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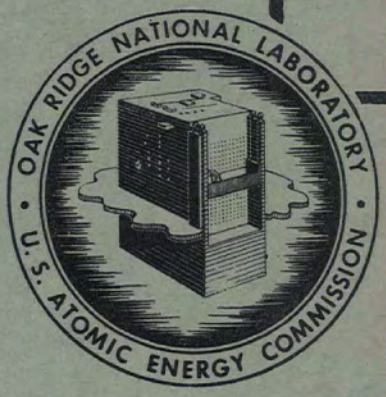
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STABLE ISOTOPE RESEARCH AND PRODUCTION DIVISION

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ABSTRACT

Results of studies of filament erosion occuring in the separation of stable isotopes is presented Erosion is shown to be dependent on arc power and a method of reducing arc power without seriously decreasing ion output is also presented

PREFACE

This report is based on research by the author under the direction of Dr J R McNally as partial fulfillment of requirements for a Master of Science degree from the Louisiana State University The cooperation of Professors V E Parker and R C Keen of Louisiana State University was particularly appreciated

FILAMENT LIFE IN LOW PRESSURE ARC TYPE ION SOURCE

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INTRODUCTION

Although the study of cathode sputtering in electrical discharges has been in progress for many years, relatively little attention has been given to cathode erosion and related phenomena occurring in low pressure, low voltage arc discharges Except for papers by A W Hull[1], C H Townes[2], no published literature on the subject has been found, however, in the unpublished work of the Stable Isotope Division of the Oak Ridge National Laboratory there is a considerable volume of data some of which will be summarized here

Attempts to lengthen cathode service life in the calutron[3] have led to tests of various cathode materials with both direct and indirect heating The cathode finally adopted for use in the separation of the stable isotopes, and still in use after seven years of the program, consists of a four-inch length of 170-mil or 145-mil tantalum, bent into an approximately U-shape and heated by the passage of currents up to 500 amperes

The service life of this type filament was found to vary markedly, and often unpredictably with the element being processed For mercury separations a filament life of 200 hours was obtained, but for iron and titanium the service life was only 15 to 20 hours For most elements the service life fell between 30-50 hours

The reasons for filament failure fall into three general categories (1) the formation of growths on the filament, (2) alloying or chemical reaction

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1 A W Hull, General Electric Review 32, 213 (1929)

2 C H Townes, Phys Rev 65, 319 (1944)

3 A H Barnes, S. M McNeille, and C Starr, NNES Div I, Vol 8, Chapter 2

of the filament with the element being processed, and (3) erosion or sputtering of the filament, particularly in the region exposed to bombardment by positive ions from the arc

Filament growths have been observed only in the processing of uranium Uranium deposited on the surface of the filament alloys with tantalum forming a low melting point alloy which migrates to one side of the filament due to electromagnetic forces perpendicular to both the magnetic field and the filament current As the growth builds up over a period of several days, large quantities of tantalum are transferred from the filament to the growth, cavitation develops in the filament and mechanical breakage or melting due to intense local heating eventually results The rate and character of growth formations were very sensitive to arc conditions and were usually controlled by restricting operation to a narrow range of arc voltage and current values Also, the use of alternating rather than direct filament heating current effectively prevented growth formation

Most materials alloy or react chemically, to some extent, with the tantalum filaments under prevailing operating conditions The result can be somewhat beneficial as in the case of low work function elements such as barium, where surface electron emission is increased, or it can be extremely detrimental as in the case of antimony and cadmium where the filament is rapidly destroyed

It has been established[4] that both the rate of growth formation and the extent of alloying or chemical reaction depend on the ion bombardment rate, and, therefore, on the ion production rate in the arc Both singly and multiply charged ions are formed in the arc and all arrive at the cathode with maximum energy approximately equal to the arc voltage

THEORY AND OPERATION OF THE ARC SOURCE

A diagram of the calutron arc source is shown in Figure 1 Electrons emitted

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4 A H Barnes, S M McNeille, and C Starr, NNES Div I, Vol 8, page 79

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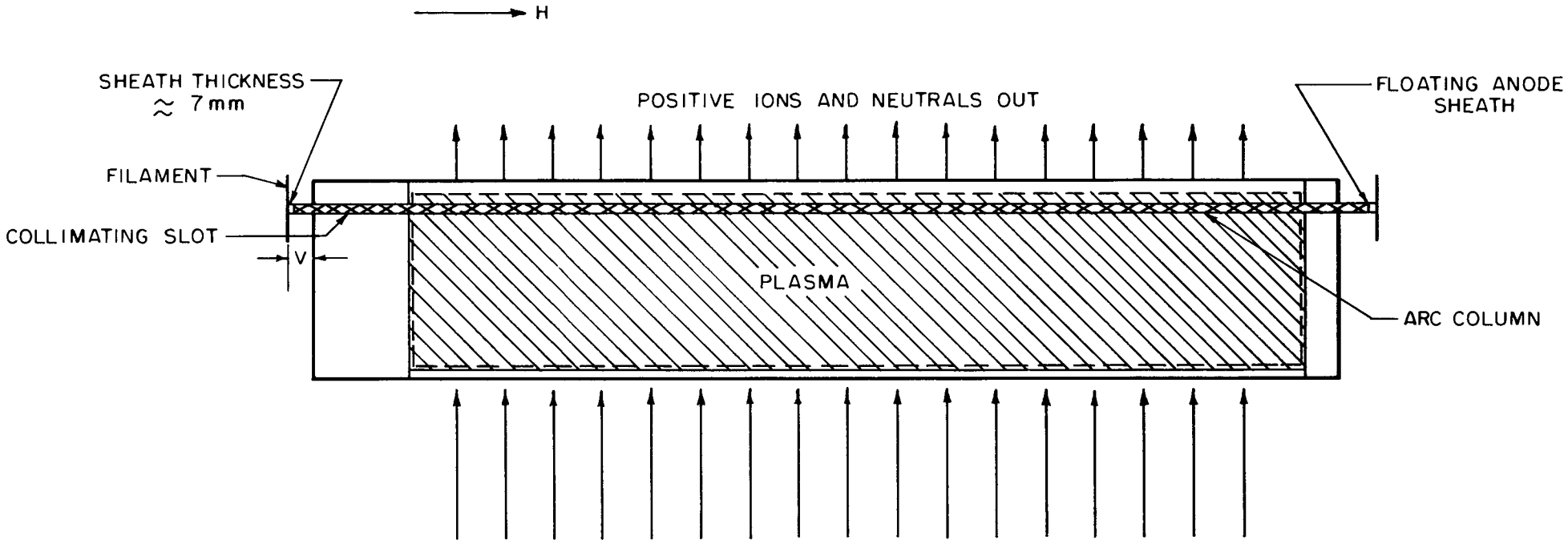


FIGURE 1 CALUTRON ION SOURCE

from the filament and accelerated by the filament-to-arc-chamber voltage are directed as a collimated beam along the length of the arc chamber to the "floating" anode where they are reflected back along their paths Constrained by the magnetic field, the electrons continue to oscillate until drained off to the walls of the arc chamber or collimating slot[5] When the gas pressure in the arc chamber is raised sufficiently ($\sim$2 microns) an arc strikes between filament and arc chamber The arc is collimated by the magnetic field and the collimating slot to a narrow column The entire arc chamber, however, is filled by the arc plasma

The ion density in the chamber[6] is given approximately by $n = n_o e^{-x/d}$ when n_o is the ion density at the column surface, x is the distance from the column, and d is the characteristic distance in which ion density falls to 1/e of its initial value Figure 2 shows a plot of the ion density in the chamber The dotted line shows the actual ion density toward the ion accelerating region This is decreased by the number of ions drawn out by the accelerating voltage

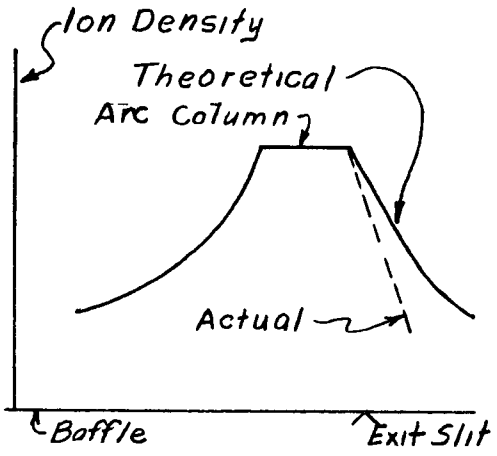


Fig 2 Arc Ion Distribution

Ion motion perpendicular to the magnetic field is constrained by the field to Larmor type orbits while along the field motion of the ions is unrestricted It is these ions moving along the field that reach the filament sheath, are accelarated by the voltage drop across the sheath, and bombard the filament As mentioned before, many schemes have been proposed to deflect or otherwise eliminate the bombarding

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5 For mecahnism involved here see A Guthrie and R K. Wakerling, NNES Div I Vol 5, page 345

6 R L Murray, Document YB-20-67 (1950)

ions The calculations below show that it is necessary for these ions to pass to the filament if arc currents of several amperes are to be obtained

With no gas present and the filament operating space-charge-limited, a good approximation of the electron current density from the filament can be obtained from Childs' law[7]

$$i = \frac{V^{3/2}}{9\, d^2\, M/2e} = \frac{2\ 334 \times 10^{-6} V^{3/2}}{d^2}$$

where d is the distance from filament to arc chamber in centimeters, V is in volts and i in amps/cm^2

For V = 150 volts and d = 0 5 cm (usual calutron conditions), the emission current density is approximately 19 ma per cm^2 of the filament surface Since the total area of a 140-mil filament facing the collimating slot is just over 0 5 cm^2, space-charge-limited current is of the order of 10 ma

When charge gas is present and the arc is struck and an ion sheath is formed, arc currents of 5 amps are easily obtainable This is a current of 10 amp/cm^2 of effective filament surface Therefore, if V is again 150 volts

$$10 = \frac{2\ 334 \times 10^{-6} \times 1\ 9 \times 10^{3}}{X^2}$$

$$X^2 = 2\ 334 \times 10^{-7} \times 1\ 9 \times 10^{3} = 44 \times 10^{-4}$$

$$X = 6\ 7 \times 10^{-2} \text{ cm}$$

or X = 67 mm

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7 Guthrie, A and R K Wakerling, NNES Div I, Vol 5, pp 88-92

The sheath thickness, is therefore, about 7 mm and this thin sheath is necessary if emission currents of observed value are to be obtained Use of anything other than an ion sheath for providing space charge neutralization appears impractical

At the 'floating anode end of the arc a sheath is also formed However, since electrons pass both in and out, twice as many positive ions are necessary at the plasma face Figure 3 shows an idealized potential plot of the arc based on probe measurements[8] Negative voltages are plotted upward Note that the plasma itself is slightly positive with respect to walls of the arc chamber Also note that with the anode "floating" the anode voltage is more negative than the filament With arc voltage at 150 volts anode voltage is approximately 170 volts

Control of the arc-type ion source used in the calutron is normally obtained by use of a "filament-arc regulator" designed to permit independent adjustment of arc current and arc voltage The filament is operated emission-limited with the limiting emission and arc current being manually adjustable by variations of the filament current The arc voltage is also manually adjustable, but changes in arc current that would normally accompany arc voltages changes are prevented by a filament-arc regulator which automatically introduces a compensating variation in the filament current Without filament-arc regulation the arc current varies with arc voltage as shown in Figure 4 Each curve corresponds to some fixed value of filament current, i e , filament temperature With regulation the current-voltage characteristics are shown in Figure 5 Here again each curve corresponds to an initial filament current (emission) setting, but filament

