STATE UNIVERSITY OF NEW YORK AT BUFFALO

LAPES 79-003

EXPERIMENTAL AND THEORETICAL INVESTIGATION
FOR THE SUPPRESSION OF THE PLASMA ARC DROP
IN THE THERMIONIC CONVERTER

BY
DAVID T. SHAW

FINAL REPORT - APRIL 1979

NASA CONTRACT NO. NSG 7071
JULY 1 1974 TO APRIL 15. 1978

Laboratory for Power and Environmental Studies

**Faculty of
Engineering and
Applied Sciences**

DEC 1979
RECEIVED
NASA STI FACILITY
ACC DRANCH

LAPES 79-003

EXPERIMENTAL AND THEORETICAL INVESTIGATION FOR THE SUPPRESSION OF THE PLASMA ARC DROP IN THE THERMIONIC CONVERTER

BY
DAVID T. SHAW

FINAL REPORT - APRIL 1979

NASA CONTRACT NO. NSG 7071
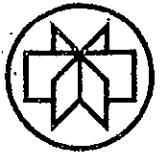JULY 1, 1974 TO APRIL 15, 1978

FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LEWIS RESEARCH CENTER
CLEVELAND, OHIO 44135

1 Report No	2 Government Accession No	3 Recipient's Catalog No
NASA CR No: 159611		

4 Title and Subtitle	5 Report Date
Experimental and Theoretical Investigation for the Suppression of Plasma Arc Drop In the Thermionic Converter	4/15/79
	6 Performing Organization Code

7 Author(s)	8 Performing Organization Report No
David T. Shaw	LAPES 79-003
	10 Work Unit No

9 Performing Organization Name and Address	11 Contract or Grant No
State University of New York at Buffalo	NSC-7071
	13 Type of Report and Period Covered

12 Sponsoring Agency Name and Address	Final 7/1/74-4/15/79
NASA Lewis Research Center Cleveland, Ohio 44135	14 Sponsoring Agency Code

15 Supplementary Notes

16 Abstract

Two novel approaches have been investigated on the maintenance of ionization in thermionic converters: the use of vibrationally excited molecular nitrogen, and microwaves. Experimental data showed a significant increase in ionization can be produced by the ground state vibrationally excited nitrogen. The spectroscopic measurements confirm that most ionization takes place near the emitter where the intensity of the vibrationally excited nitrogen is the highest. In the microwave thermionic experiment a resonant cavity is used for microwave pumping. It was found that the motive potential peak near the emitter disappears when a very small amount of microwave is used. This phenomenon- the removal of motive peak with microwave - is of great interest in the future work on the reduction of plasma arc drop.

17. Key Words (Suggested by Author(s))	18 Distribution Statement
Microwave thermionic, nitrogen-cesium plasma interaction, thermionic plasma converters	

19 Security Classf (of this report)	20 Security Classf (of this page)	21 No of Pages	22 Price*

NASA C-168 (Rev. 10-75)

September 6, 1979

Mr. James E. Morris
National Aeronautics and Space
  Administration
Mail Stop 302-1
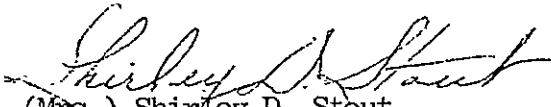Lewis Research Center
Cleveland, Ohio   44135

Dear Mr. Morris:

RE: NSG-7071

Mr. Louis Light, Grants Officer at the Lewis Research Center,
has written to state that Dr. David Shaw's report did not carry
the NASA Contract Report Number nor did it include the title page,
form NASA-C-168. Potential readers, therefore, would not know
that it is CR-159611.

Enclosed are a title page indicating the NASA CR number and
a NASA-C-168 form which you can attach to your copy of the report.

Sincerely yours,

(Mrs.) Shirley D. Stout
Assistant Vice President
      for Research

SDS:pfm
encs.

LAPES 79-003

EXPERIMENTAL AND THEORETICAL INVESTIGATION
FOR THE SUPPRESSION OF THE PLASMA ARC DROP
IN THE THERMIONIC CONVERTER

BY
DAVID T. SHAW

FINAL REPORT – APRIL 1979

NASA CONTRACT NO. NSG 7071
JULY 1, 1974 T.O APRIL 15, 1978

FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LEWIS RESEARCH CENTER
CLEVELAND, OHIO 44135

TABLE OF CONTENTS

This material covers the results of the experiments carried out during the period, July 1, 1974 to April 15, 1978 for the NASA Grant No. NSG 7071. The author would like to acknowledge the technical assistance of Dr. James F. Morris during the entire grant period.

