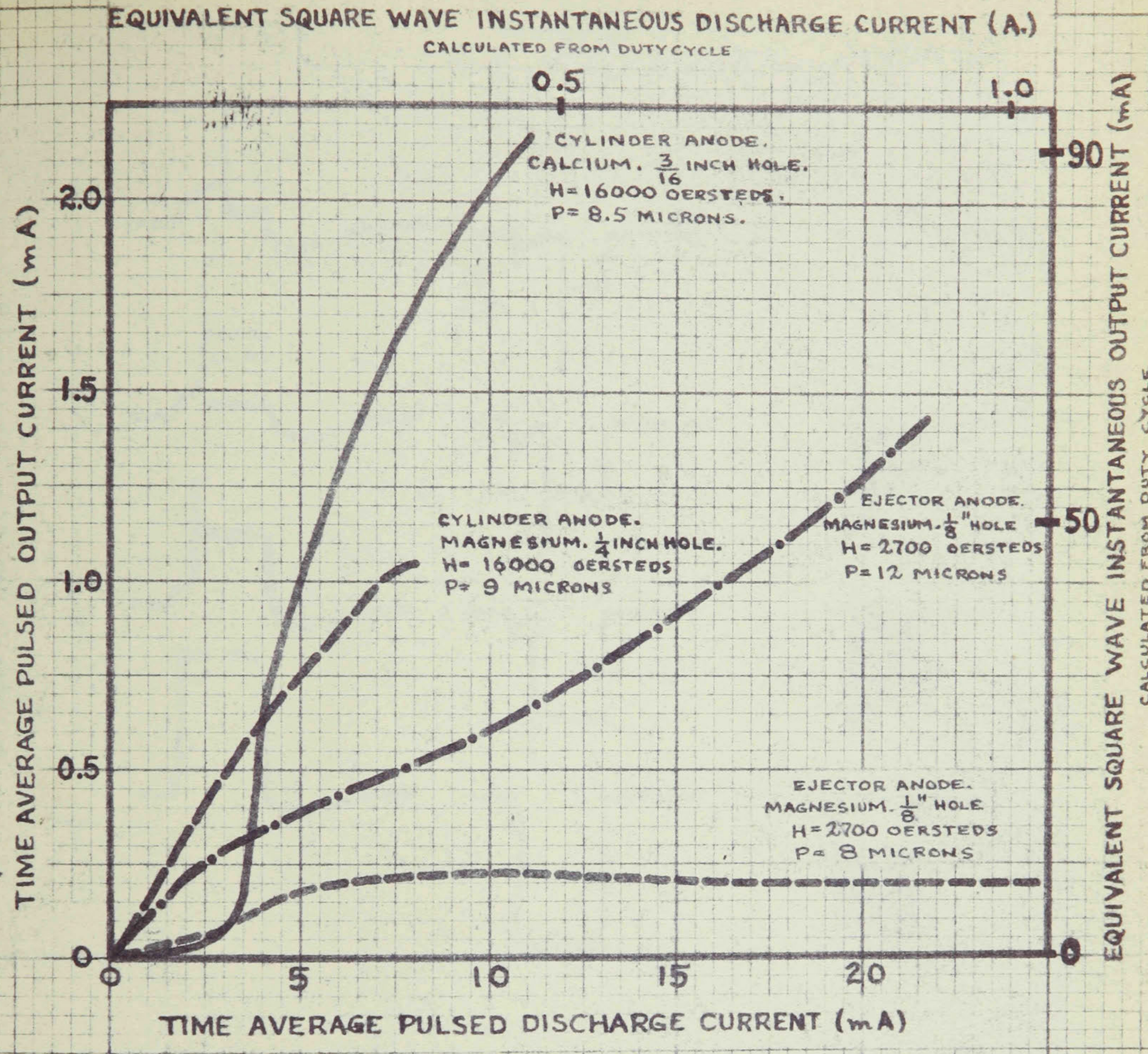


FIG. 38

OUTPUT CURRENT vs. DISCHARGE CURRENT; ASYMMETRIC PULSING

Repetition frequency = 796 cy/sec, pulse length = 30 μsec
Duty cycle = 1/42; $V_g = 0$

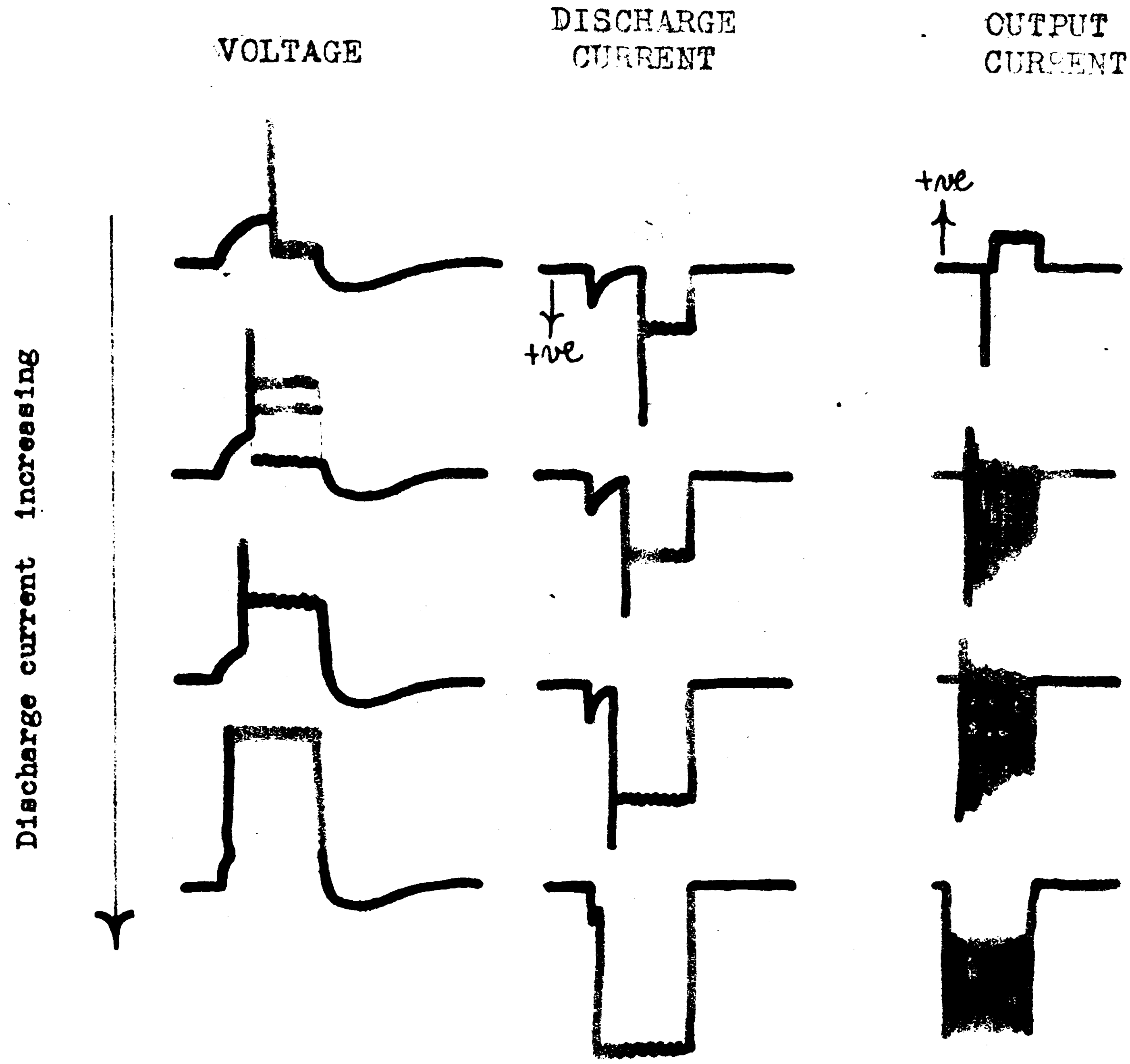


FIG.39

SKETCHES OF TYPICAL PULSE SHAPES – SYMMETRIC OPERATION

Ejector anode; no attempt has been made in these sketches to maintain a vertical scale. The shapes are qualitatively the same in high and low fields.

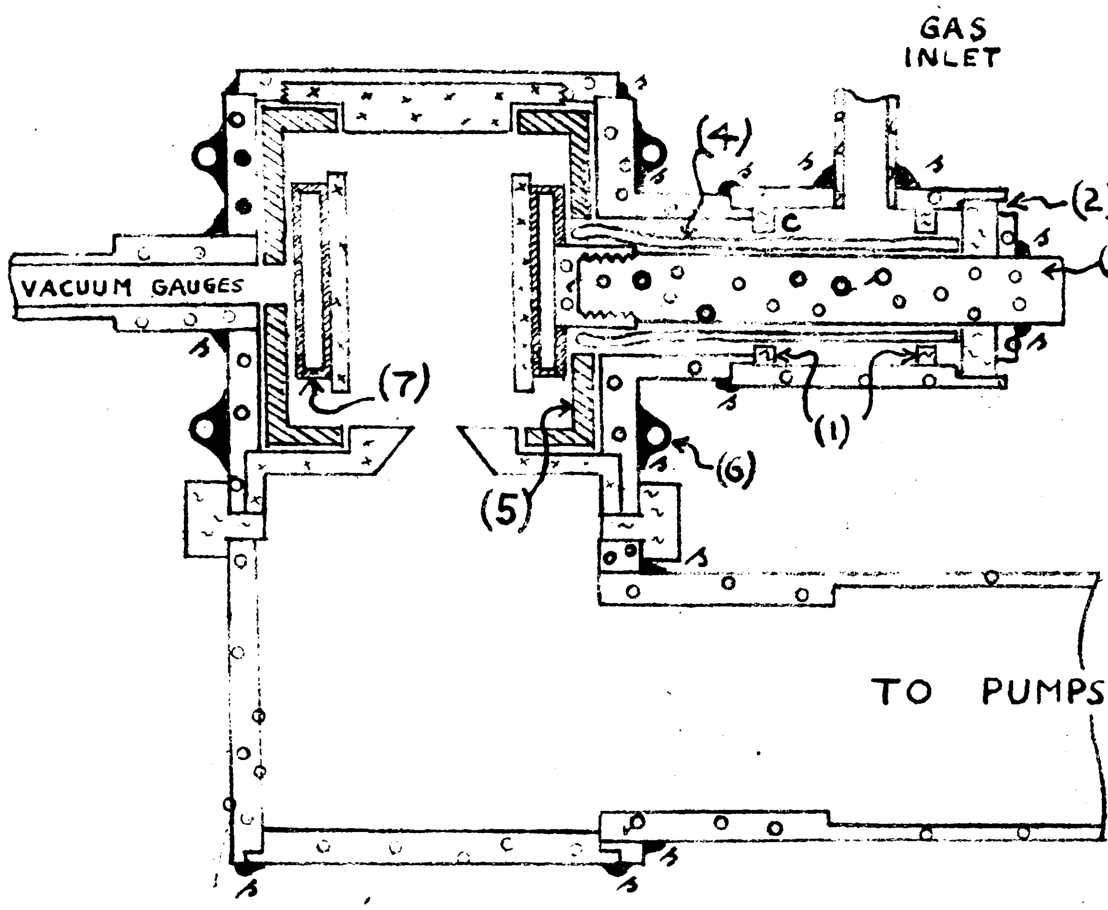


FIG. 40

ENCLOSED SOURCE

(small vacuum chamber)

(1) Spacers

(2) Joint Apiezon-W sealed

(3) Lead for anode cooling
cf. Fig.