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8 R L Murray, Document YB-20-67 (1950)

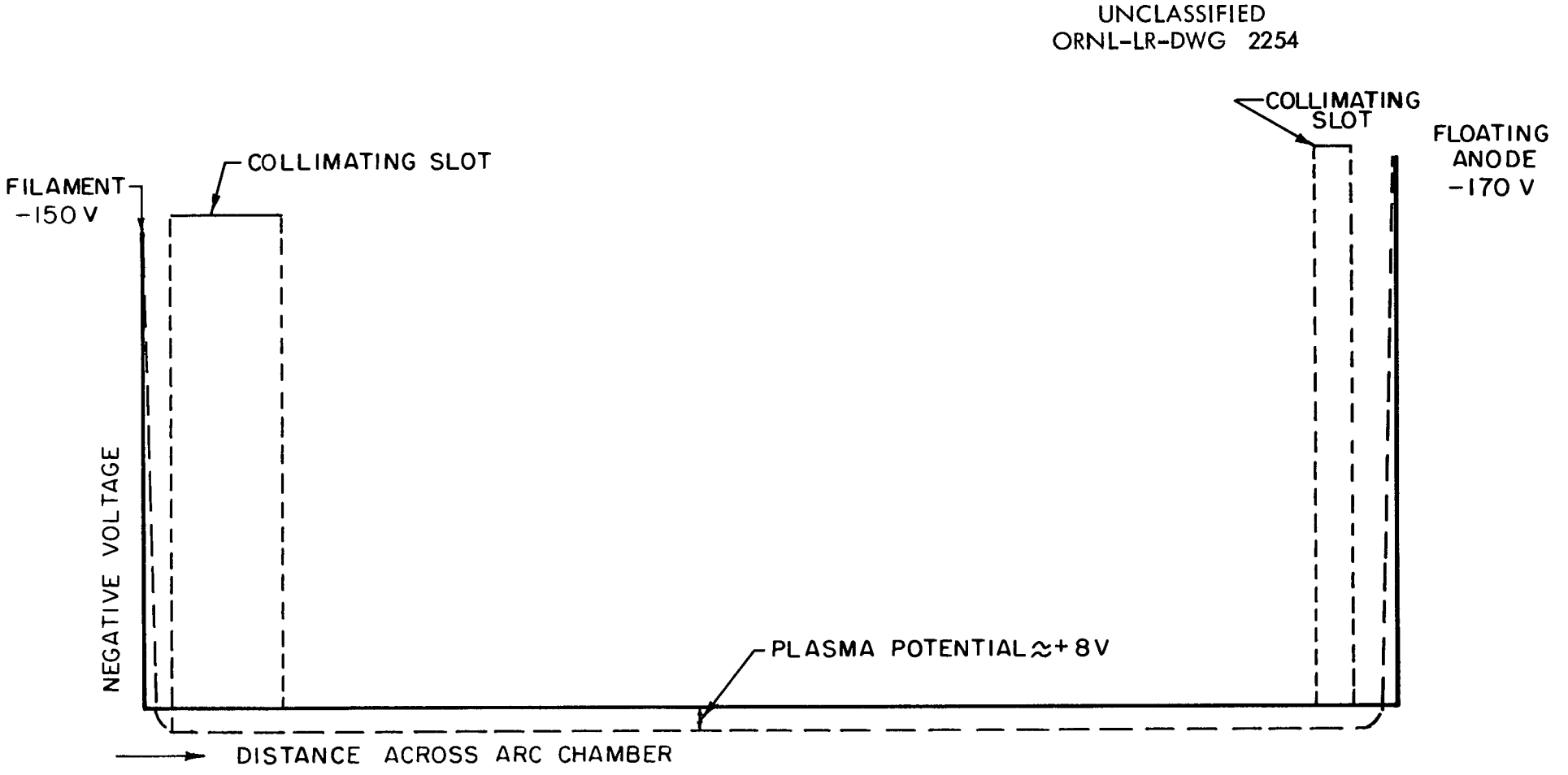


FIGURE 3 POTENTIAL DISTRIBUTION ACROSS THE CALUTRON ARC CHAMBER

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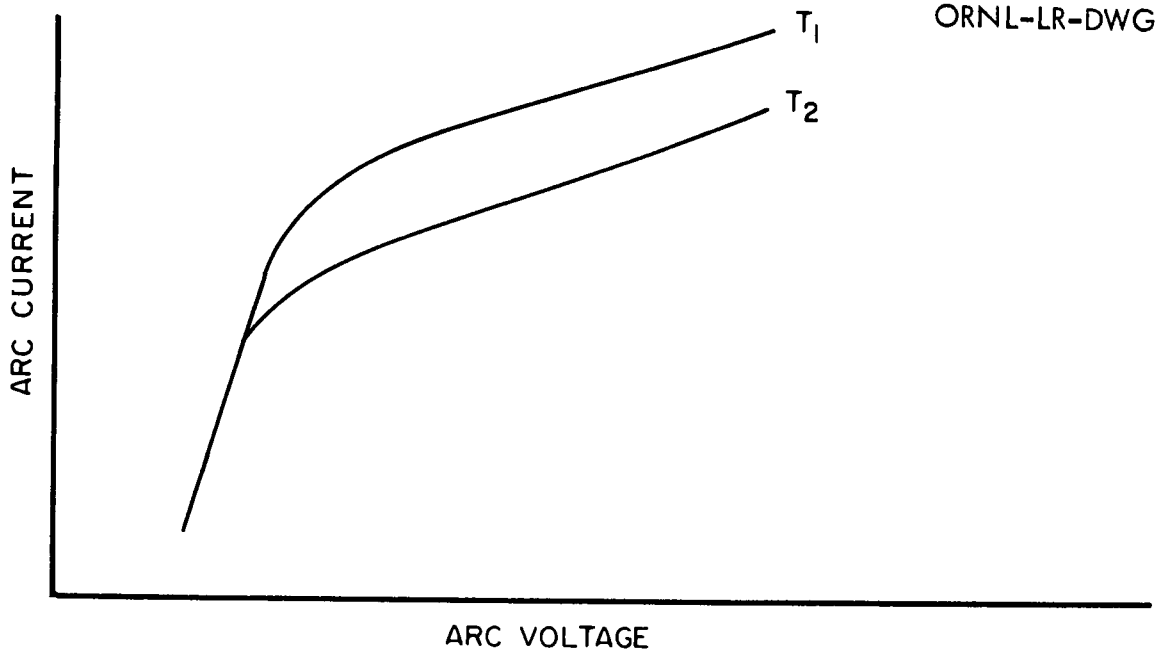


FIGURE 4 CURRENT-VOLTAGE CHARACTERISTIC CURVE OF THE CALUTRON ARC

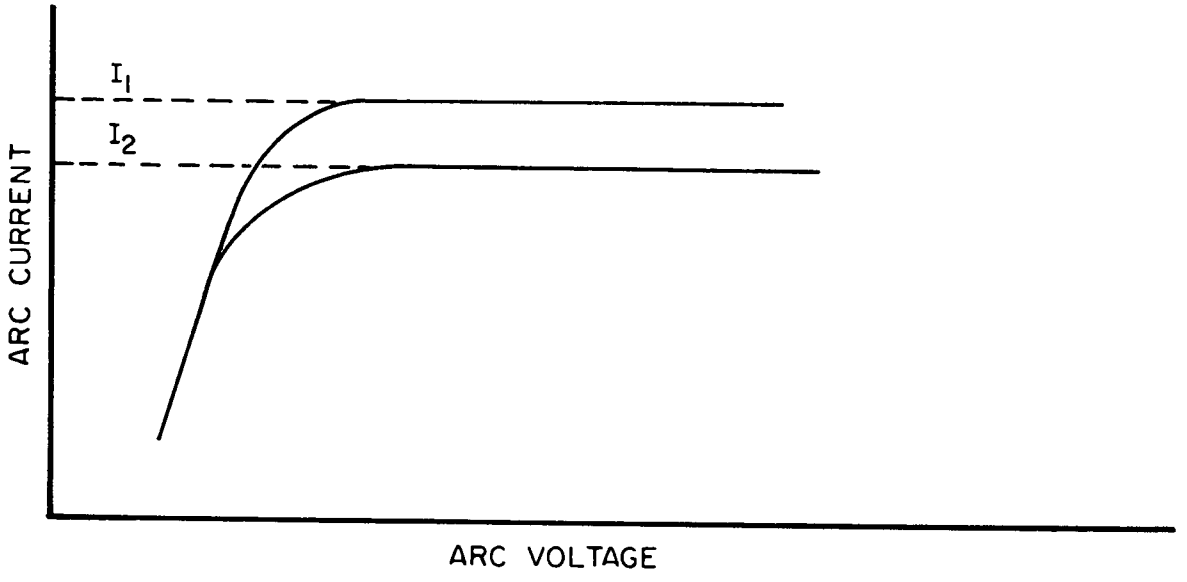


FIGURE 5 REGULATOR-MODIFIED CHARACTERISTIC CURVE OF THE CALUTRON ARC

current has been varied slightly to maintain the arc current constant over most of the voltage range

The possibility that filament-arc regulation might have an adverse effect on filament life was first seriously considered in connection with the separation of the isotopes of iron[9] Filament life was notoriously short in this case, and one attempt to improve this condition consisted of a test series in which the filament-arc regulator was by-passed and the filament was manually operated at essentially constant current Filament life was almost doubled (to 25-30 hours for 170-mil filaments) by this mode of operation, and as a result of this experience the work herein reported was undertaken

As an extension of this manual method of control, it was decided to abandon the filament arc regulator entirely and use a ballast resistor in series with the arc to limit the current Voltage drop across the arc would be controlled by varying the arc chamber pressure In the beginning the idea was to operate at the minimum obtainable voltage across the arc for a given charge material This would be in accord with gas filled diode and thyratron practice Hence, this type of operation was called diode-like-operation as opposed to normal operation in which the filament arc regulator was used

It was felt that operation in this fashion should also give minimum erosion of cathodes in ion source service The preliminary experiments reported below were undertaken to check this hypothesis

PRELIMINARY EXPERIMENTS

Two preliminary experiments were carried out in a small 180° Dempster-type mass spectrograph of 3-inch radius The filaments used were of 145-mil

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9 C E Normand, and R Baldock, Document YB-20-81 (1950)

tantalum operated from a 6v-500a, d-c power supply Arc current was supplied by a current regulated, d-c supply rated at 10a-300v Source and focusing electrode voltages were each supplied by a 5kv-1a, d-c supply Ions were collected on a carbon plate located on a 3-inch radius in the 180° position Ferrous chloride was used as a charge material, and each run was of approximately 16 hours duration

In the first run, full diode-like operation was used The voltage drop across the arc was 20 v and the average arc current was 2 3a In the second run, normal operation with filament-arc regulation was used The average arc voltage was 150v and the average arc current was 2 0a A summary of data from the two runs is given in Table I[10], and a comparison of the filaments at termination is shown in Figure 6

Significant differences between the two runs are (1) reduction in average arc power (46 versus 300 watts), (2) loss in average ion output current(2 0 versus 4 0 ma), (3) reduction in filament erosion Both filaments showed a high rate of loss due to evaporation, as evidenced by visual inspection and by measurements of filament diameters This excessive evaporation loss is attributed to the fact that filament temperatures above 2200°C were required in both runs because of low vapor density in the arc region due to open construction of the arc chamber In addition to evaporation loss, however, the filament operated under normal conditions showed heavy local erosion in the region exposed to direct ion bombardment