I. VIBRATIONALLY EXCITED MOLECULAR NITROGEN AS AN IONIZATION SOURCE IN THE THERMIONIC PLASMA

1. Introduction

Processes in discharge through gases are governed mainly by energy exchange among electrons, atoms, and molecules of the gases. It has been known for sometime that the presence of molecular nitrogen in alkali metal discharge will quench the resonance radiation of alkali metals under a variety of laboratory conditions [1,2]. The excitation of alkali atoms by vibrationally excited or electronically excited molecular nitrogen has also been reported [3,4,5]. These reactions are important in the understanding of certain types of aurora in which strong alkali metal radiation is observed. In recent years, interest in the transfer of vibrational energy from N_2 to excite other atomic or molecular gases has been expanded because of the rapid development of high power lasers. For such high power gas lasers, the vibrationally excited states of N_2 can be produced or diminished by the presence of the alkali metal atoms presented as additives.

The present study has been carried out to investigate the possibility of using N_2 as a gas additive for the development of thermionic topping generators. In such a generator, it is desirable to produce an enhanced Cs ionization in the interelectrode space. In the following section the experimental procedure used in the present study will first be described. This will be followed by a discussion on these experimental observations.

2. Experiment

The plasma under investigation is produced in a thermionic discharge tube which is completely demountable, constructed with 1.5" I.D. high vacuum components (Fig. 1). The emitter is made of spiraling tungsten filament and the collector is a 1" diameter stainless steel (#304) dish. The interelectrode spacing is set at 0.5". The system is outgassed at 350°C for 24 hours until system pressure of 10^{-7} torr is reached. High-grade nitrogen(impurity < 0.5 ppm) is introduced into the system through stainless steel transfer tubing. Cesium vapor is introduced into the system by breaking the glass capsule in the reservoir and heating up the reservoir. The test section during the experiment is maintained at a temperature about 50°C higher than the reservoir temperature. The emitter is heated to a temperature of 1180°K for all runs. A thin electric probe is placed in the interelectrode spacing near the collector to measure the electron temperature density. Optical measurement is conducted through the optical windows on the discharge chamber using a Jarrell-Ash 0.5 m scanning monochrometer.

The I-V characteristics as shown in Figure 2 with the cesium pressure fixed at 0.1 torr and N_2 pressure varying from 0 to 1 torr are basically those of cesium thermionic discharge in which N_2 acts as an energy absorber which quenches the cesium radiation produced by thermionic discharge.

As the N_2 pressure continues to increase while cesium pressure stays low, a new phenomenon is observed as indicated in Figure 3. Here the discharge produced at much higher ignition voltage than those of pure cesium (> 30 volts for our experiments)is similar to a pure nitrogen discharge.