(4) Insulator

(5) Lavite insulators

(6) Cathode cooling pipe

(7) Anode cooling jacket

ꞩ - soft solder

Lavite

Bakelite

Copper

Glass

Brass

Magnesium

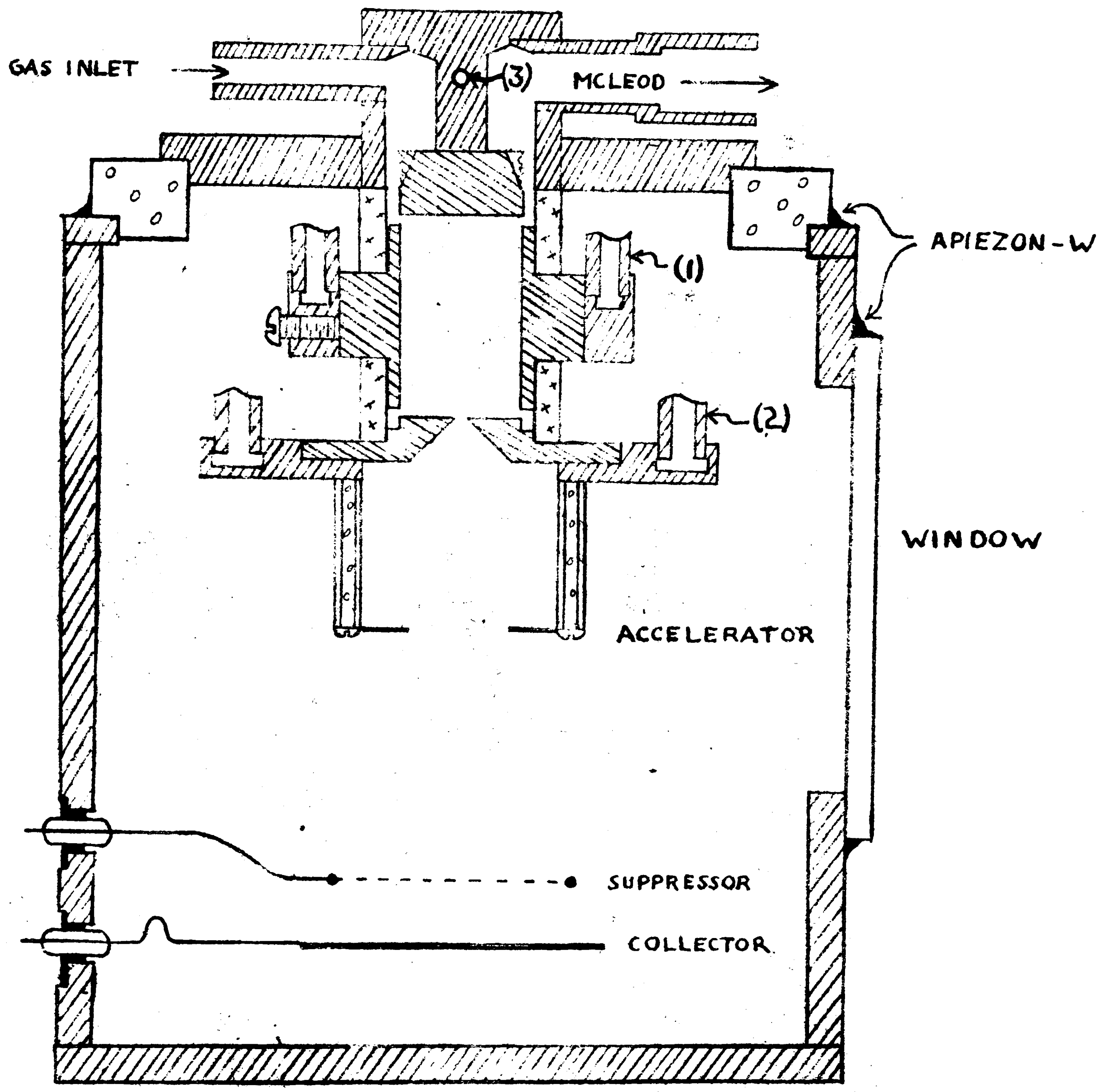


FIG. 41

SCALE: ACTUAL SIZE

SPACER MODEL SOURCE - LARGE VACUUM CHAMBER (cf. Plate III)

The [illegible] anode is rotated 45° clockwise, the lower cathode 45° counter-clockwise.

Brass Magnesium Bakelite

Glass Lavite

(1),(2) - Anode and lower cathode cooling and electrical leads

(3) - section of upper cathode cooling canal

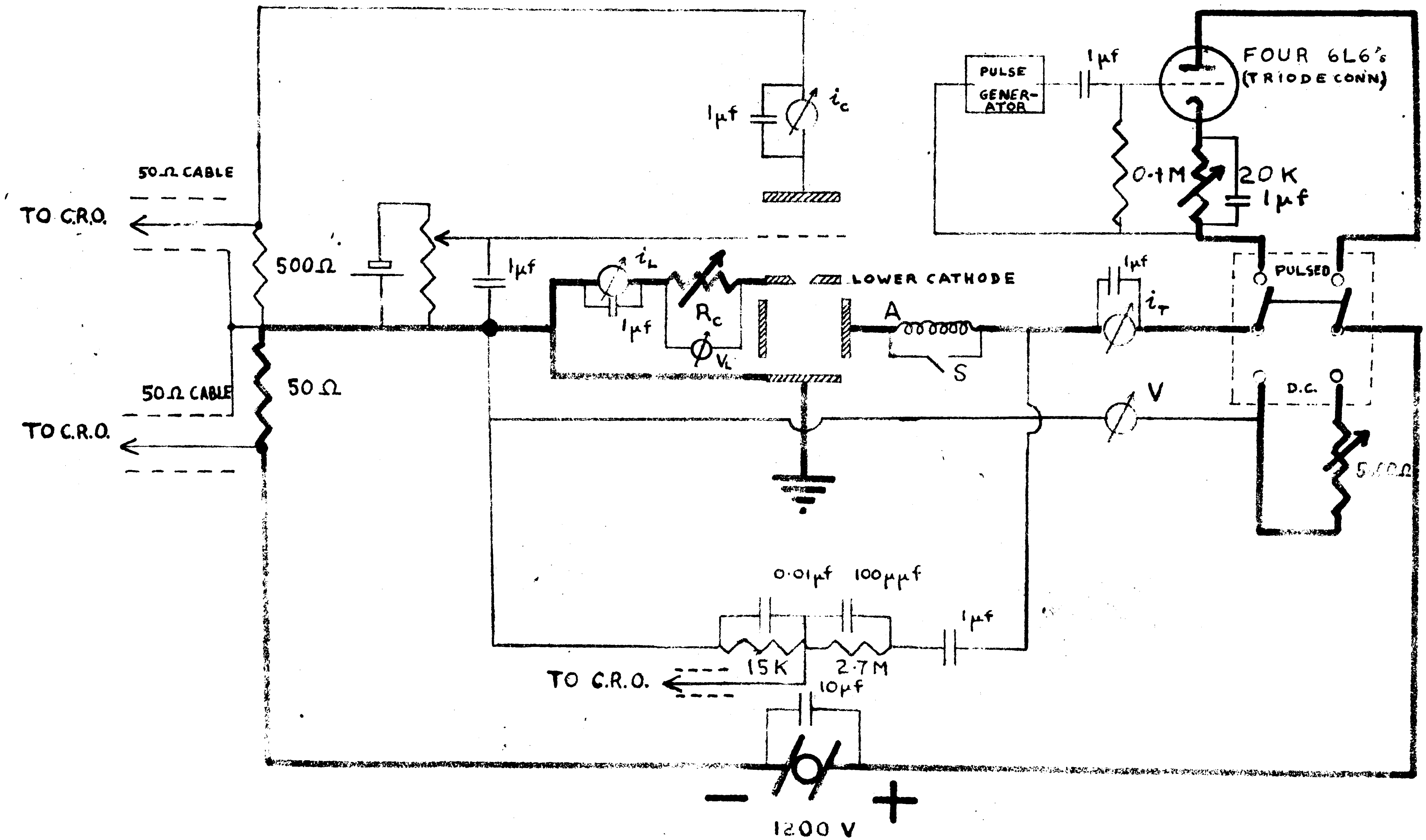


FIG. 42

ELECTRICAL CIRCUIT (schematic)

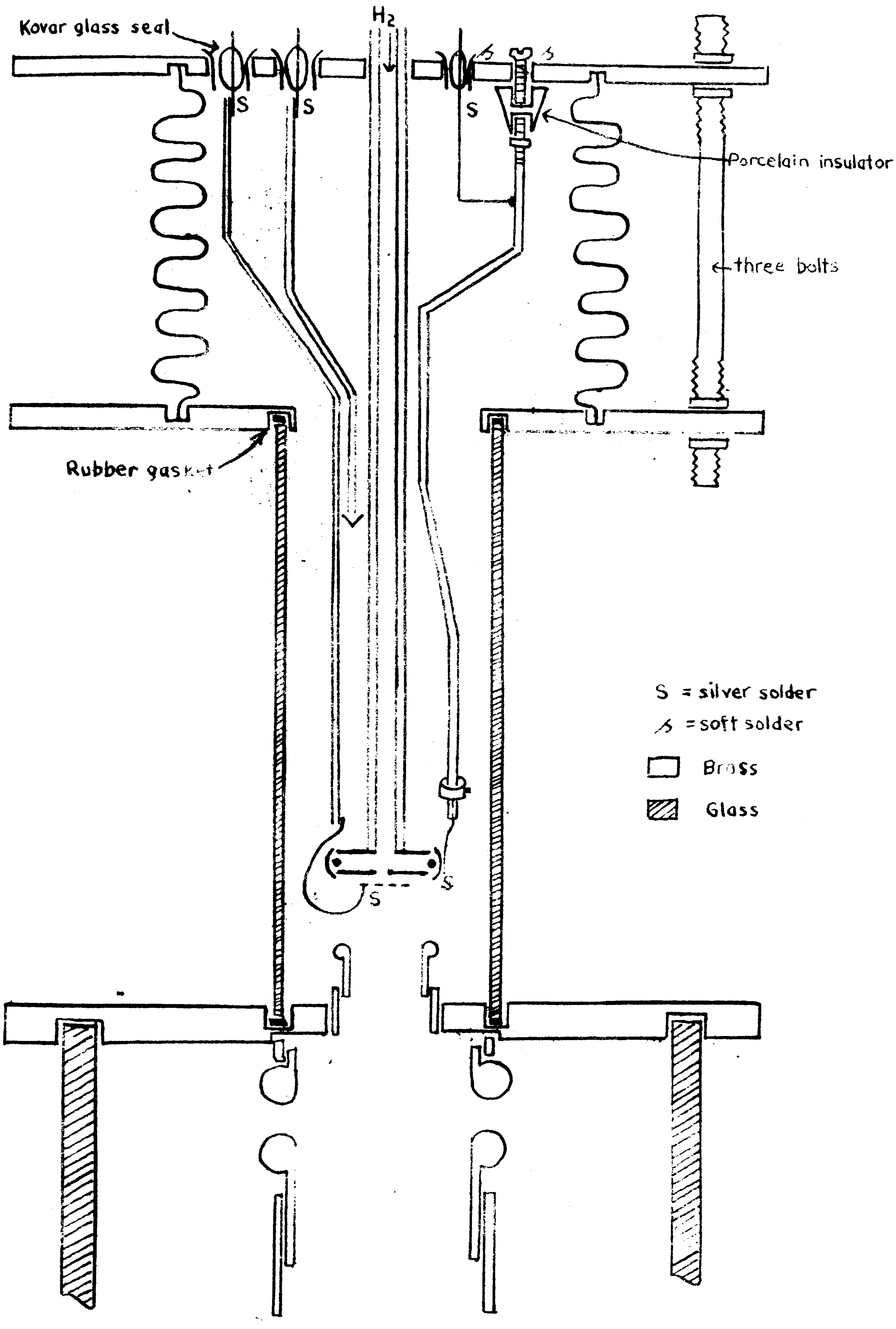


Fig. 4[illegible]

ION SOURCE (actual size)

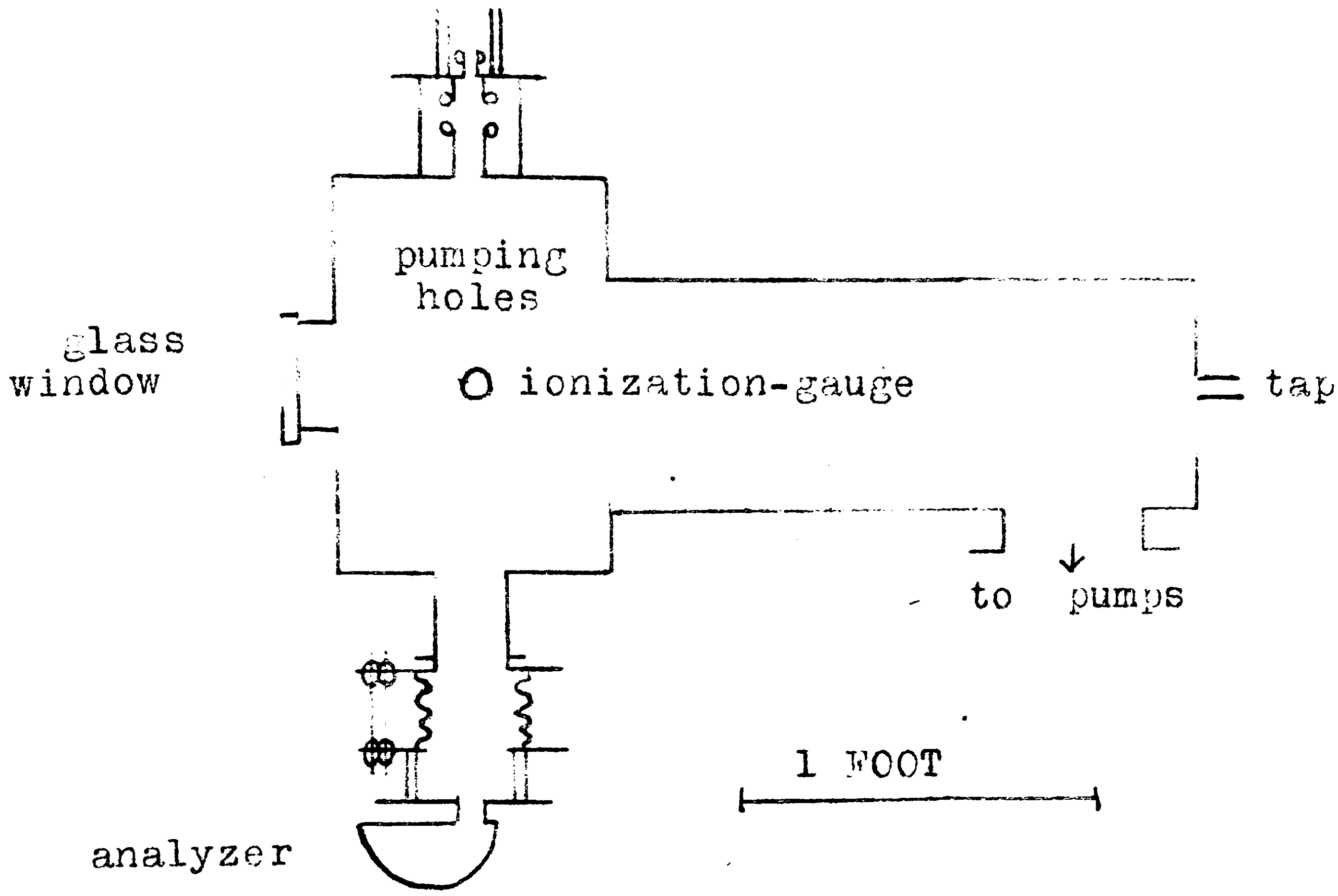


FIG.44

VACUUM SYSTEM (OVERALL)