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10 Tables I and II and Figures 6, 8, 12, and 13 are from Document ORNL-1525, O C Yonts, 1953

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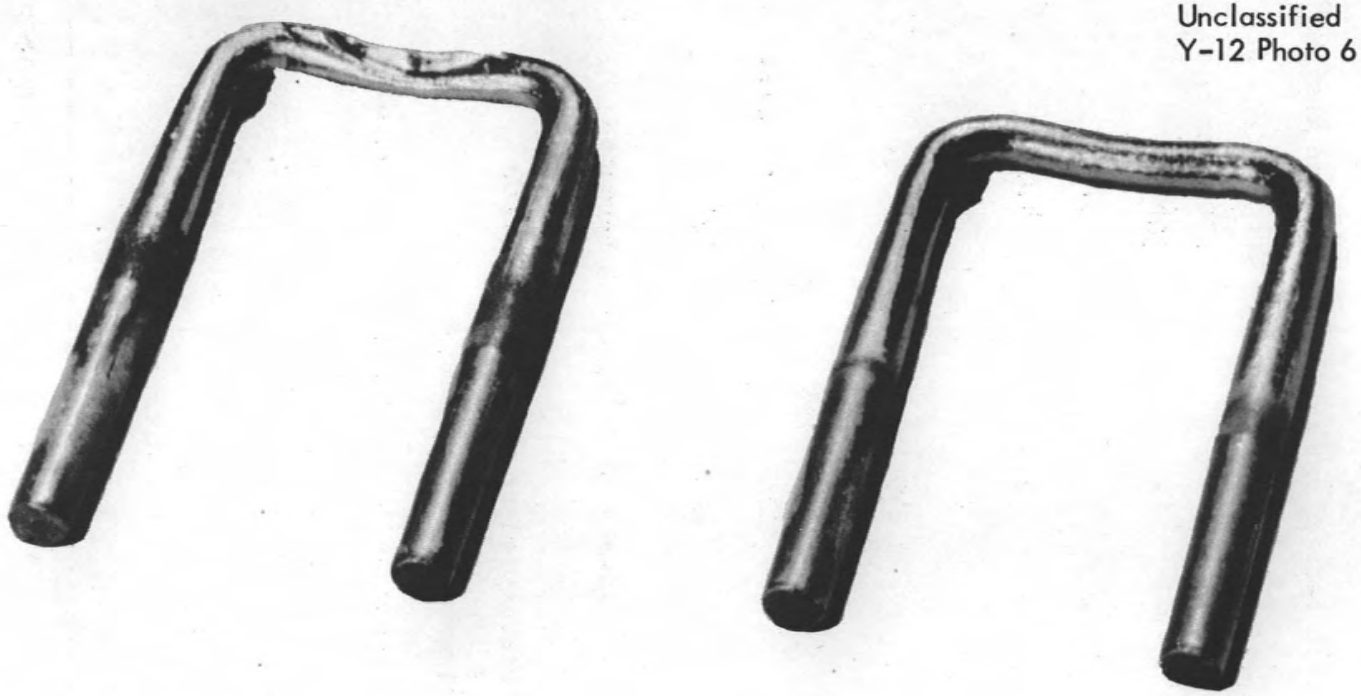


FIGURE 6. NORMAL AND DIODE OPERATED FILAMENTS USED IN THE PRELIMINARY EXPERIMENT

TABLE I

OPERATIONAL SUMMARY OF PRELIMINARY EXPERIMENT

Condition	Type of Operation	
	Diode	Normal
Bake-out time (hrs)	6[c]	4
Run time with Fe (hrs)	10	12
Total run time (hrs)	17	16
Average arc power (watts)	46	300
Peak ion current (ma)	36	50
Average ion current (ma)	20	40
Filament[c] diameter (mils)		
Start	145	145
Finish		
At center	115	badly eroded
At bends	126	126

a Two hours of lithium arc discharge in bake-out because of dirty unit

b ion beam partially intercepted by accelerating slit

c For diode operation loss due to evaporation

For normal operation loss due to evaporation and erosion

At bends loss due to evaporation only

PRODUCTION EXPERIMENTS

Following the two preliminary runs, arrangements were made to continue the experiments in one of the calutrons used in the Stable Isotope Production Program This calutron was a 180° Dempster-type mass spectrometer of 24-inch radius using either 145-mil or 170-mil tantalum filaments Arc current was supplied by a 300-volt, 10-ampere current regulated supply The entire ion source, including all source power supplies was operated at 30 to 40 kv, positive potential with respect to ground The positive ion accelerating voltage maintained by a 40 kv, one-ampere voltage regulated supply Focusing voltage was obtained from an unregulated 35 kv supply

The receiver generally used consisted of carbon "pockets" located at the 180° position

Source and receiver units were enclosed in a vacuum tank between the poles of an electromagnet Two 20-inch diffusion pumps, backed by a 5 H P mechanical pump provided adequate pumping speed for maintaining a pressure of 0 03 to 0 05 micron during operation Normal pump down time with new source and receiver was from 3 to 6 hours During experimental runs with gaseous charge, however, it was possible to remove the source, change a filament, and re-evacuate the system with less than one hour loss in operating time

The magnetic field was variable from 500 to 7000 oersteds and was adjusted to the value appropriate for collecting the desired ion beam on a two-foot radius Figure 7 shows a cross sectional diagram of a calutron The magnetic field is perpendicular to the plane of the paper and the direction is into the paper

A silicon collection series was in progress at the time of transferring experimental activities to the 24-inch calutron, consequently, the first experimental runs were made using $SiCl_4$ charge and the silicon collection

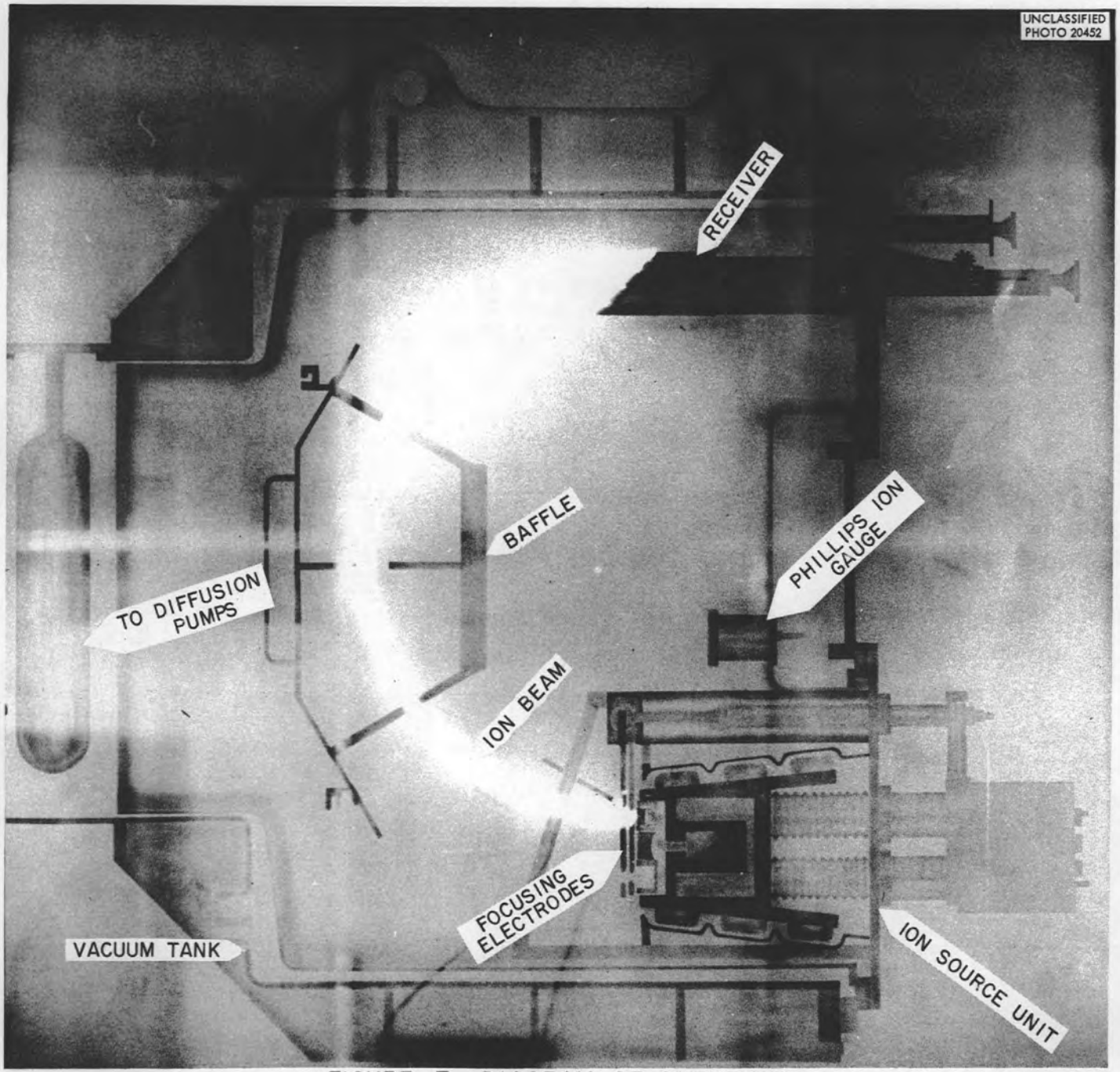


FIGURE 7. DIAGRAM OF CALUTRON

equipment Of the eleven runs comprising this series, three were with diode-like operation, four were with modified diode operation (term explained below), three were with normal operation in which a standard filament arc regulator was used, and one was made with manual control of the arc current as recommended for iron An operating summary of the eleven experimental runs and of six normal production runs is given in Table II

Runs 1 to 5 cannot be compared directly with subsequent runs because of a change made in the arc chamber beginning with run 6 In runs 6-17, however, the source unit remained unaltered except for necessary filament replacements A comparison of the average ion output from straight diode-like operation (runs 7, 10, 11) with that for normal operation (runs 6, 12, 13, 14, 16) shows a reduction of almost 50 per cent This is in good agreement with the results of the two preliminary experiments

Visual observation of the arc during diode-like operation suggested that this low output was probably due to failure of the arc to extend the full length of the arc chamber In appearance, the arc was extremely bright at the filament end and very weak at the opposite end of the arc chamber

On increasing the arc voltage from 38 volts (the normal diode voltage for $SiCl_4$ charge) to 80-100 volts the arc was observed to extend the full length of the arc chamber, and the ion output rose to about the value characteristic of normal operating voltage (150-175 volts) This increase of voltage across the arc was accomplished by reducing the filament temperature slightly This type of operation, called modified diode operation, was used in runs 8, 9, 15, and 17, and resulted in a substantial increase in service life of the filament over that of normal operation with little, if any, loss of output

Filament erosion patterns typical of the three modes of operation are shown in Figure 8 Each filament was operated for approximately 24 hours in

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a. b. c.

FIGURE 8. REPRESENTATIVE FILAMENT AND EVAPORATION WEAR FOR THREE MODES OF ARC OPERATION: a. NORMAL (23 HOURS), b. MODIFIED D-O (24 HOURS), c. D-O (24 HOURS).