To vacuum pump

gas inlet

Filament Emitter

Plate Collector

Leads to filament

optical window

cesium reservoir
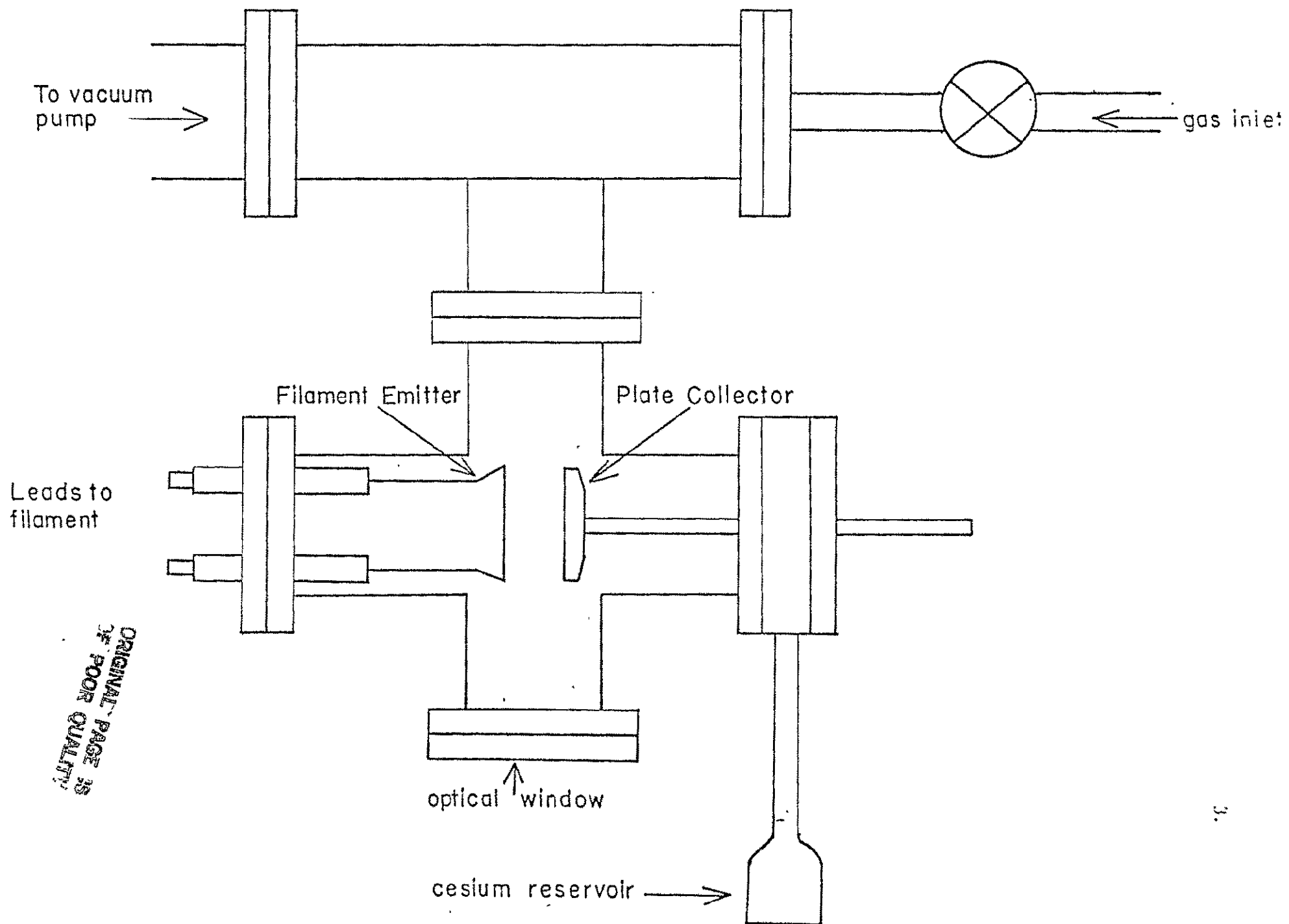