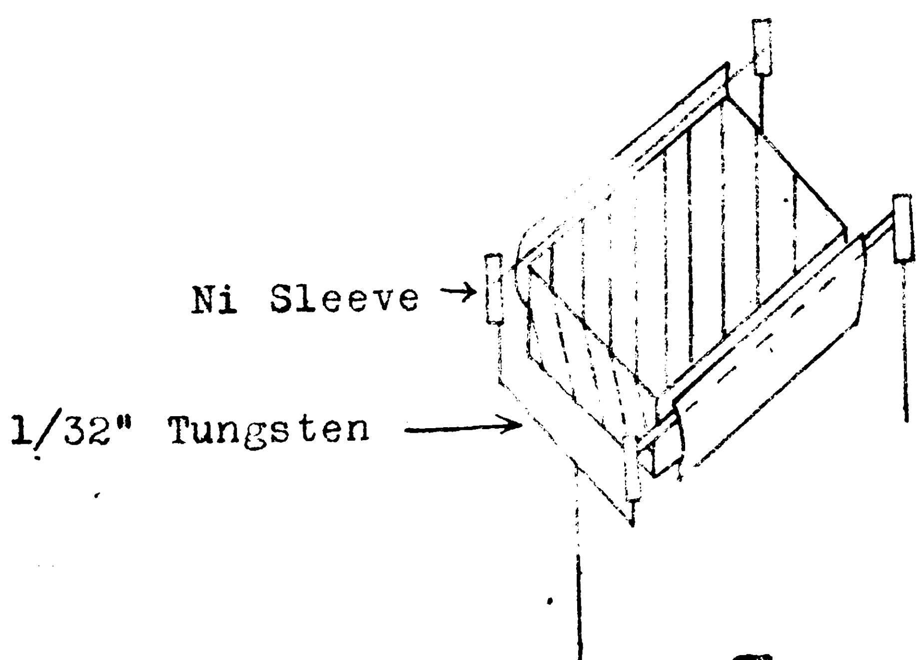


FIG.45

ANODE BOX, FILAMENTS, AND SHIELDS

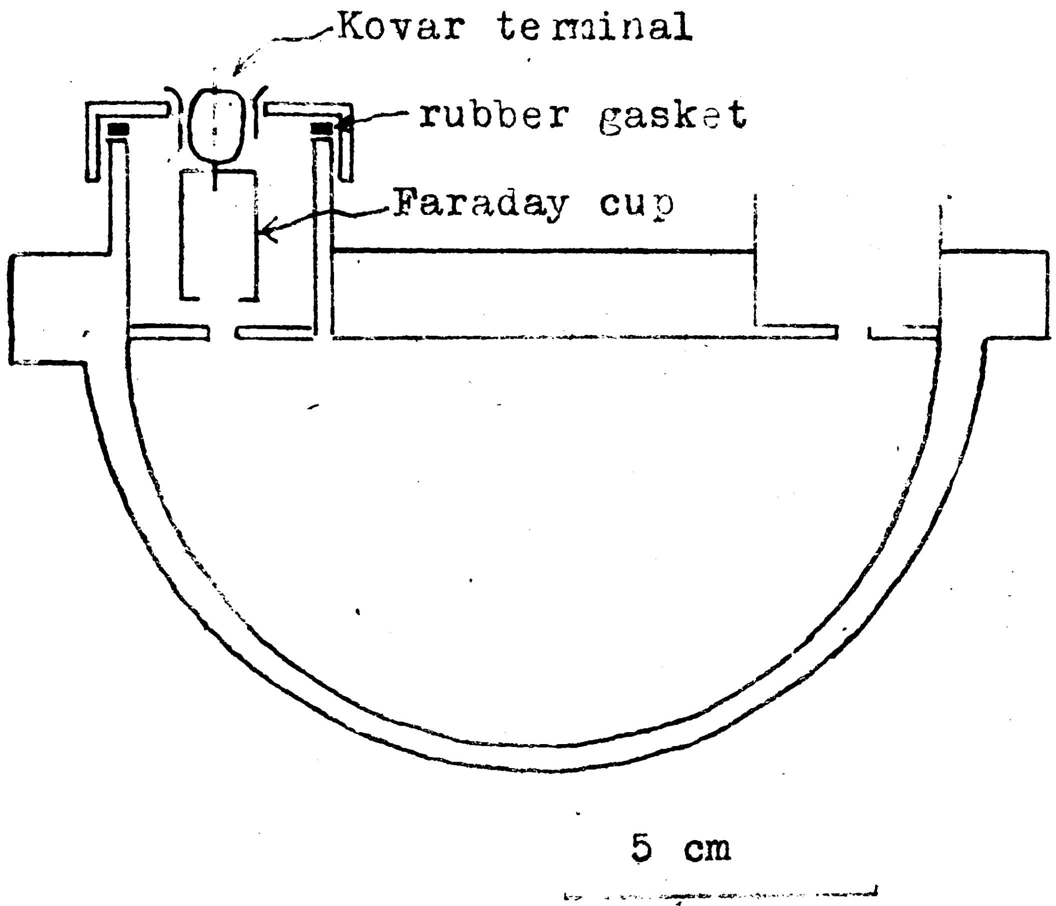


FIG. 46

ANALYZER

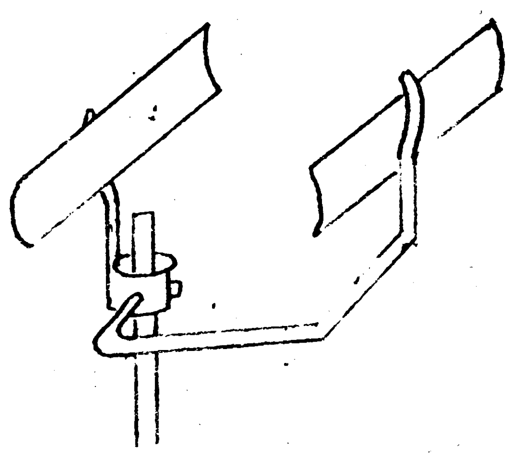


FIG. 47

REFLECTING SHIELD ASSEMBLY

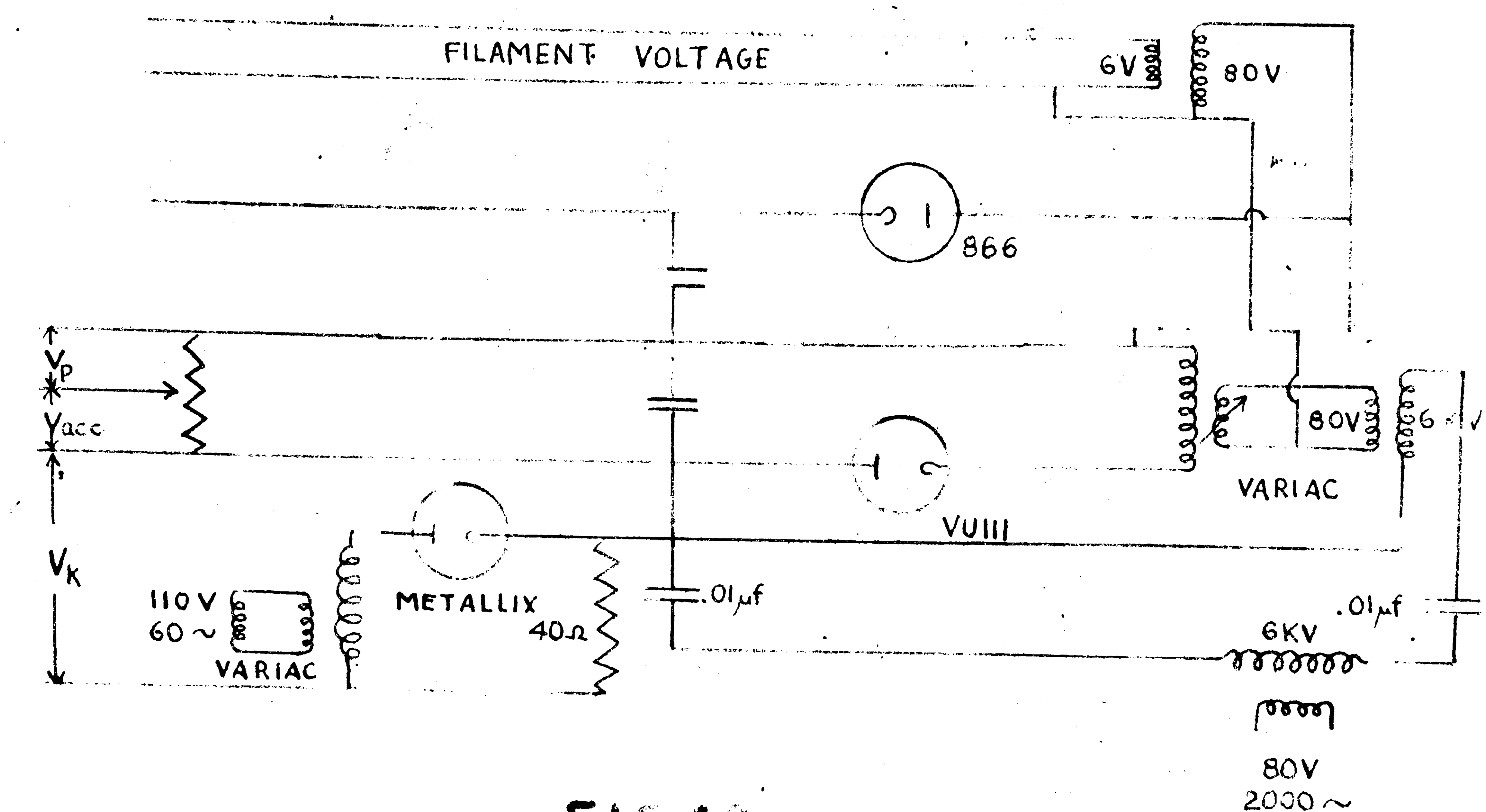
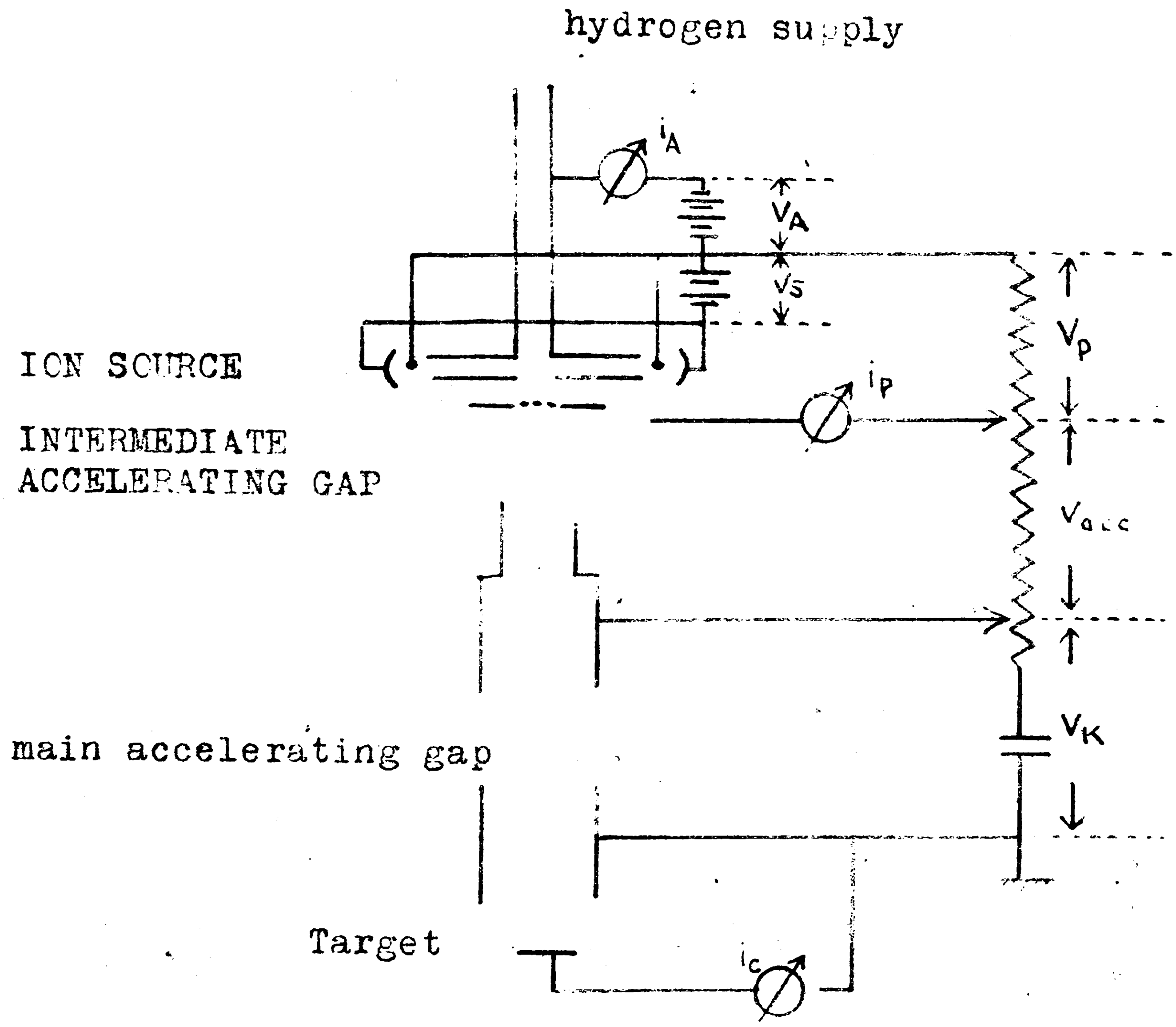