TABLE II

RUN SUMMARIES OF OPERATIONAL EXPERIMENTS

Run No	Type Operation	Filament Diameter (mils)	Filament Life (hrs)	Average Output of Si 28 (ma)	Charge Consumption gm/hr	Average Arc Power (watts) Dissipation
1	Normal	170	24	19 63	3 09	342 6
2	Normal	170	13	18 67	3 24	364 5
3	Normal	170	15	18 30	3 24	382 6
4	Normal	170	30	26 55	-	316 8
5	Normal	170	26	25 44	2 84	321 1
6	Normal	170	20	24 95	-	560 3
7	Diode[1]	140	24	14 08	2 04	182 5
8	Modified Diode[2]	140	24	12 54	2 16	325 5
9	Modified Diode	140	47	24 1	2 74	366 1
10	Diode	140	51	13 45	2 33	184 4
11	Diode[2]	140	66	9 13	2 86	203 4
12	Normal	140	17	18 47	1 71	514 6
13	Manual[3]	140	23	18 91	3 90	526 2
14	Normal	170	37	32 2	3 90	427 7
15	Modified Diode[4]	170	85	26 9	4 54	225 1
16	Normal	170	28	33 6	2 86	345 0
17	Modified Diode[5]	170	75	30 1	2 84	280 0

1 Runs 7 and 8 stopped after 24 hours for comparison of filament wear

2 Floating anode shorted out on runs 8 and 11, reducing output

3 Current regulator bypassed and arc controlled manually

4 Normal run until filament current decreased to 4 5 amps, then operated as modified diode until burn-out Average output for 15 hours of normal operation 30 3 ma, average output for next 15 hours of modified diode operation 28 9 ma

5 Same as 15 except that when modified diode filament current decreased to 4 amps, returned to normal operation

Average output for first 13 hours of normal operation	34 2 ma
Average output for next 13 hours of modified diode oper	33 7 ma
Average output for last 16 hours of modified diode oper	25 9 ma
Average output for last 16 hours of normal operation	25 0 ma

$SiCl_4$ Ion erosion was the predominant factor in all three cases Evaporation losses from filaments used in the calutron were extremely low, compared with the losses observed in the earlier preliminary experiments This difference is attributed to the lower temperatures at which these filaments were operated in the calutron The filament temperature was measured with a Leeds and Northrup optical pyrometer sighted on the filament through a quartz window The observed "brightness temperatures" were corrected by use of the temperature correction curves[11] given in Figure 9 and based on work by Malta and Langmuir[12], and Fiske[13] Corrected filament temperature is plotted as a function of the primary current to the filament transformer in Figure 10 For normal operation the filament temperature was in the range 1950°C to 2000°C For modified diode type operation the temperature range was 2000°C to 2075°C and for diode type operation the temperature tange was 2100 - 2150°C It has been shown by Normand[14] that evaporation loss from tantalum filaments in this operating range is less than 1 milligram per hour (See curve, Figure 11) Weight gains shown on the curve are due to "gettering" action of the tantalum

In operation the net erosion of a filament is reflected in a decrease of filament primary current In Figure 12 the filament primary current is plotted as a function of operating time for run 15 This run was started as a normal run, curve 1a, and allowed to operate as such until the filament primary current had decreased from 5 to 4 5 amperes At this point the series resistance was

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11 Curves for Figures 10 and 11 used with permission of C E Normand

12 L Malta and D B Langmuir, Phys Rev 55, 743 (1939)

13 M D Fiske, Phys Rev 61, 513 (1942)

14 C E Normand, Document Y-563

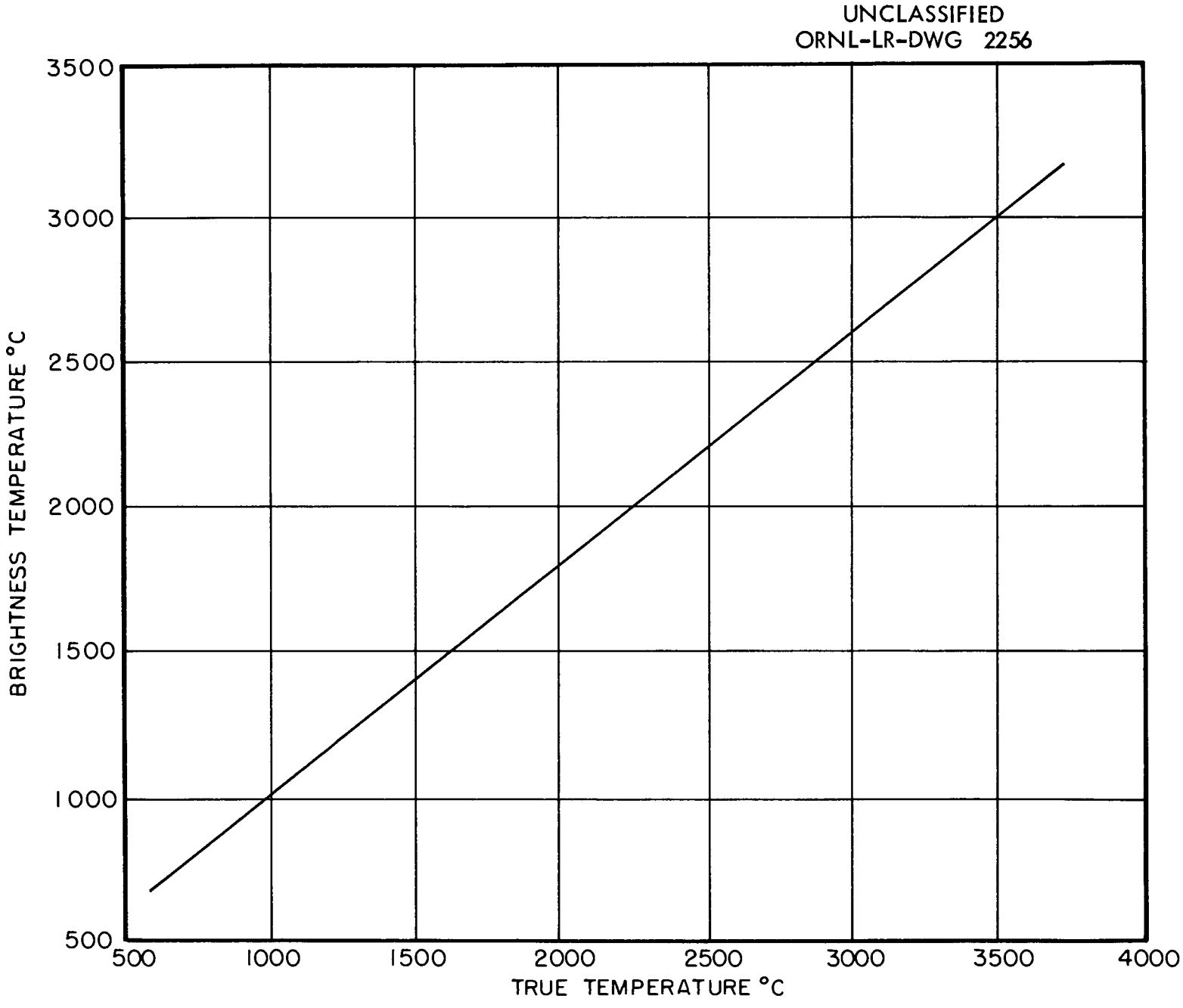


FIGURE 9 TEMPERATURE CORRECTION CURVE FOR TANTALUM

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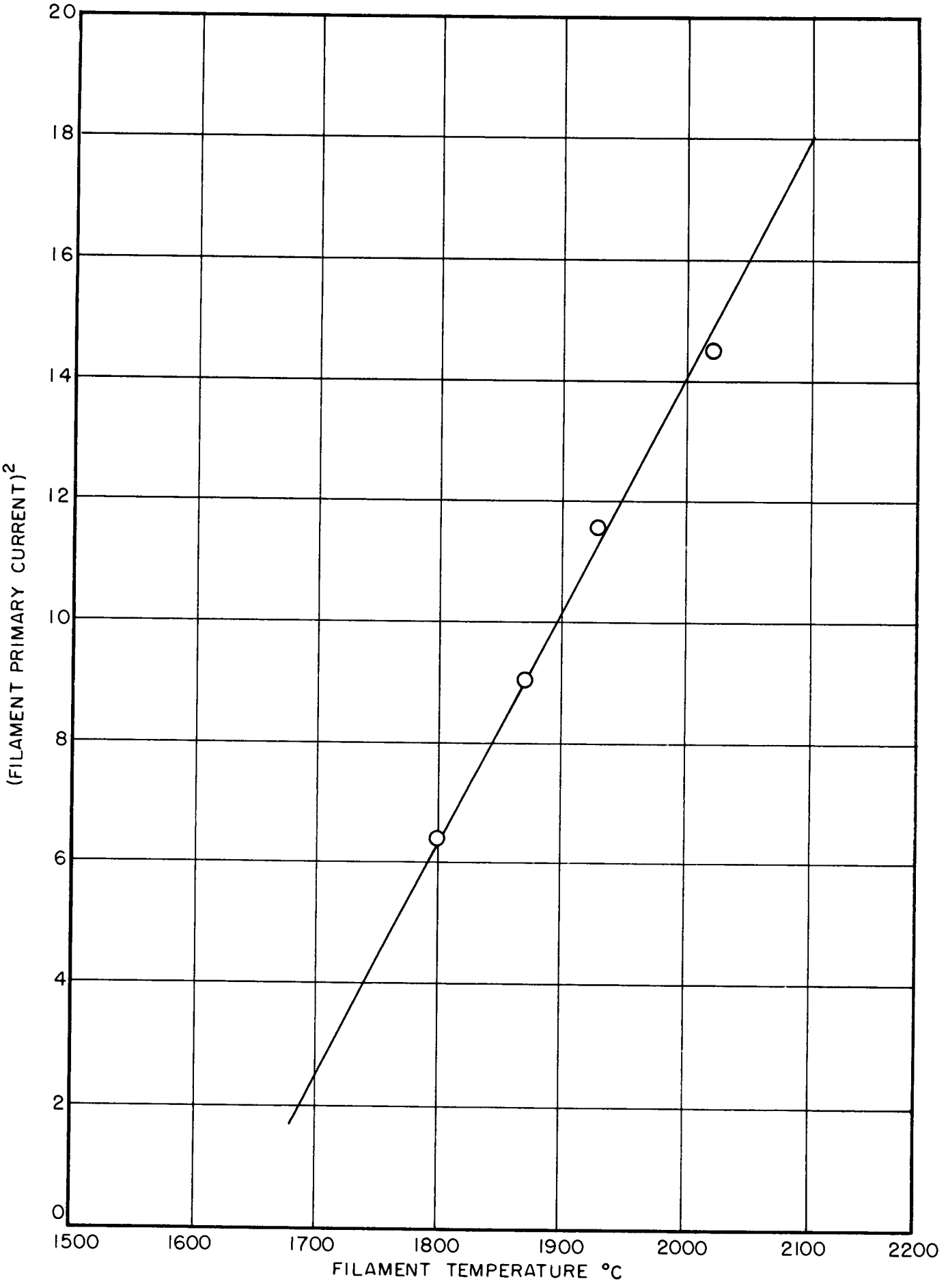