Fig. 1   Schematic diagram of the experimental thermionic discharge tube.
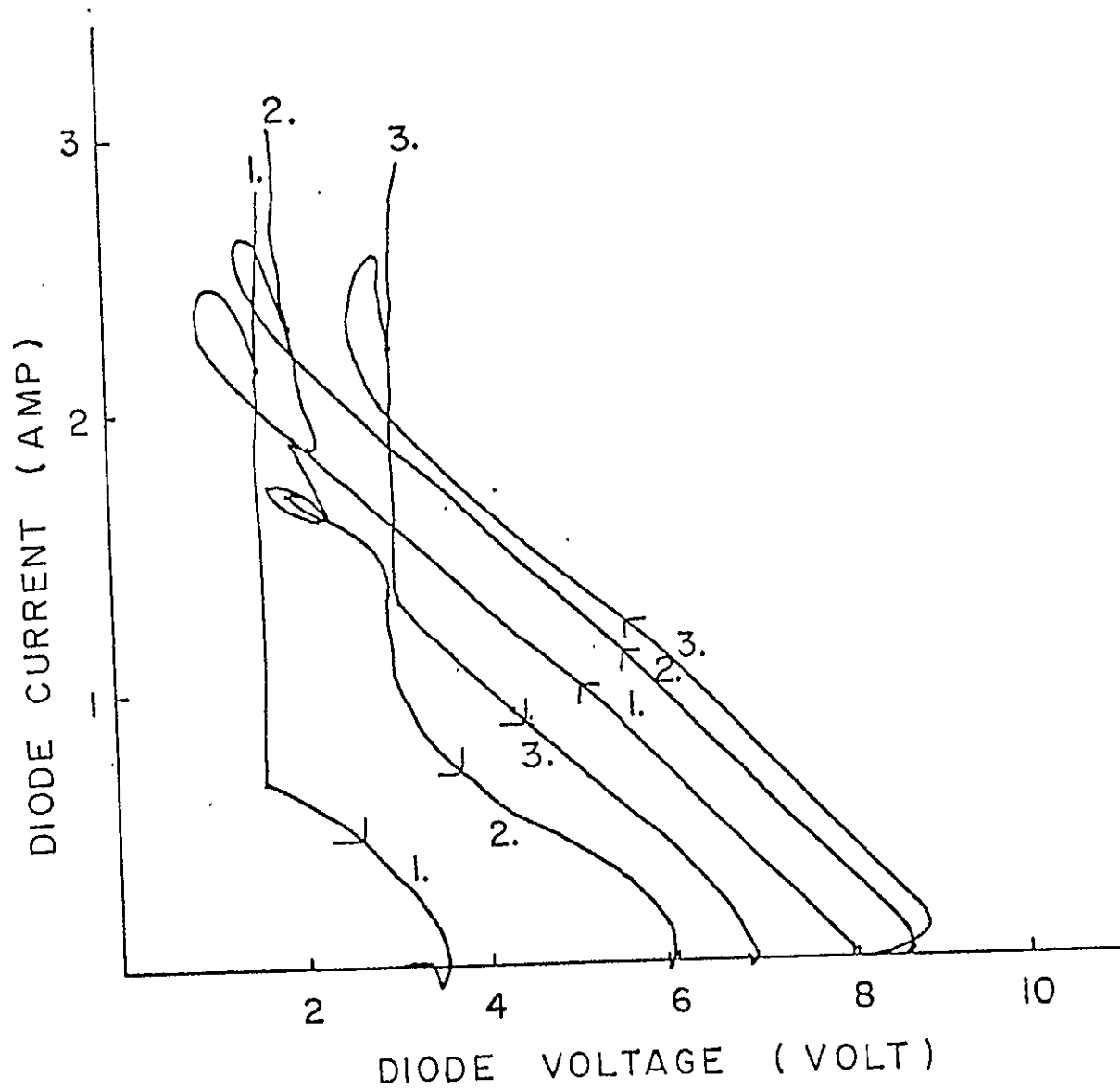
Fig. 2   I-V characteristic curve for P_{N_2}/P_{Cs} 40