FIG.48

ELECTRICAL CIRCUITS FOR THE HEIL-v.ARDENNE SOURCE
(Operation and Acceleration)



ELECTRICAL CONNECTIONS TO THE ION SOURCE

FIG. 49

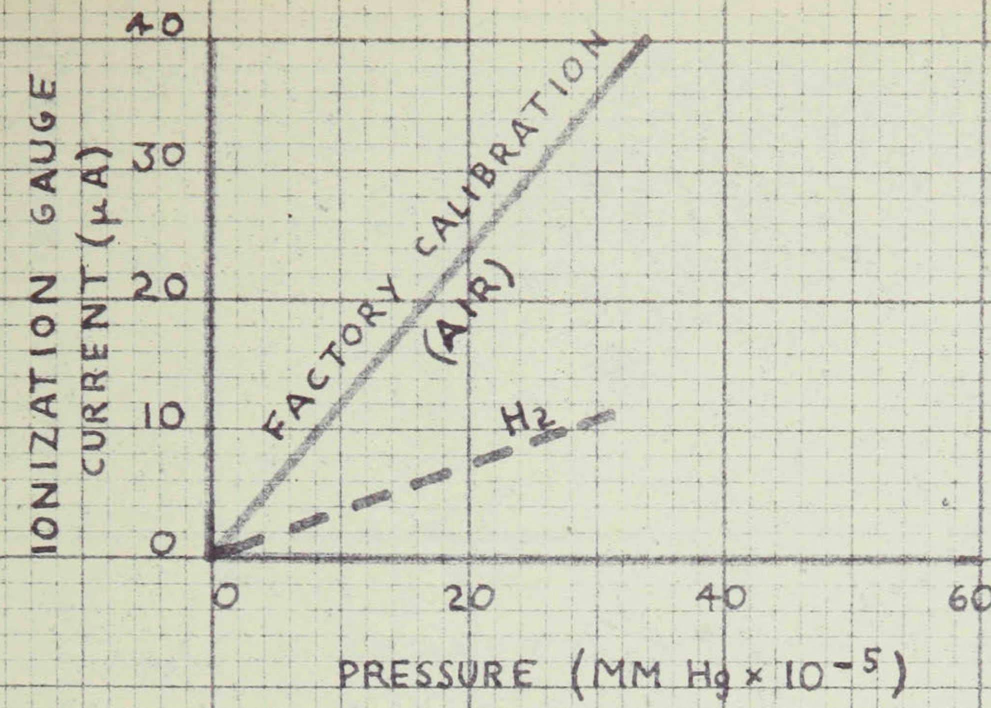


FIG. 50

AIR AND HYDROGEN CALIBRATION OF IONIZATION-GAUGE.

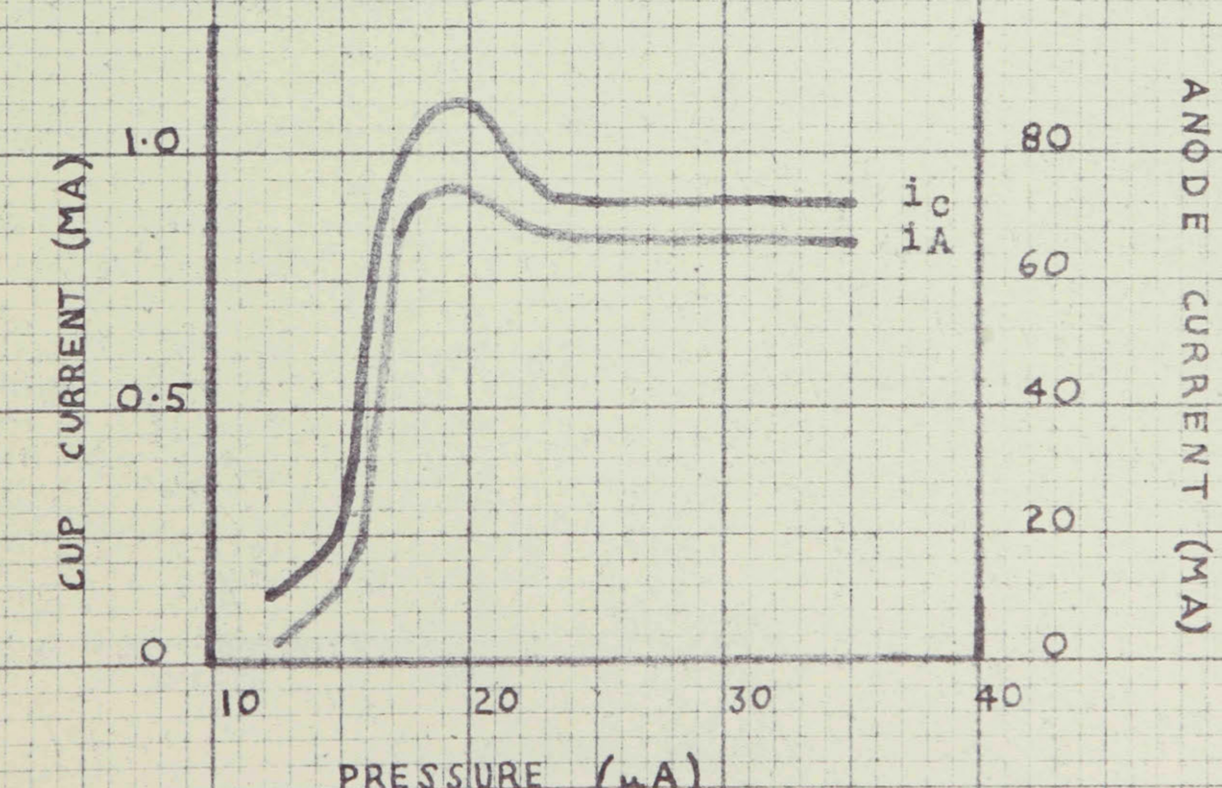


FIG. 51

CUP AND DISCHARGE CURRENTS vs. PRESSURE

($V_A = 233$ V; $V_p = -466$ V)

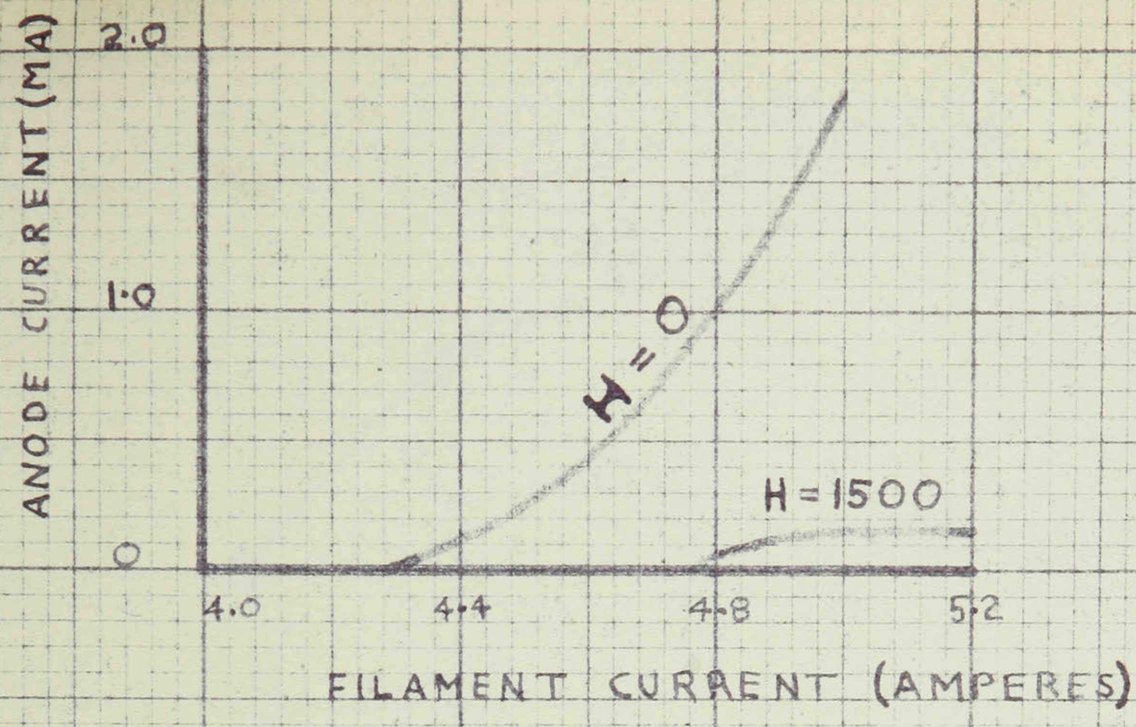


FIG.52

CURVES SHOWING EFFECT OF FIELD ON ANODE CURRENT
($p = 7\mu A$; $V_A = 200$ V; $V_S = -50$ V)

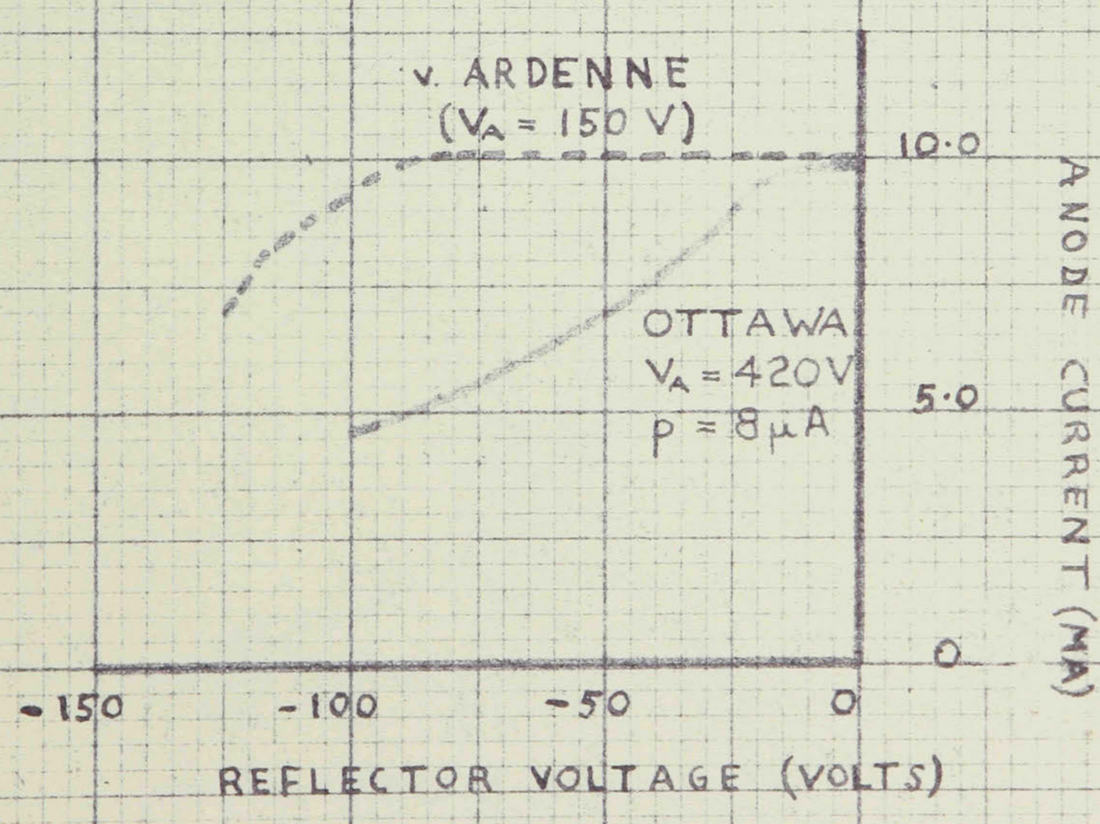


FIG. 53

EFFECT OF REFLECTOR VOLTAGE ON ANODE CURRENT.
von Ardenne's curve is given for comparison.