FIGURE 10 FILAMENT TEMPERATURE VS (PRIMARY CURRENT)^2

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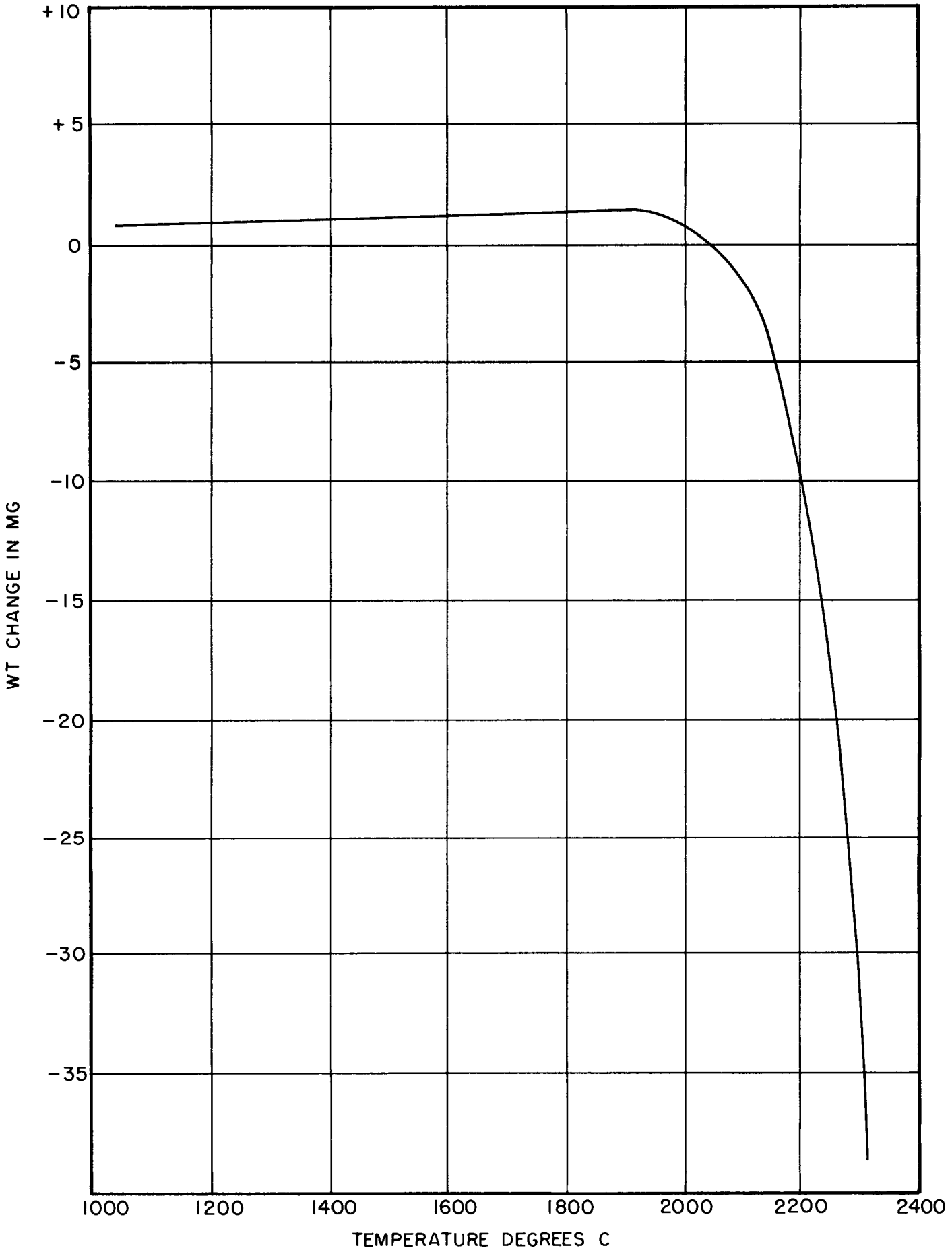


FIGURE 11 WEIGHT CHANGE VS TEMPERATURE ONE HOUR EXPOSURE IN VACUUM

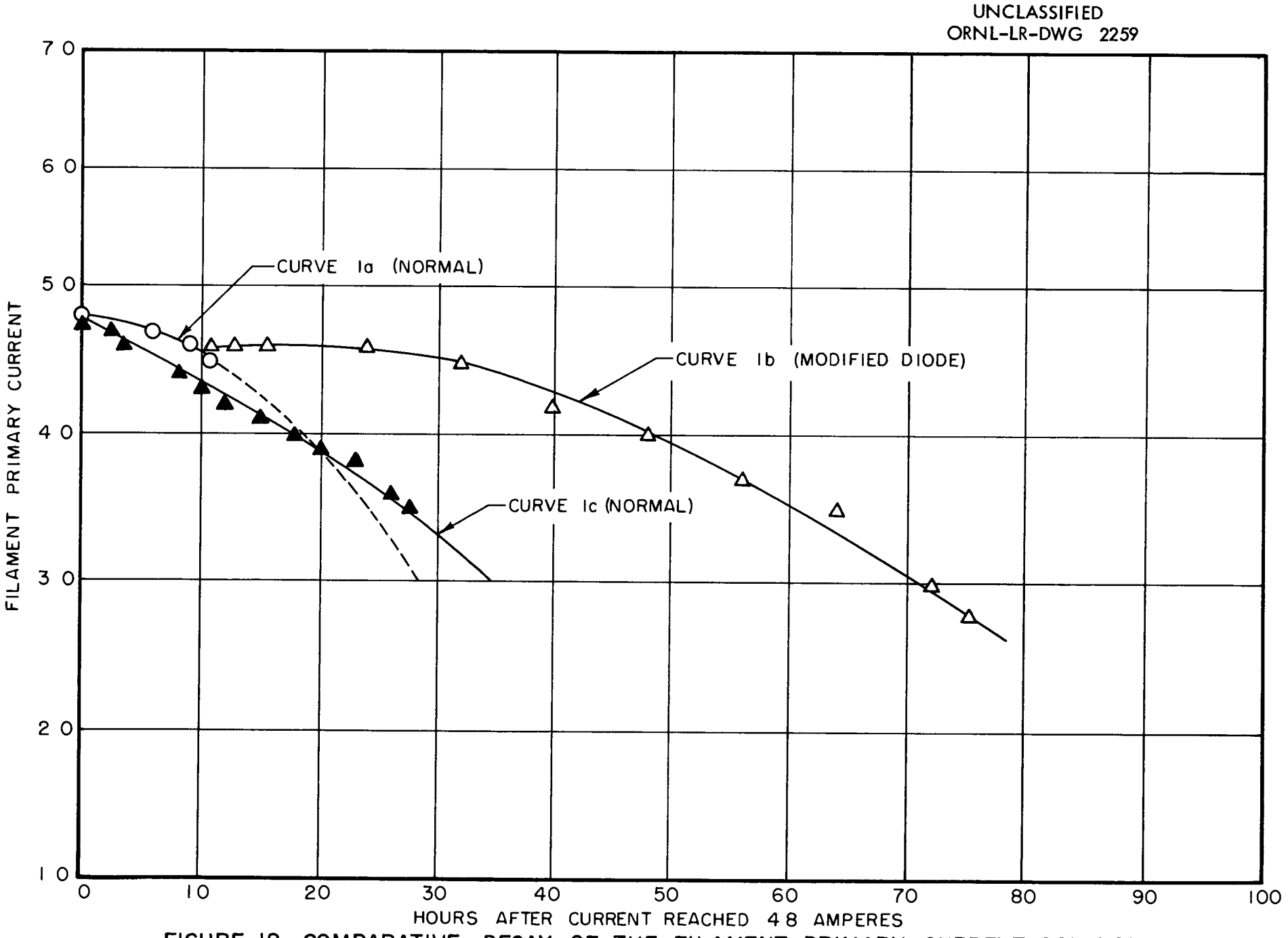


FIGURE 12 COMPARATIVE DECAY OF THE FILAMENT PRIMARY CURRENT FOR NORMAL AND "MODIFIED-DIODE" OPERATION

switched into the circuit and the run was continued with "modified diode" operation The lower rate of filament erosion with "modified diode" operation is indicated by the change in slope of the curve at the change-over point For comparison the corresponding curve for run 16 is also shown as curve 1c (Figure 12) Normal operation was used throughout run 16

From the filament current decay curves of the individual runs one may read off the time required for the filament current to drop through any arbitrary chosen range These decay times are inversely proportional to the average filament erosion rates during the selected period of operation, and correlations between these times and certain source operating parameters were sought The two curves in Figure 13 show decay times plotted as a function of arc power for 145-mil and 170-mil tantalum filaments All decay times are taken over the range 4 8 amps to 3 0 amps

Following completion of the silicon collection series a short series of lithium collections were made in the 24-inch calutrons One experimental run and five normal isotope production runs were made in the calutron equipped for experimental operation The experimental run (run 7) began under normal operation, but was converted to modified diode operation as soon as erosion of the filament was sufficient to permit attainment of the required filament temperature -- within the range of the filament power supply

A summary of the lithium runs is given in Table III The low average output of the experimental run is due to interruptions of the operation by conditions external to the experiment The average ion output for the last 50 hours, a period of continuous operation, was 98 1 ma, which compares favorably with the 101 1 ma on run 5 Lower arc power, and correspondingly longer filament life are prominent features of run 7

Filament current decay curves for the lithium runs 1, 4, and 7 are shown in Figure 14 Run 1 is the longest and run 4 is the shortest of the normal runs