1. N_2 = 0 torr, Cs = 0.1 torr

2. N_2 = 0.05 torr, Cs = 0.1 torr

3. N_2 = 0.2 torr, Cs = 0.1 torr
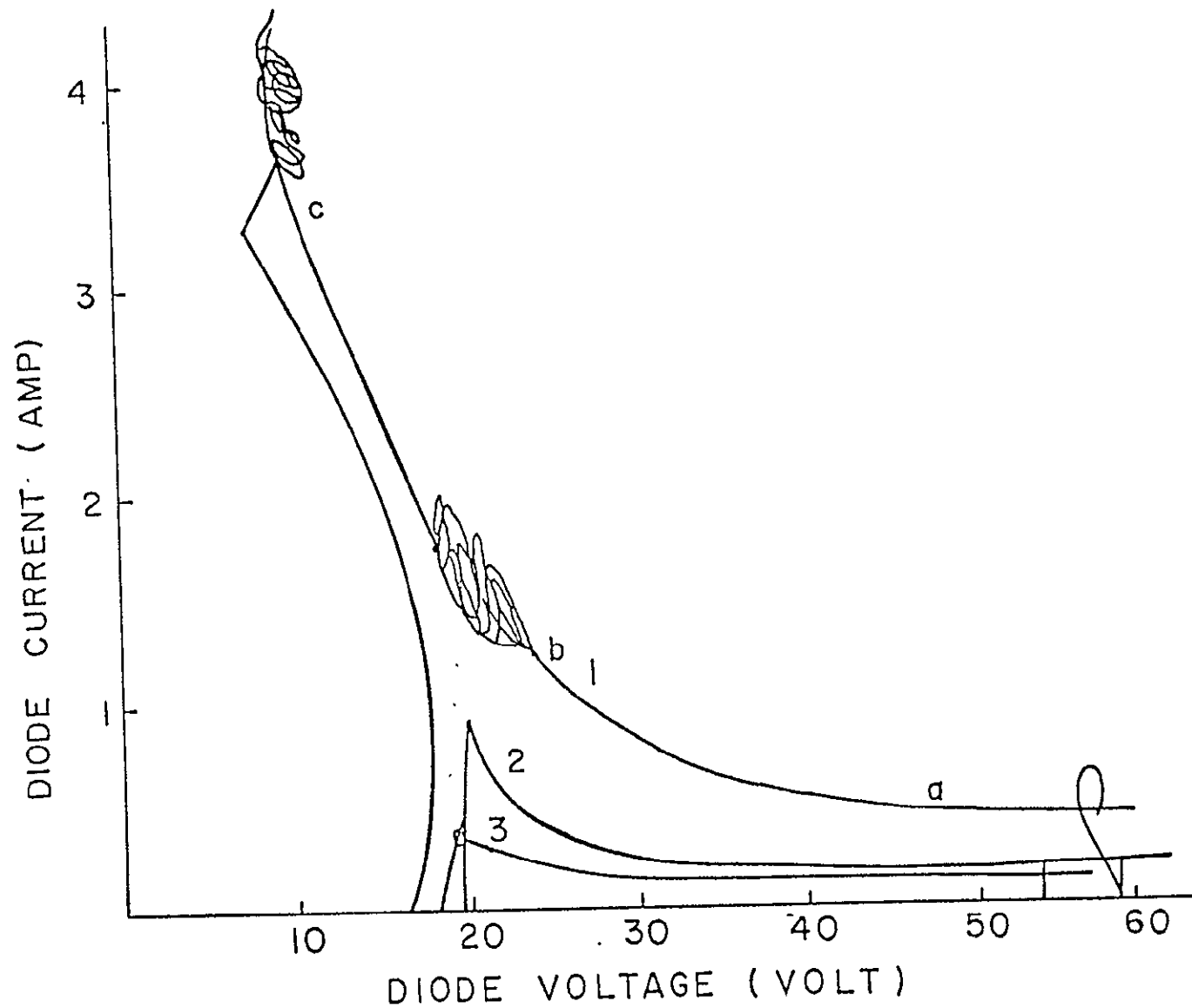
Fig. 3   I-V characteristic curve for P_{N_2}/P_{Cs} 40

1. N_2 = 20 torr, Cs = 0.3 torr plasm oscillation occurs

2. N_2 = 30 torr, Cs = 0.1 torr

3. N_2 = 20 torr, Cs = 0.02 torr

This is verified by spectoscopic measurement (Fig. 4) which shows predominantly the first and the second positive bands of N_2. Cesium radiations are observed at much lower intensities. The dependence of the intensities of N_2 and cesium radiation against applied voltage is shown in Figure 5. The response of cesium radiation to the applied voltage is exactly the same as the response of discharge current to the applied voltage. After ignition, further increase in voltage does not lead to a noticeable increase in current or cesium radiation. However, if one steadily reduces the voltage, the current or the intensity of cesium radiation increases, reaching a maximum and then plunging to zero. As the applied voltage is reduced manually in steps, step-increases in current and cesium radiation occur. The step increase is small initially, but increases drastically as the voltage is further reduced, reaches a maximum then drops to zero as shown in Figure 6. All step-increases in current take place after a delay of about a couple of seconds wherever the voltage is reduced.

The ignition voltages are directly proportional to the pressure and relatively independent of the cesium pressure because of large values of the pressure ratio used in our experiment (P_{N_2}/P_{Cs} 40). At high cesium pressure the increase in current is so pronounced that plasma oscillations occur as shown in Figure 3. The radiation of cesium and nitrogen are not uniformly distributed along the interelectrode spacing as shown in Figure 7.