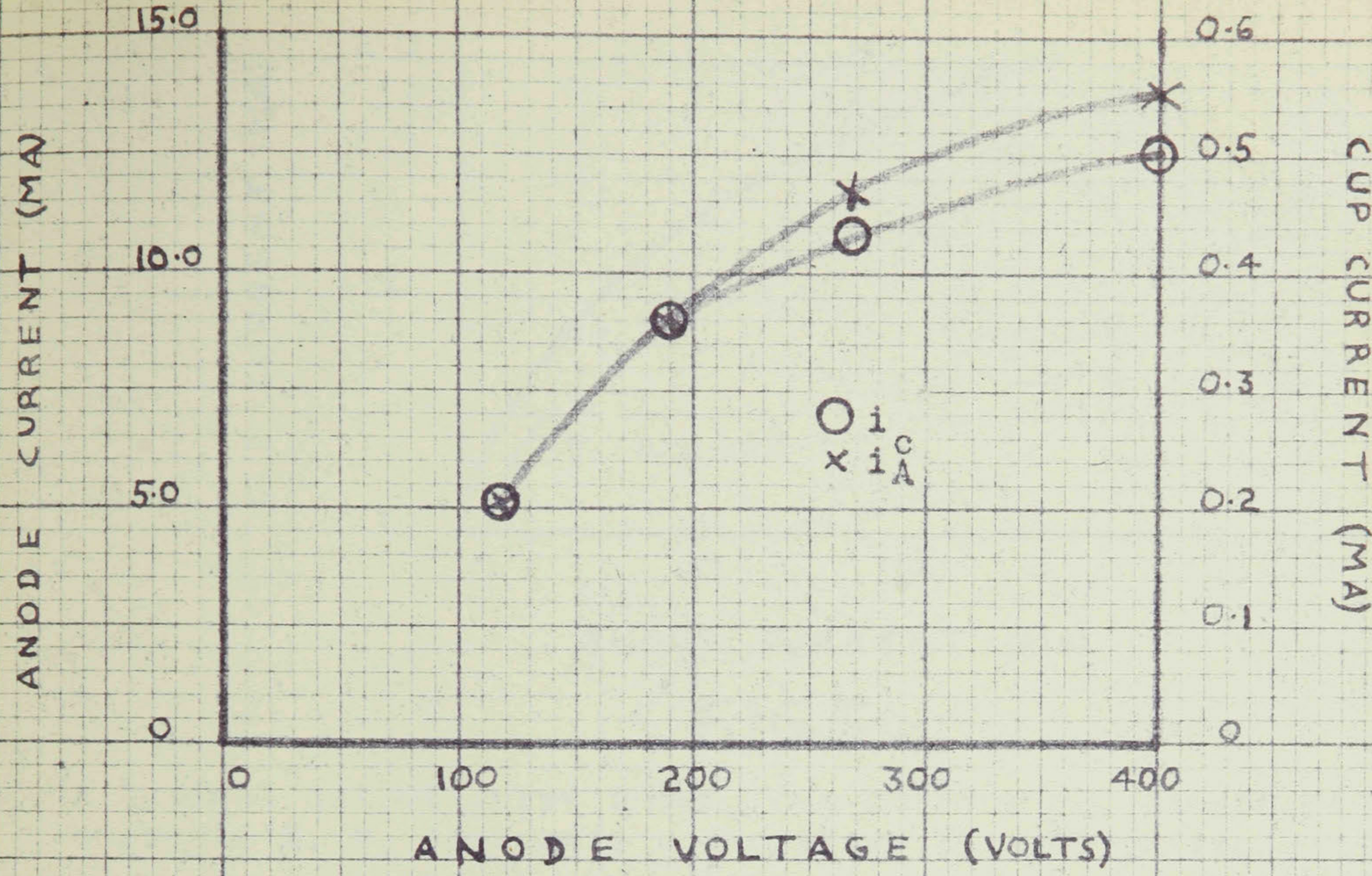


FIG. 54

CUP AND ANODE CURRENTS vs. ANODE VOLTAGE
($p = 15\mu A$; $V_s = -15V$; $V_p = -410$ V)

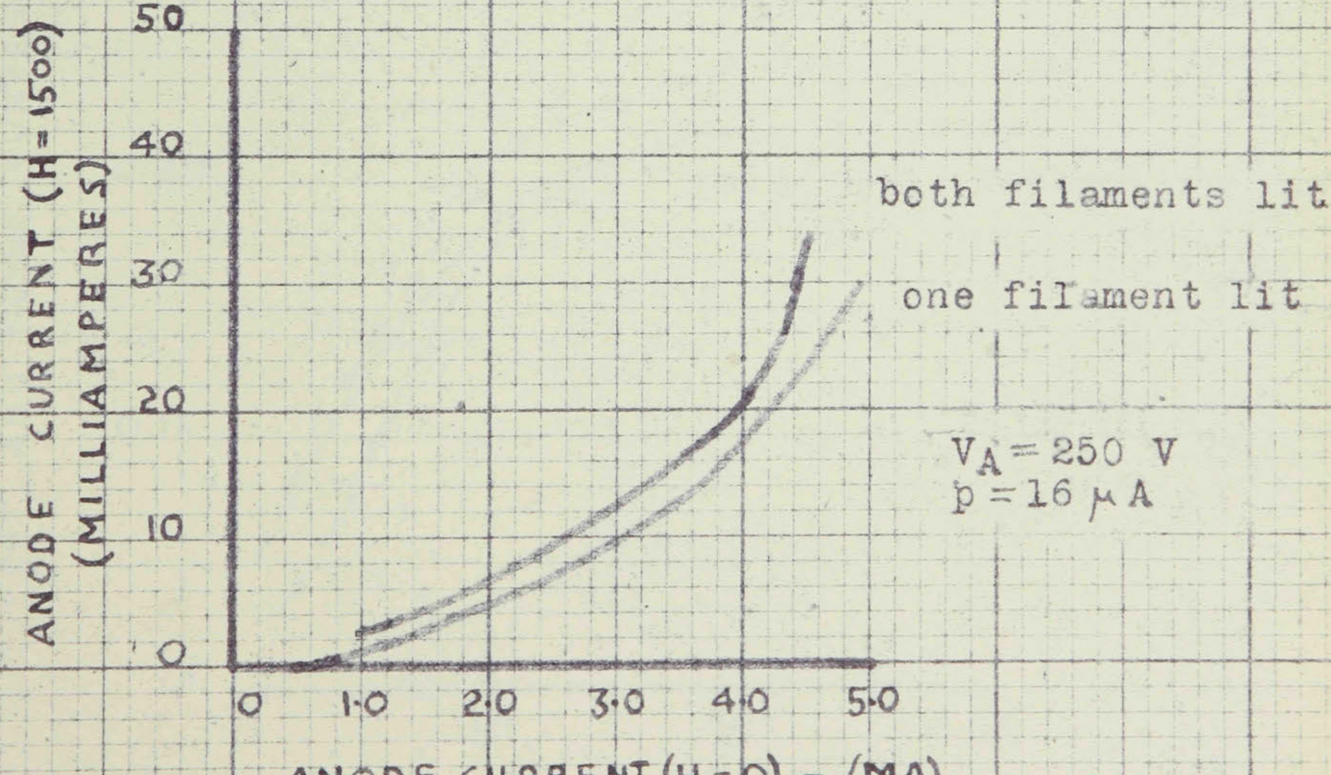


FIG. 55

CURVES SHOWING ANODE CURRENT WITH MAGNETIC FIELD ON FOR ONE AND TWO FILAMENTS RESPECTIVELY. THE ABSCISSA REPRESENTS REFERENCE VALUES OF ANODE CURRENT WITH FIELD OFF (STRAIGHT DIODE EMISSION)

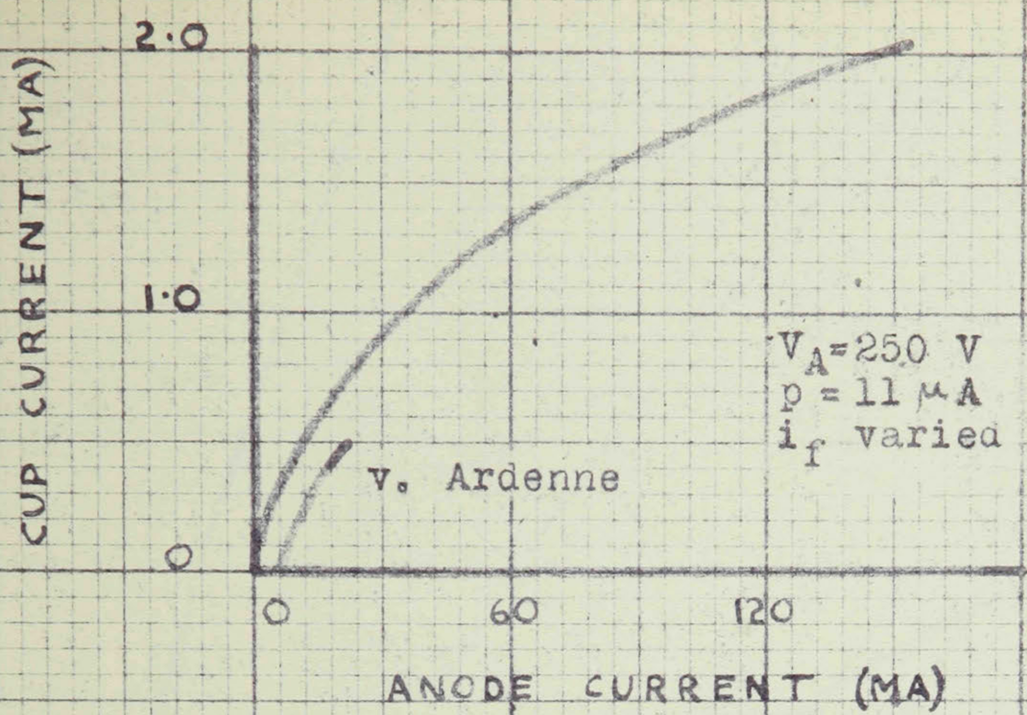


FIG.56

A typical output curve showing cup current vs. discharge current. M. v. Ardenne's curve shown for comparison.