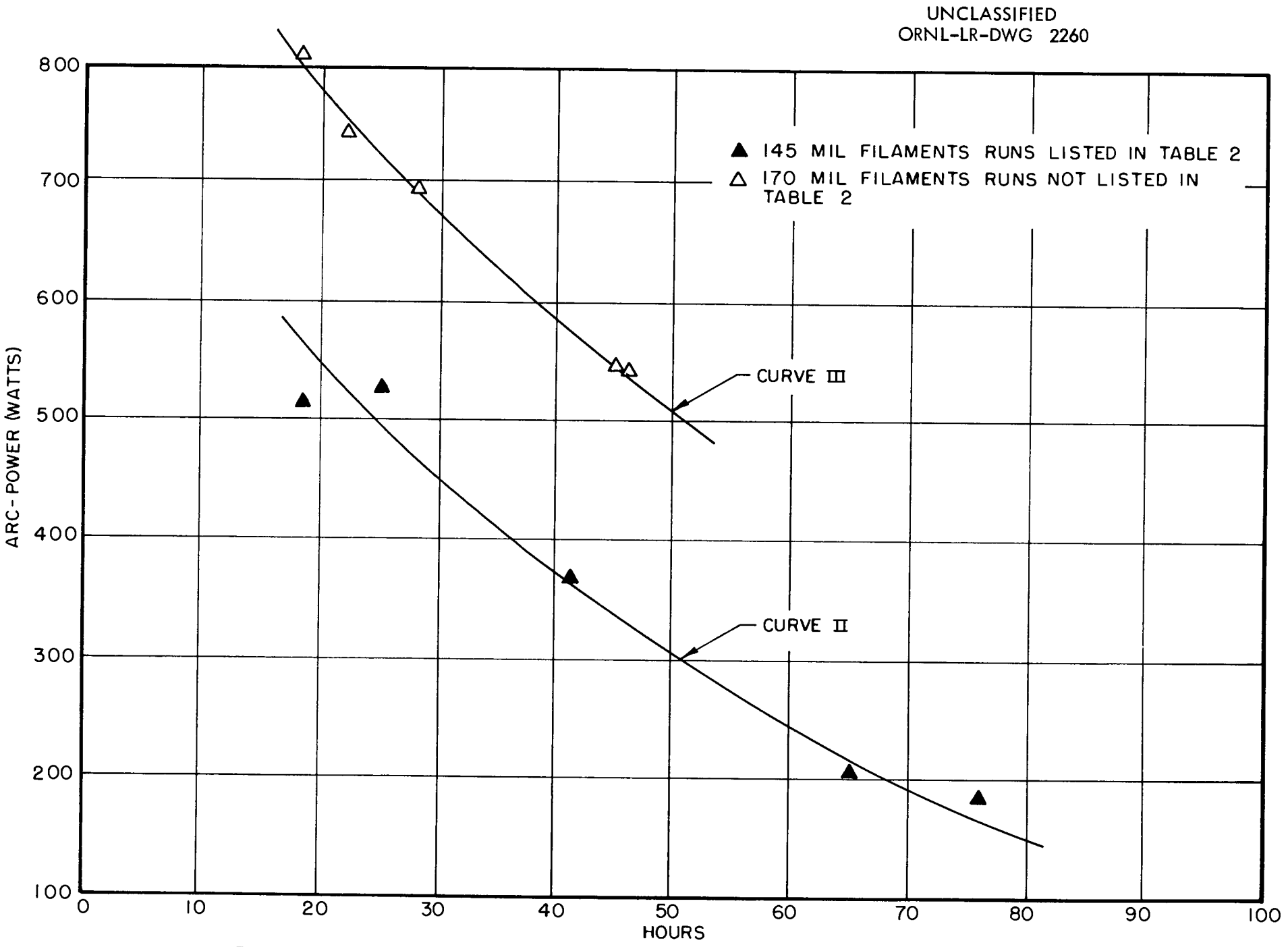


FIGURE 13 INFLUENCE OF ARC POWER ON USEFUL FILAMENT LIFE

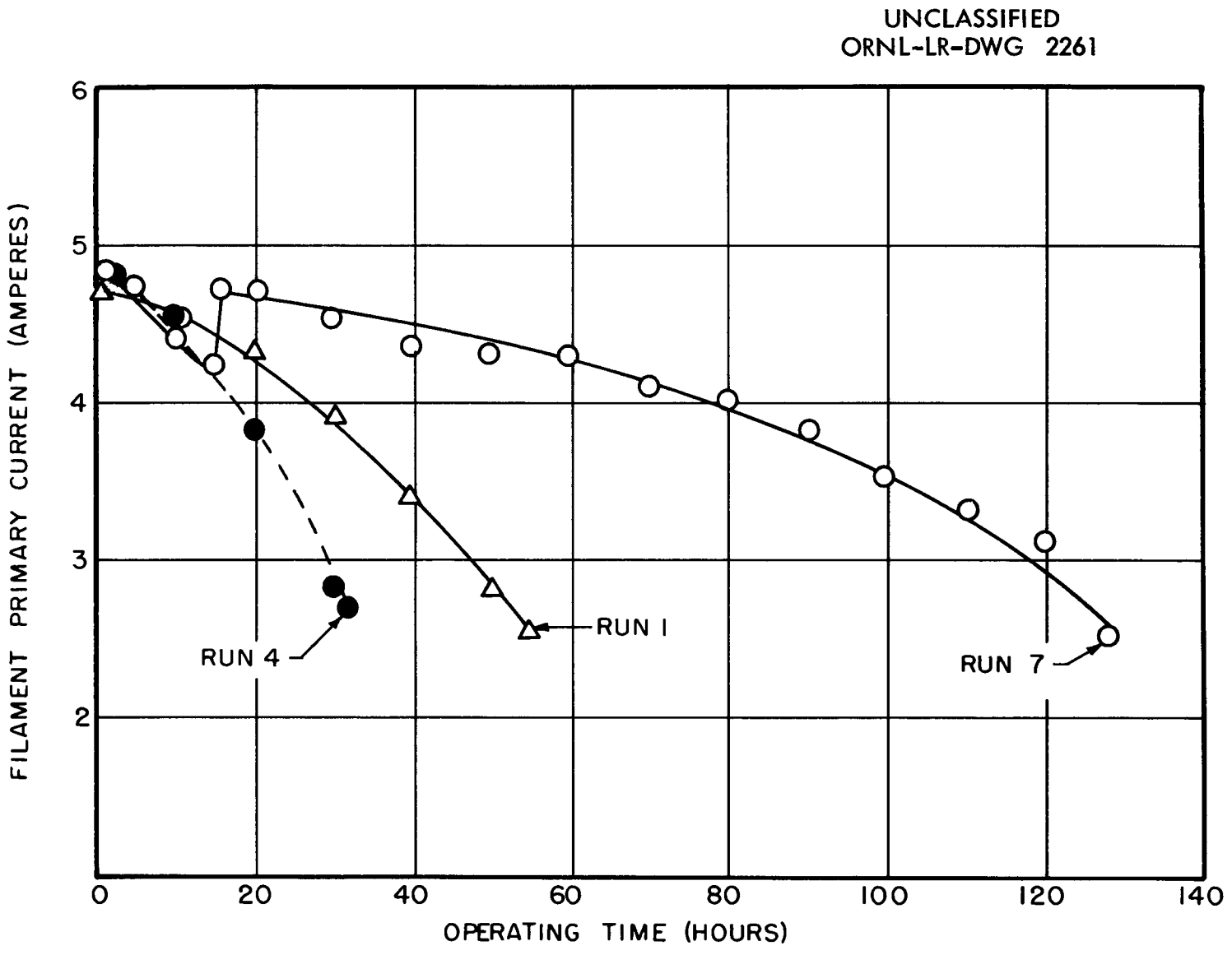


FIGURE 14 FILAMENT DECAY CURVES FOR SELECTED LITHIUM PRODUCTION RUNS

TABLE III

LITHIUM SERIES

Run No	Ave Ion Current (ma)	Ave Arc Voltage	Ave Arc Current (amps)	Arc Power (watts)	Filament Life (hrs)
1	81.5	171 0	4 08	698	54
2	terminated for mechanical failure				
3	97 4	168 9	3 67	620	34
4	87 0	188 8	3 87	731	32
5	101 1	167 7	3 27	549	44
6	95 4	171 4	4 30	737	42
7	87 9	100 0	4 40	440	128

Erosion time (between 4 4 and 3 0 amps), which is inversely proportional to the erosion rate, is shown as a function of arc power and arc voltage in Figure 15 In this case over the range observed, the arc voltage gives a better correlation with the erosion time than does the arc power

Completion of the lithium collection series prevented other experimental runs than run 7 being made with this element

OPTIMIZING OPERATION

A series of additional experimental runs were made with the aim of establishing optimum operating conditions for both normal and modified diode types of operation Titanium tetrachloride was used as charge, and the experiments were planned to show the variations of collected ion current with arc current, arc voltage, and to some extent pressure Since ion collection is the primary aim of calutron operation, conditions giving maximum ion currents at the receiver were sought at all times The procedure used was as follows Standard operating procedures were followed in baking-out the unit and bringing it into steady operation After steady operation was attained, the pressure and filament current were held constant while the arc current was changed by varying the total voltage applied to the arc and its series resistor For each value of the arc current, corresponding values of arc voltage and ion current were read Typical results are shown in Figure 16 for diode-like operation where arc voltage and ion current are plotted as functions of the arc current

The most interesting feature displayed by these curves is that the metered ion current attained a maximum value rather than continuing to increase indefinitely with increasing arc current and voltage To understand this behavior, account must be taken of the fact that ion current measured is not the total ion output of the arc, but represents only those ions which emerge from the source, pass through imposed focusing and accelera ing fields and arrive as focused beams