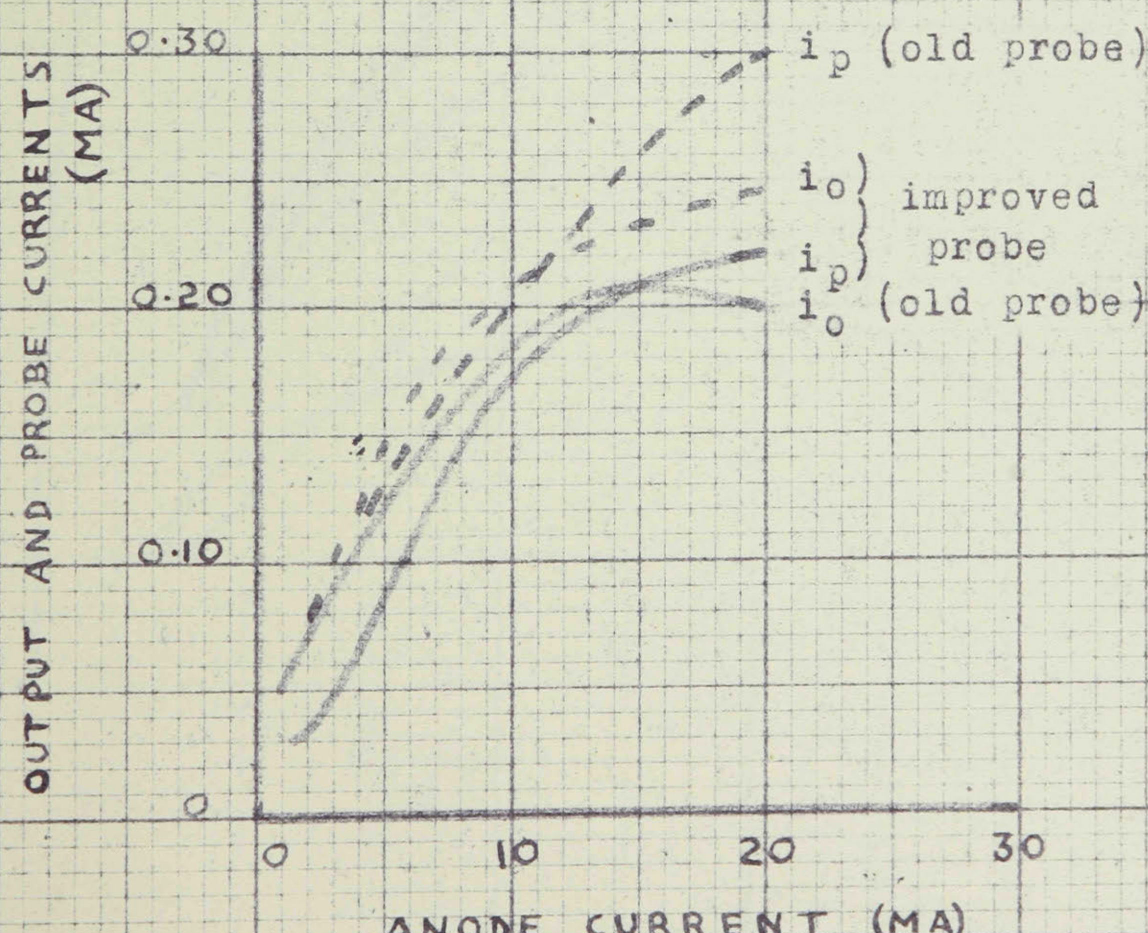
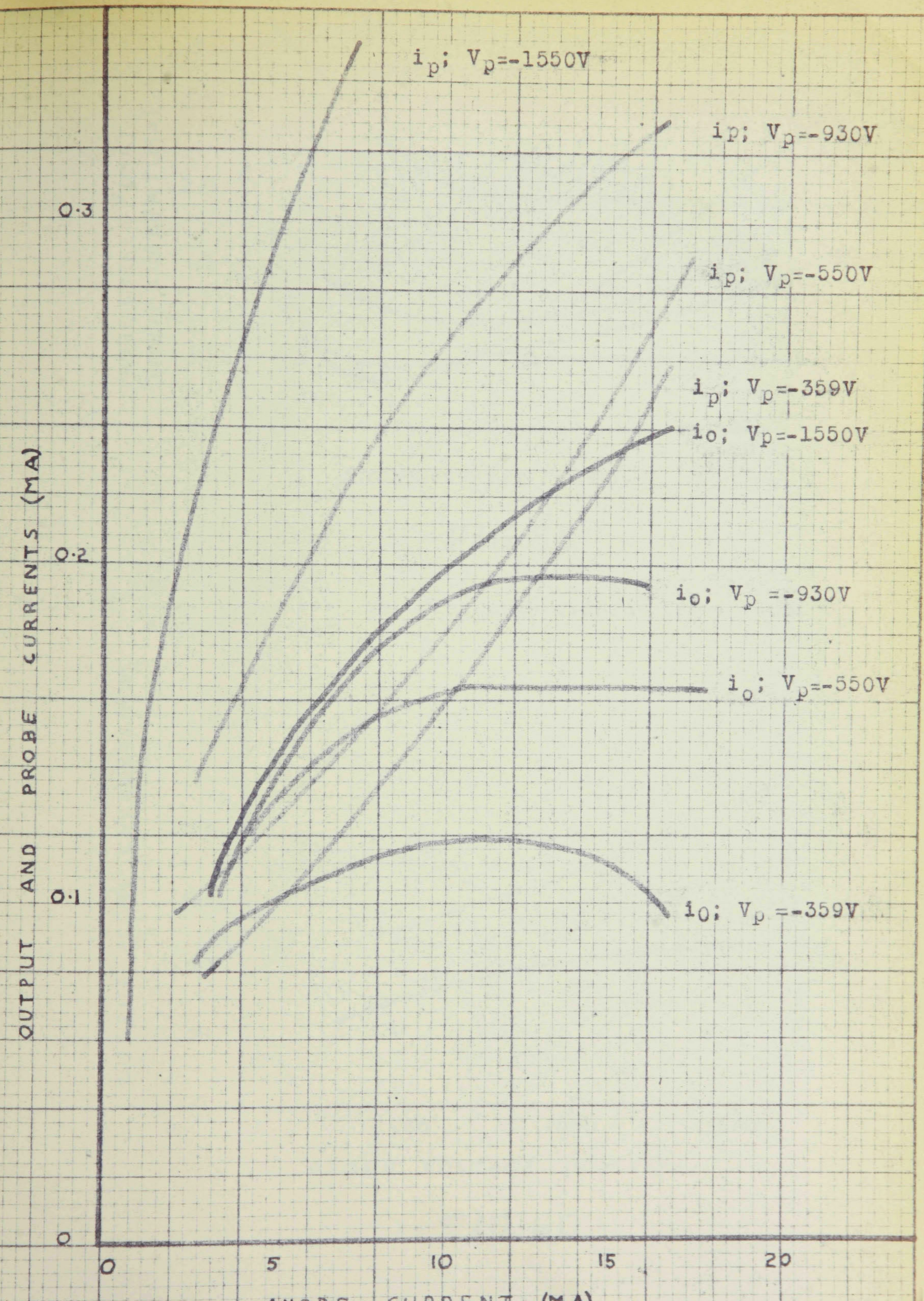


FIG.57

Improvement of output by use of a differently constructed probe.



i_p; V_p=-1550V
i_p; V_p=-930V
i_p; V_p=-550V
i_p; V_p=-359V
i_o; V_p=-1550V
i_o; V_p =-930V
i_o; V_p=-550V
i_o; V_p =-359V
0.3
0.2
0.1
0
0
5
10
15
20
OUTPUT AND PROBE CURRENTS (MA)
ANODE CURRENT (MA)

FIG. 58

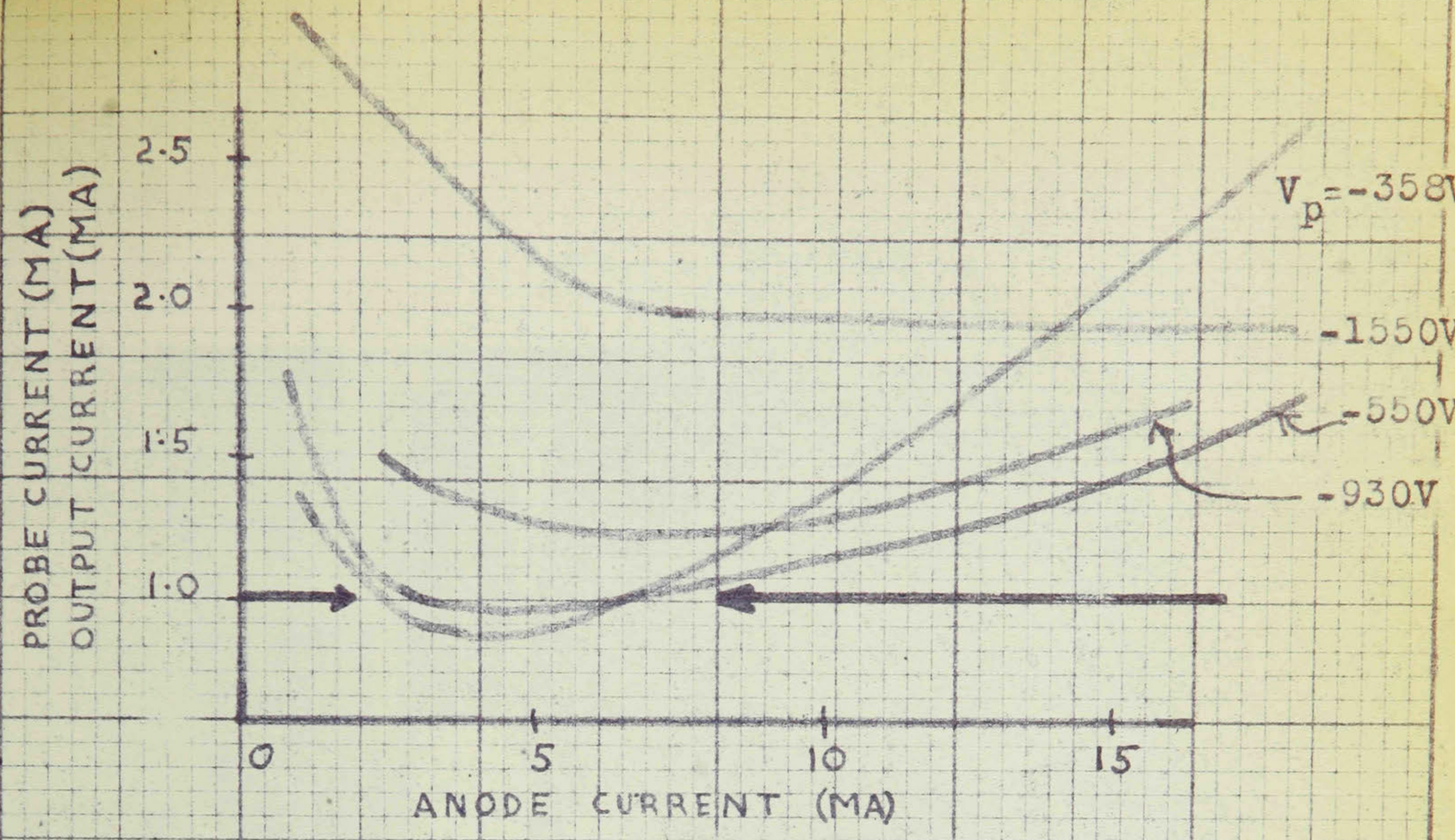


FIG. 59

Ratio of $\dfrac{\text{probe current}}{\text{output current}}$ vs. discharge current for various V_p

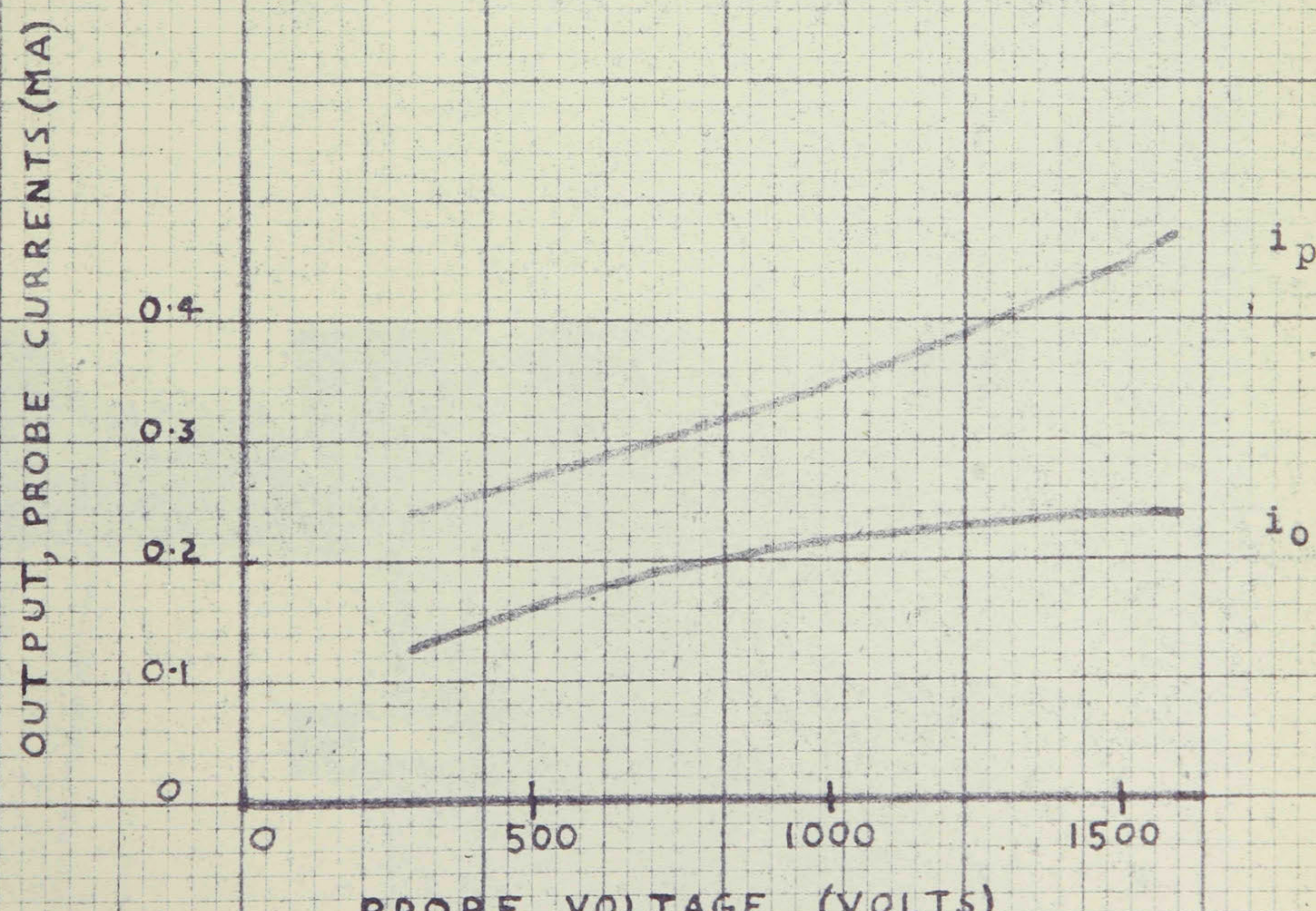
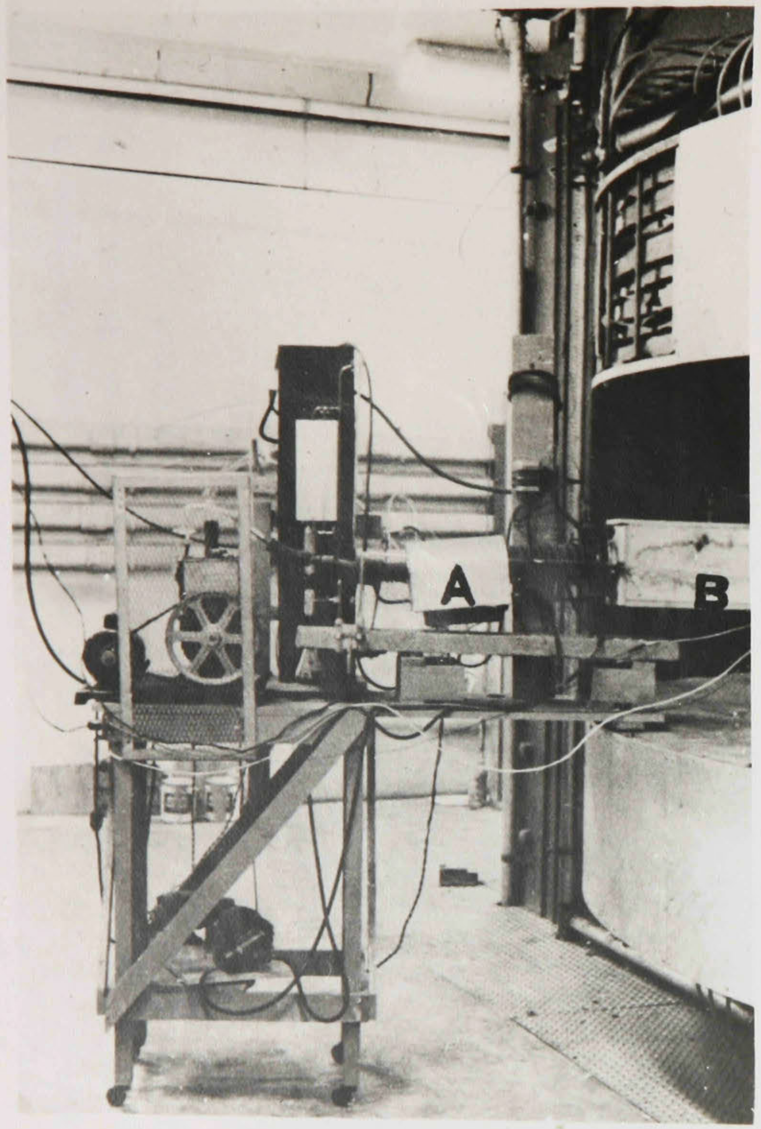
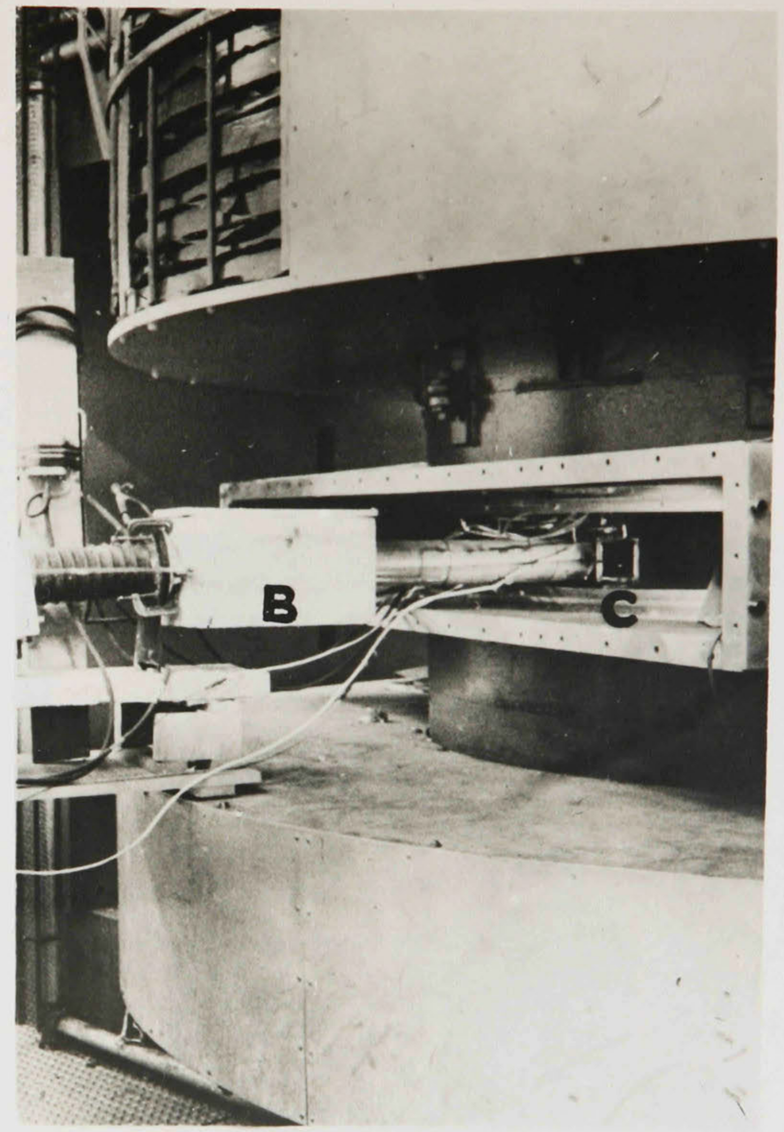