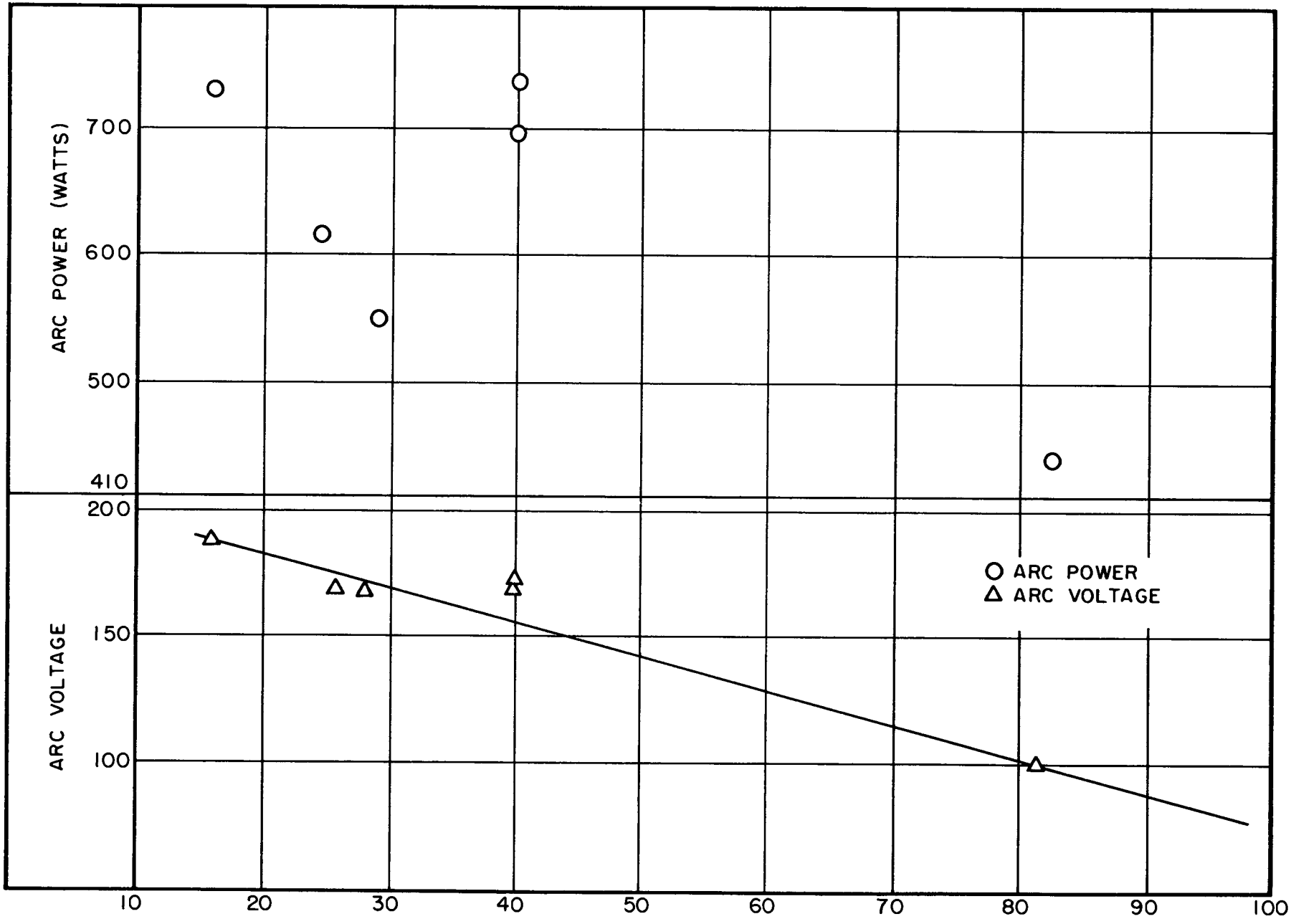


FIGURE 15 ARC VOLTAGE AND ARC POWER VS EROSION TIME

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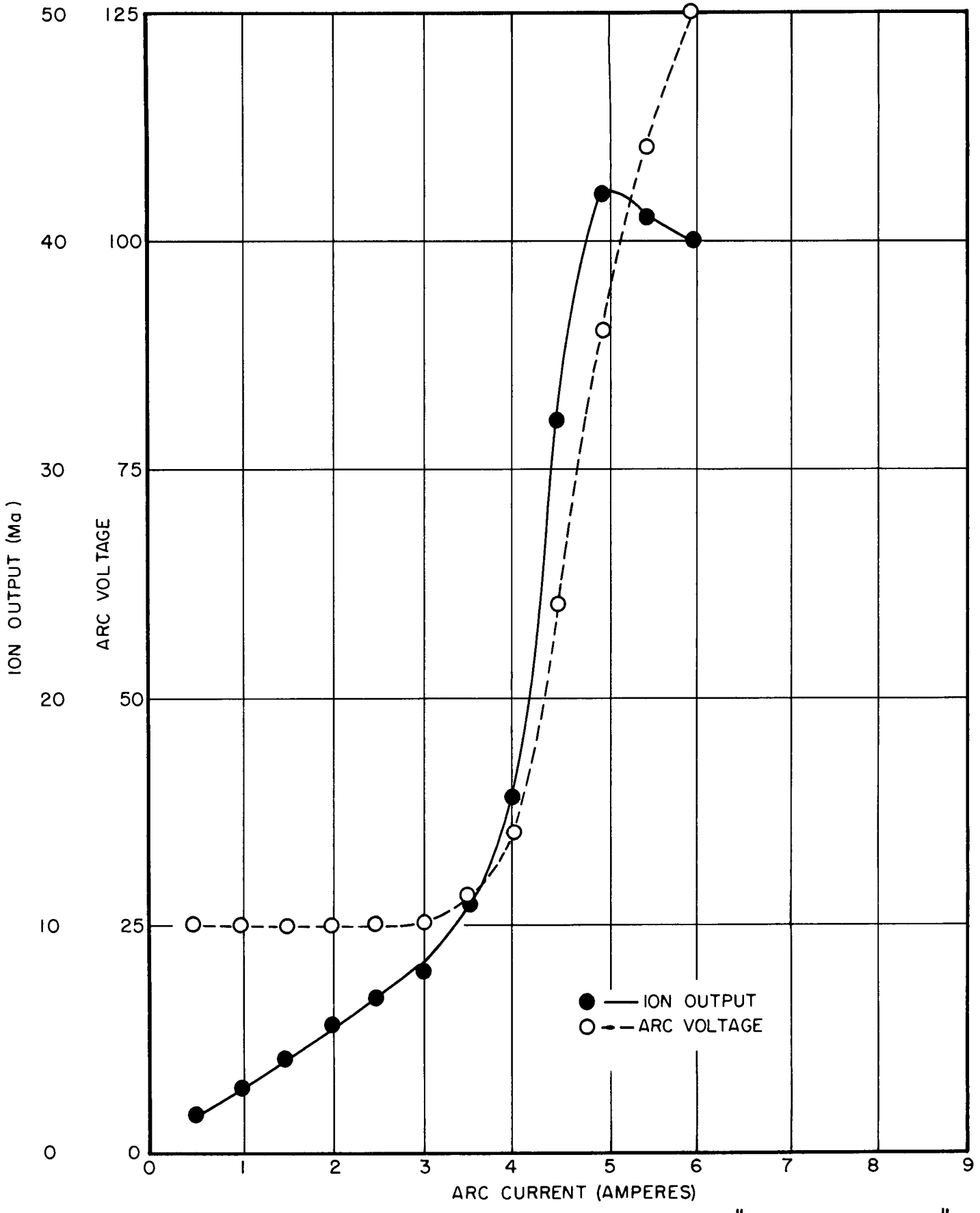


FIGURE 16 SOURCE PERFORMANCE CURVE FOR "MODIFIED DIODE" OPERATION $TiCl_4$ CHARGE

at the remote receiver Total ion output probably does continue to increase[15,16] with increasing arc current, but as ion density in the ion exit region increases, a strong defocusing action arises to reduce the ion current entering the receiver The effect of this defocusing action can be visually observed either, in spreading out of the beams arriving at the receiver or in erosion patterns produced at the receiver The exact values of arc current and voltage at which strong defocusing sets in depends on both the configuration of the accelerating electrode system and on the accelerating and focusing voltages applied Consequently, the optimum arc conditions found for a particular source unit may not apply to a unit having a different electrode configuration, nor to the same unit operated at different accelerating or focusing voltages

Corresponding curves for normal operation are shown in Figure 17

Taking as optimum those values of arc current and voltage for which the maximum ion current at the receiver was obtained, (Figures 16 and 17) optimized runs were made with normal and with modified-diode operation Each of these runs was of 13 hour duration, and the filaments used were weighed before and after running to provide a quantitative comparison of filament erosion under the two types of operation In normal operation, filament weight loss occurred at the rate of 95 5 mg/hr, while with modified-diode operation the rate of weight loss was only 49 4 mg/hr, a reduction of almost 50 per cent Both localization of erosion and the low value of operating filament current (3 9 amperes) corresponding to a temperature of 2050°C) indicate that the observed losses in filament weight were due almost wholly to ion bombardment,

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15 Guthrie and Wakerling, NNES Div I, Vol 5, p 151

16 A H Barnes, S M McNeille, and C Starr, NNES Div I, Vol 8, p 42

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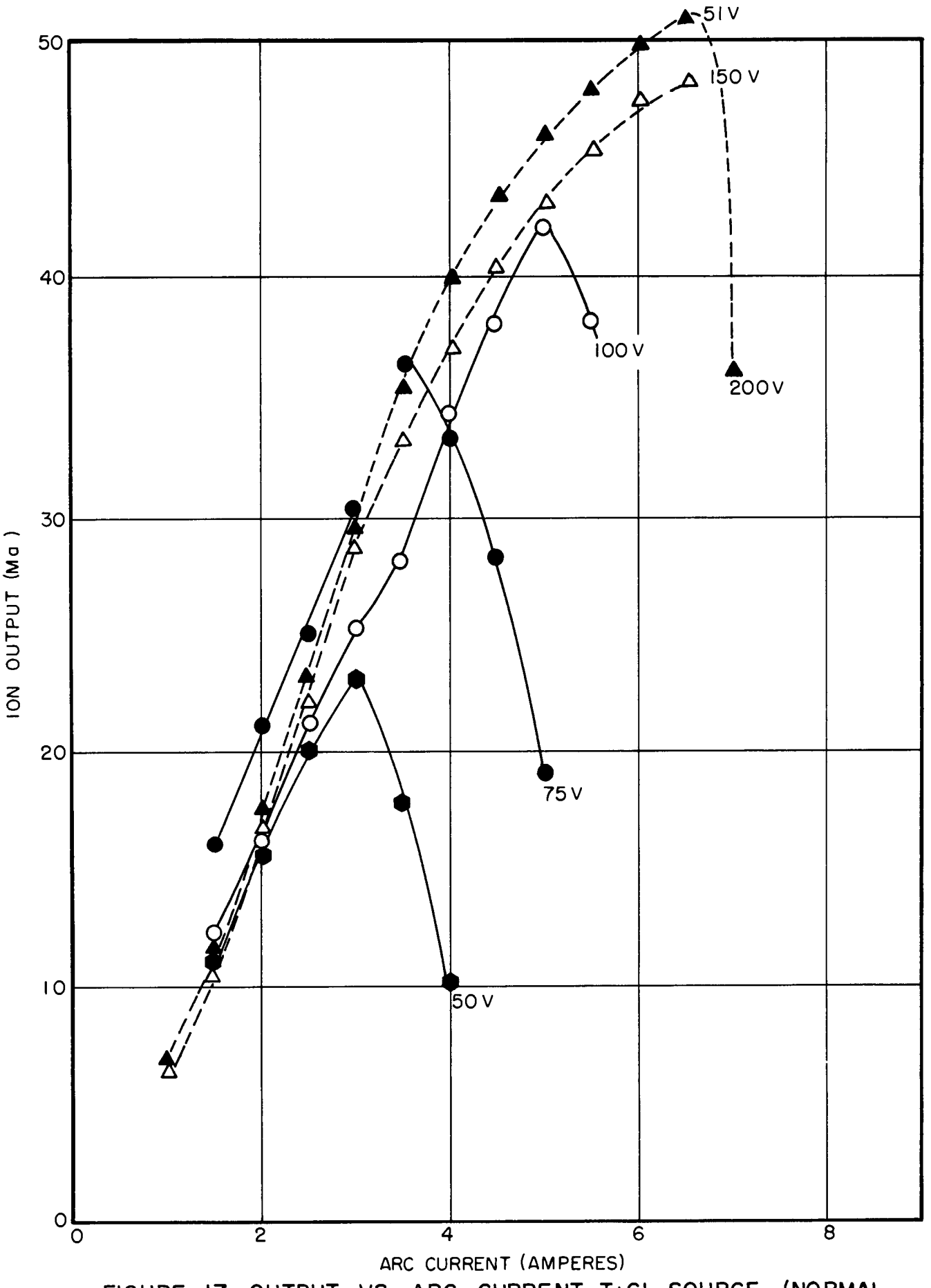


FIGURE 17 OUTPUT VS ARC CURRENT $TiCl_4$ SOURCE (NORMAL OPERATION)

and that simple evaporation contributed only slightly to these losses

Additional 13 hour runs were made in which arc conditions were varied away from the optimum values Both normal and modified diode type operations were used A summary of these operations if given in Table IV

The plot of total weight loss versus arc power is shown in Figure 18 Normal operation is indicated by circles and modified diode operation by triangles

Townes[2] has shown that provided the energy of the ions reaching the cathode in a cold cathode gaseous discharge tube is large compared to 10 ev the sputtering rate is given by

$$J = \frac{AI}{p}\left(\frac{Vi}{p^2}\right)^{3/5}$$

where A is a constant depending on discharge geometry and the physical constants of the discharge gas and cathode material, I is the total discharge current, p is the pressure, i is the current density at the cathode, V the cathode voltage drop

Although this equation was obtained on a basis of cold cathode discharge it was felt that direct application to the calutron arc might be feasible Figure 19 shows the results of plotting mg weight loss/ampere hour against arc power to the 3/5 Unfortunately it is not possible to measure pressure in the arc during operation The scatter on some points (run 4 in particular) might be lessened if pressure corrections could be made During run 4 tank pressure, measured with a Phillips ion gauge located approximately 2 feet from source, was substantially lower than for any other run This would indicate less pressure in the arc chamber and correspondingly higher erosion rate

TABLE IV

$TiCl_4$ OPERATIONAL EXPERIMENTS

	Run and Type	Arc Voltage	I Arc Current (amps)	Average Output (ma)	P Average Arc Power	P 3/5	J mg/hr	Cube J/I	Actual J/I
1	Normal*	158 8	5 03	30	798 8	55 2	95 5	20 9	18 98
2	Normal	166 3	4 99	36 2	746	53 0	79 9	19 6	16 01
6	Normal	130 1	4 16	32 1	541 2	43 6	69 0	16 1	16 58
9	Normal	138 0	4 8	29 1	635 1	38 7	71 8	14 3	14 95
3	Modified Diode	89 5	4 23	41 6	377 7	36 1	49 4	13 4	11 67
4	Modified Diode	129 6	4 27	31 8	553 3	44 3	91 9	16 4	21 52
7	Modified Diode	168 0	4 43	28 9	744 2	52 9	89 9	19 2	20 29
8	Modified Diode	96 5	4 51	35 9	435 2	38 2	63 4	14 1	14 05

5 N G High Pressure ruined filament before $TiCl_4$ arc

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* Receiver shorted on this run