FIG. 60

Variation of output and probe current with probe voltage

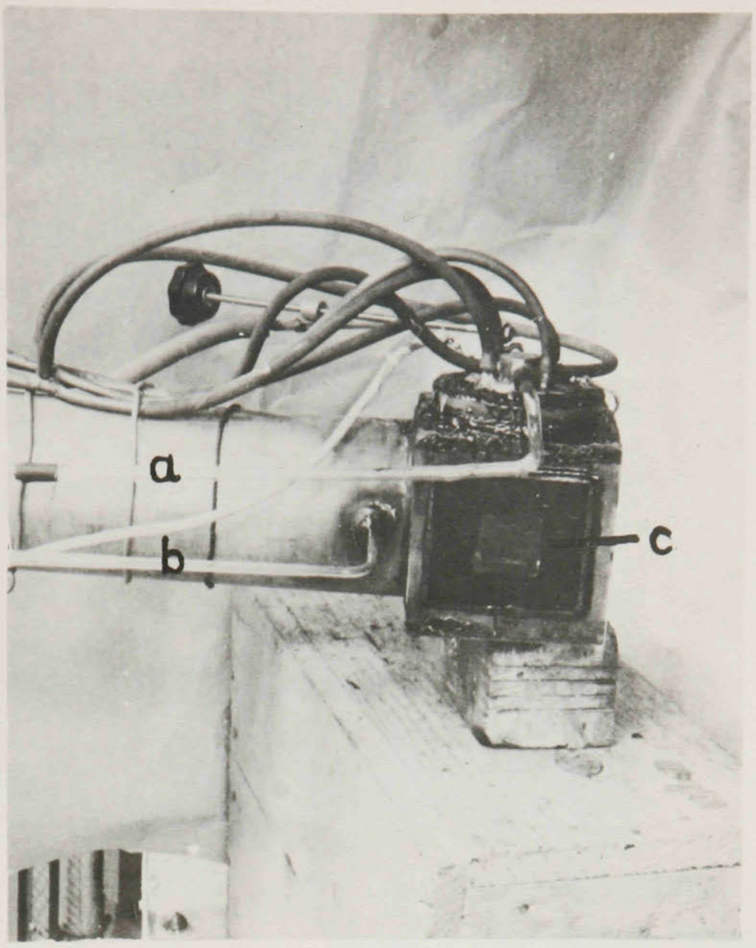


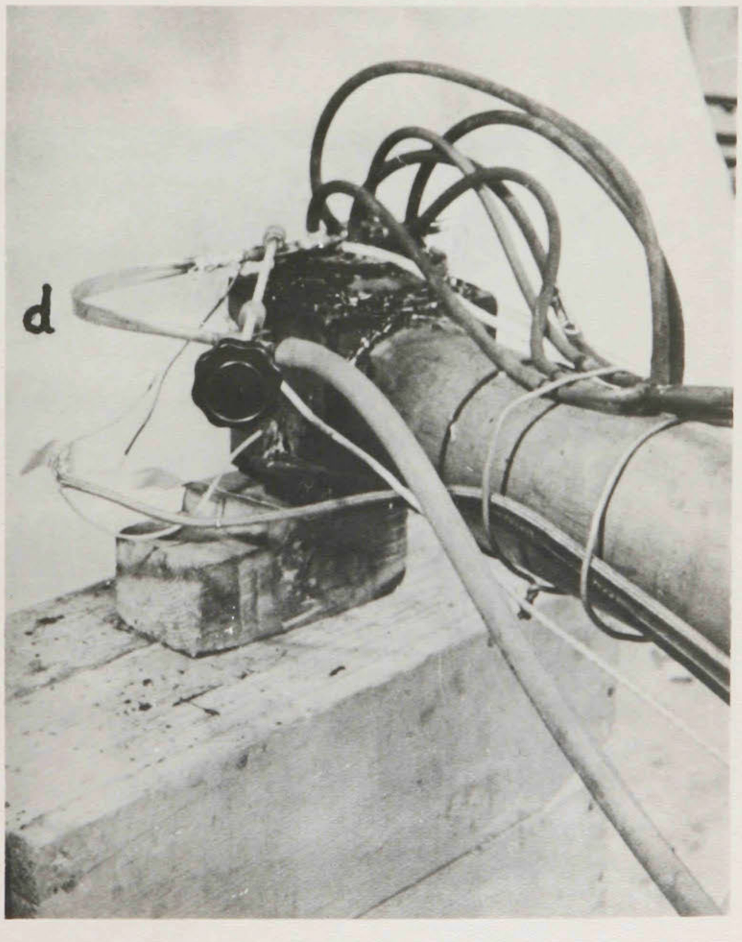


THE PUMPING SYSTEM IN POSITION IN THE CYCLOTRON MAGNET

A - DIFFUSION PUMP B - DRY ICE BOX C - ION SOURCE CHAMBER AND ION SOURCE

PLATE I





ION SOURCE VACUUM CHAMBER WITH SPACER MODEL IN POSITION

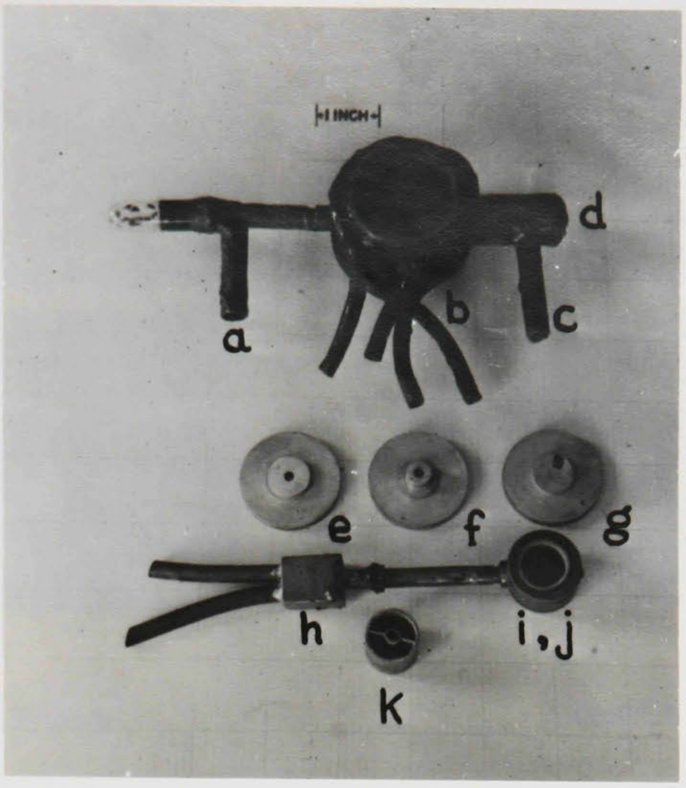
a. ION SOURCE PRESSURE MEASURING LEAD

b. CHAMBER PRESSURE MEASURING LEAD

c. WINDOW FOR OBSERVING BEAM

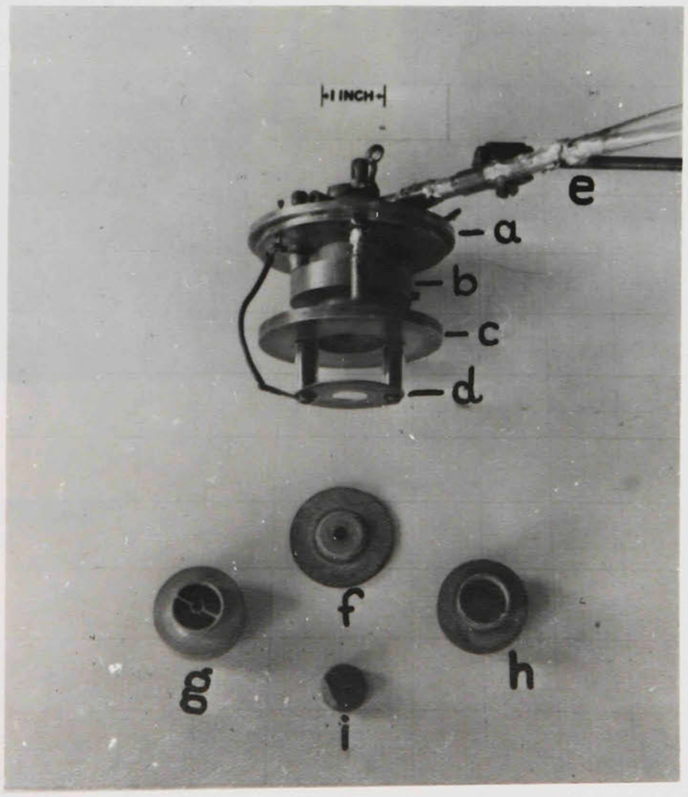
d. FOWLER VARIABLE GAS LEAK

PLATE 11



ENCLOSED MODEL SOURCE-COMPONENTS

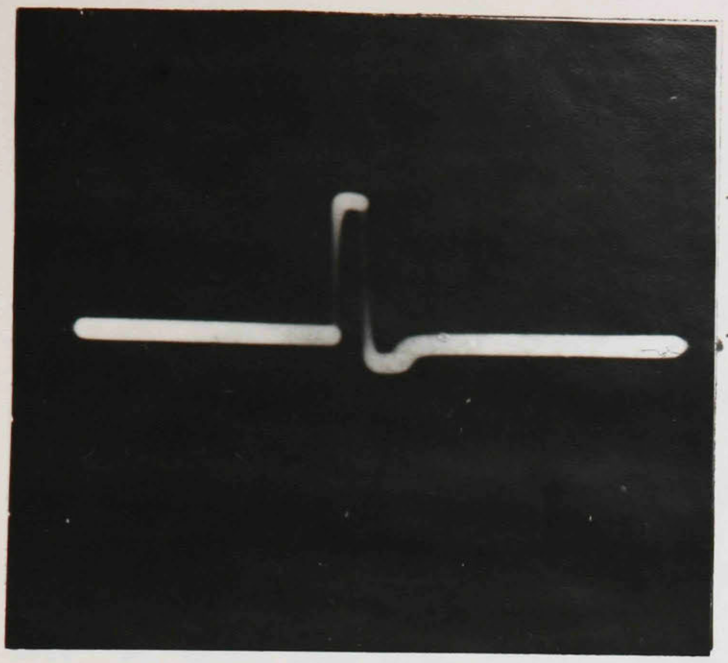
a – ATTACHMENT FOR McLEOD GAUGE
b – BODY OF SOURCE. CATHODE VISIBLE AT BOTTOM
c – ATTACHMENT FOR FOWLER LEAK
d – SHEATH FOR COAXIAL ANODE LEAD
e, f, g – EXTRACTING CATHODES
h – WATER COOLED ANODE LEAD
i, j – ANODE JACKET, CYLINDER ANODE
k – EJECTOR ANODE



SPACER MODEL SOURCE AND ELECTRODES

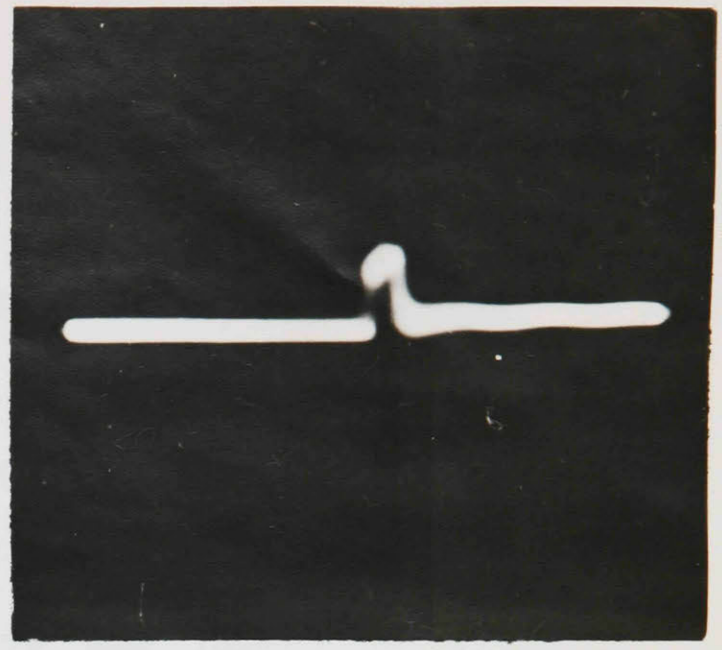
a – TOP CATHODE HOLDER
b – ANODE JACKET
c – LOWER CATHODE JACKET
d – ACCELERATOR
e – FOWLER LEAK
f – LOWER CATHODE
g – EJECTOR ANODE
h – CYLINDER ANODE
i – TOP CATHODE (INVERTED, SHOWING BEVELLING FOR GAS INLET AND OUTLET TO McLEOD GAUGE.)

PLATE III



153v

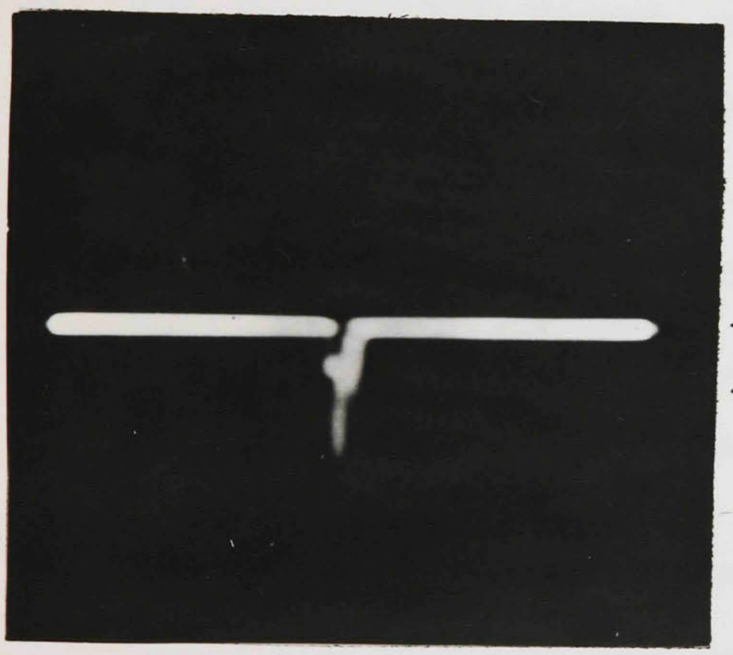
PULSE APPLIED TO GRID OF 6L6



450v

SOURCE VOLTAGE TRACE

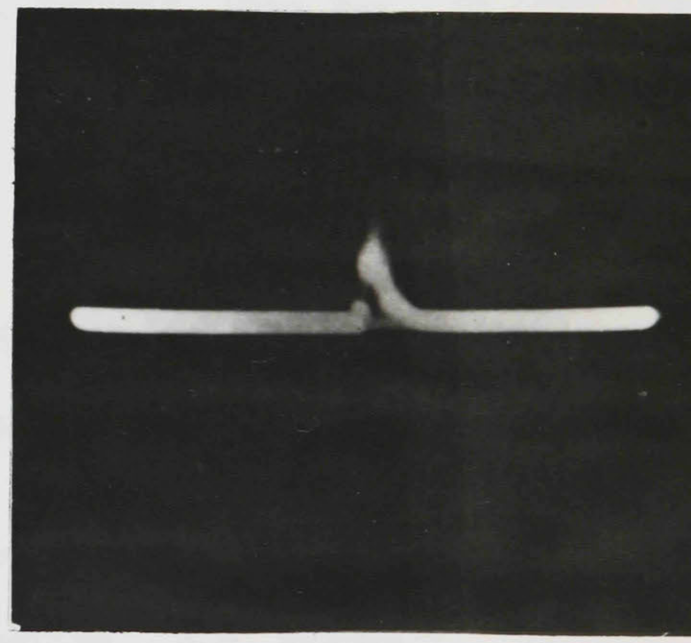
POSITIVE



320 mA

POSITIVE

DISCHARGE CURRENT TRACE



26 mA

ION OUTPUT CURRENT TRACE

PHOTOGRAPHS OF OSCILLOGRAPH TRACES IN PULSED OPERATION

ASYMMETRIC OPERATION, CYLINDER ANODE, CALCIUM ELECTRODES, 3/16 INCH HOLE.

H=16,000 OERSTEDS, P= 8.5 MICRONS, V_G=0. BIASING RESISTANCE = 276 KΩ

REPETITION FREQUENCY = 796/SEC. PULSE LENGTH = 30 μSEC.

SWEEP: LEFT TO RIGHT

PLATE IV

BIBLIOGRAPHY

A1. N.Z. Alcock, N.R.C. Laboratories, Chalk River, private comm.

A2. M. v.Ardenne, Physik. Zeitsch., 43, 91, 1942

A3. M. V.Ardenne, Zeitsch. f. Phys., 121, 236, 1943

B1. A.J. Bayly and A.G. Ward, Can.J.Res., A26, 69, 1948

B2. D. Bohm and L.L. Foldy, Phys.Rev., 72, 649, 1947

B3. Brillouin, Proc. I.R.E., 32, 216, 1944

B4. W.E. Burcham, N.R.C. Document MP-176, 1945

C1. K.T. Compton, L.A. Turner, and W.H. McCurdy, Phys.Rev., 24, 597, 1924

C2. H.R. Crane, C.C. Lauritsen, and A. Soltan, Phys. Rev., 45, 507, 1934

D1. Dushman and Young, Phys. Rev., 69, 278, 1945

F1. A.T. Finkelstein, Rev. Sci. Inst., 11, 94, 1940

F2. R.D. Fowler, Rev. Sci, Inst., 6, 26, 1935

G1. "Pulse Generators", G.N. Glasoe and J.V. Lebacqz ed., McGraw Hill Book Co., 1948

H1. Handbuch der Experimentalphysik, Vol.14, part II, section 18

H2. "Principles of Electricity and Magnetism", G.P. Harnwell, McGraw Hill Book Co., 1938

H3. H. Heil, Zeitsch. f. Phys., 120, 212, 1943

H4. Hull, Phys. Rev., 23, 438, 1922

L1. E.S. Lamar and O. Luhr, Phys.Rev., 46,87, 1934

L2. E.S. Lamar, E.W. Samson, and K.T. Compton, Phys.Rev., 48,886,1935

L3. M.S. Livingston, Rev.Mod.Phys., 18, 293, 1946

L4. P. Lorrain, N.R.C. Document PD-158, 1945

Can.Jour.Res., A25, 338, 1947

M1. L.R. Maxwell, Rev.Sci.Inst., 2, 129, 1931

P1. F.M. Penning, Physica, III, 873, 1936 and IV, 71, 1937

P2. R. Planiol, Comptes Rendus, 200, 539 and 730, 1935

Ann. de Physique, 9, 177, 1938

R1. J.R. Richardson, B.T. Wright, E.J. Lofgren, and B. Peters, Phys.Rev., 73, 424, 1948

S1. G.W. Scott, Phys.Rev., 55, 954, 1939

S2. R.L. Stewart, Phys.Rev., 45, 488, 1934

S3. L.P. Smith and P.L. Hartman, J.App.Phys., 11, 220, 1940

T1. M.A. Tuve, O. Dahl, and L.R. Hafstad, Phys.Rev., 48, 241, 1935

W1. A.G. Ward, N.R.C. Document PM-148, 1945

Z1. W.H. Zinn, Phys. Rev., 52, 655, 1937