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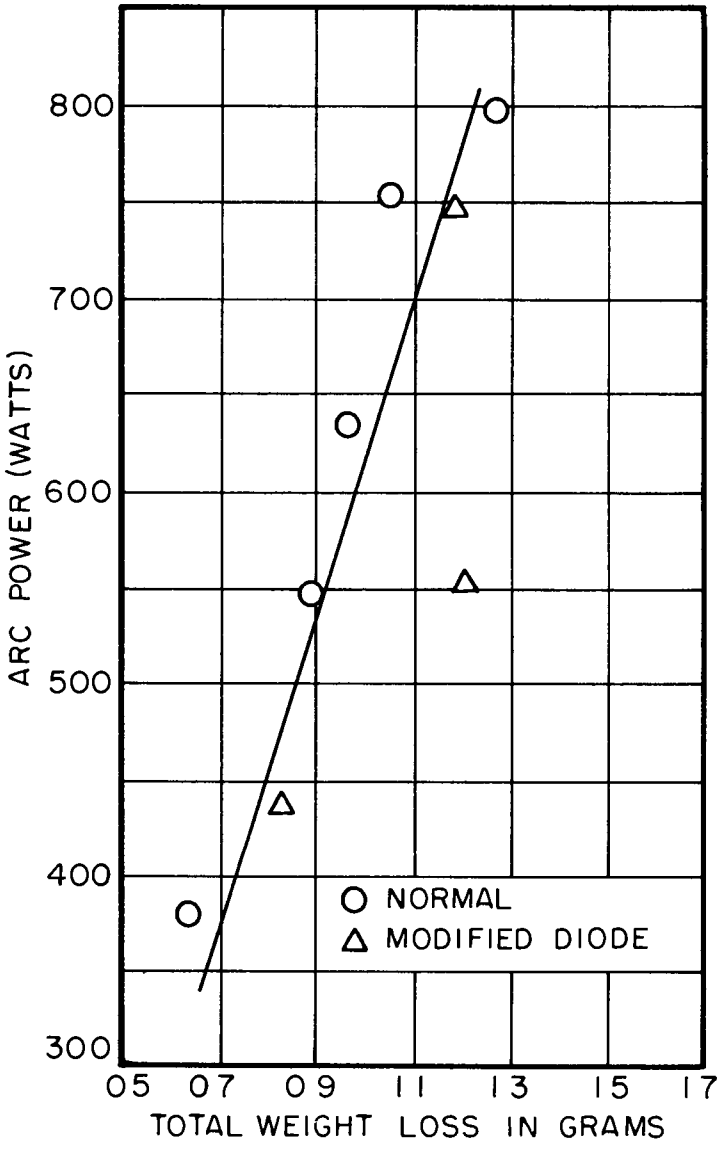


FIGURE 18 FILAMENT WEIGHT LOSS FOR 13 HOURS OPERATION WITH $TiCl_4$

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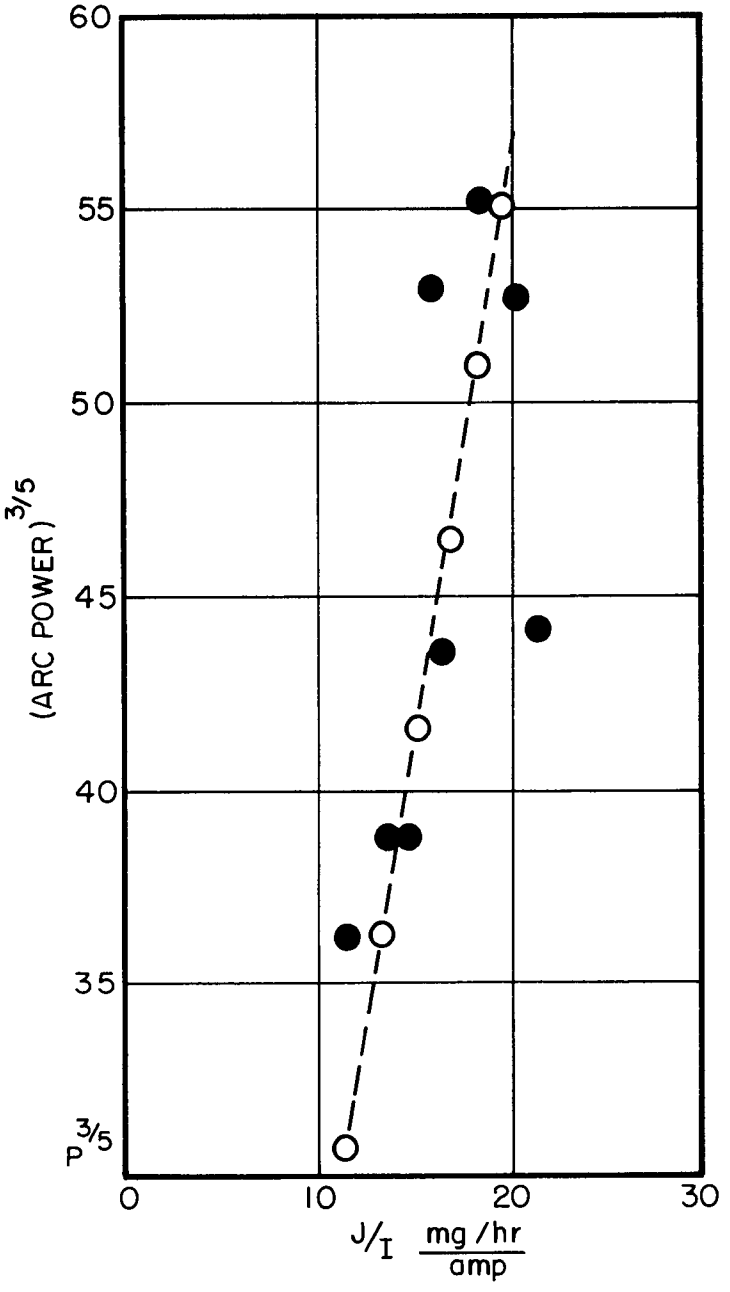


FIGURE 19 GRAPH OF TITANIUM DATA FITTED TO TOWNES EQUATION FOR SPUTTERING

Plots of net weight loss versus arc voltage or arc current give a wild scatter of points which indicate only a positive slope

Of some interest is the difference between peak output and average output on the 13 hour runs On both runs 1 and 2, peaks of 50 ma were obtained, average, however, was below 40 ma In run 3, peak was 45 ma and average was 41 ma

Figure 20 shows characteristic performance curves of the $SiCl_4$ source used in the production experiments Only the two best curves of normal operation are plotted The reason for two peaks in the modified diode type operation is not at all clear The seond peak is due to defocusing, as can easily be determined by observing current to electrode structure or by visual examination of the receiver during operation As far as can be determined nothing unusual happens during the first peak or down to the minimum The first peak is characteristic of $SiCl_4$ since it does not appear when the $SiCl_4$ charge is replaced by $TiCl_4$ in the same unit

CONCLUSIONS

It has been shown that filament erosion is increased with increase in arc power An approximate expression for erosion rate can be obtained from the points of Figure 19 The equation $J/I = AP^{3/5}$ is plotted in Figure 19 as a dotted line The form of this equation was suggested by Townes' equation above The value of A is computed to be 0 36 It has also been shown that operation of the full diode type reduces filament wear to a minimum but also reduces ion output to the point of uselessness A compromise arrangement in which the filament is operated at higher temperature than normal thus allowing maximum ion current to be reached at a lower arc voltage has been shown to give, on the average, received ion currents approximately equivalent to normal operation At the same time filament erosion is reduced and useful life is

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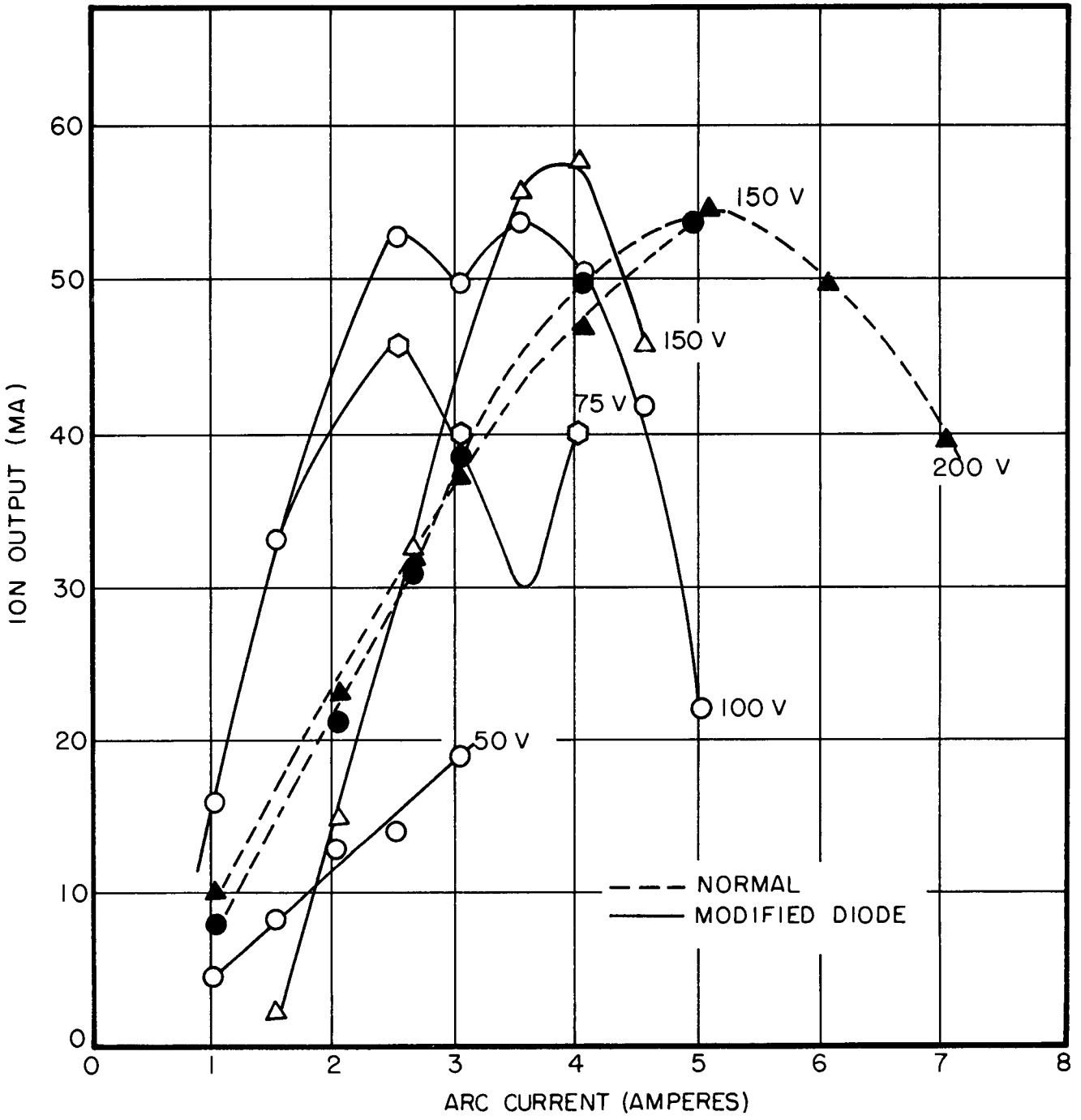


FIGURE 20 SOURCE PERFORMANCE CURVE USING $SiCl_4$

increased by a factor of at least 2 over normal operation Under these conditions average ion output has varied from 10 per cent less than normal output for silicon ions to 8 per cent greater than normal for titanium ions

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