3. Discussion of results

In the low nitrogen to cesium pressure ratio discharge system, as the voltage increases between the electrodes, the cesium atoms win the competition for the electron energy and become excited and ionized because the
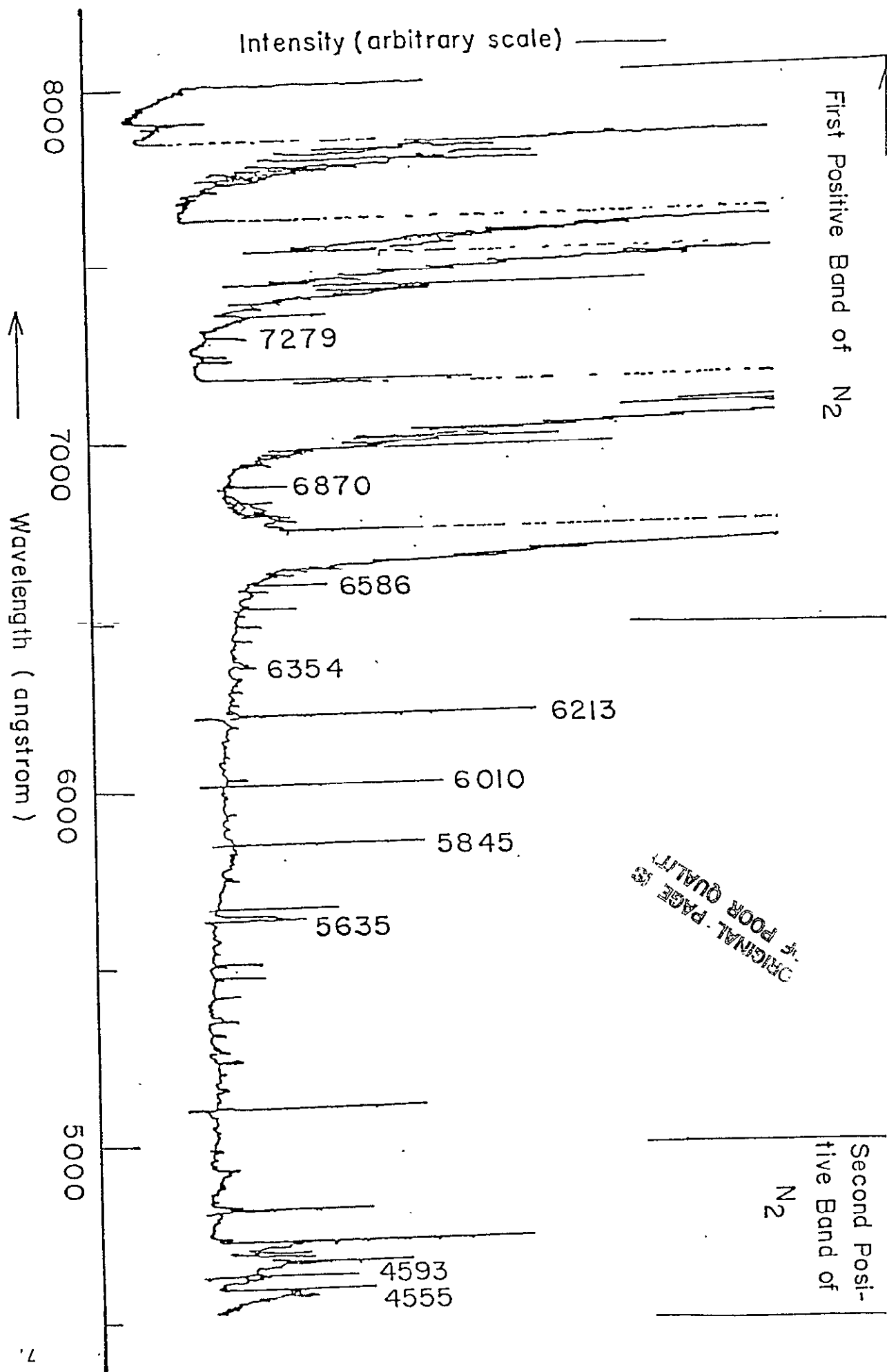
Fig. 4   Spectroscopic measurement 50 volts, for N_2 = 20 torr, Cs = 0.1 torr.

First Positive Band of N_2

Second Posi-tive Band of N_2

Intensity (arbitrary scale)

Wavelength (angstrom)

8000   7000   6000   5000

7279

6870

6586

6354

6213

6010

5845

5635

4593
4555

7.

Fig. 5   Radiation intensity of nitrogen and cesium against applied voltage.
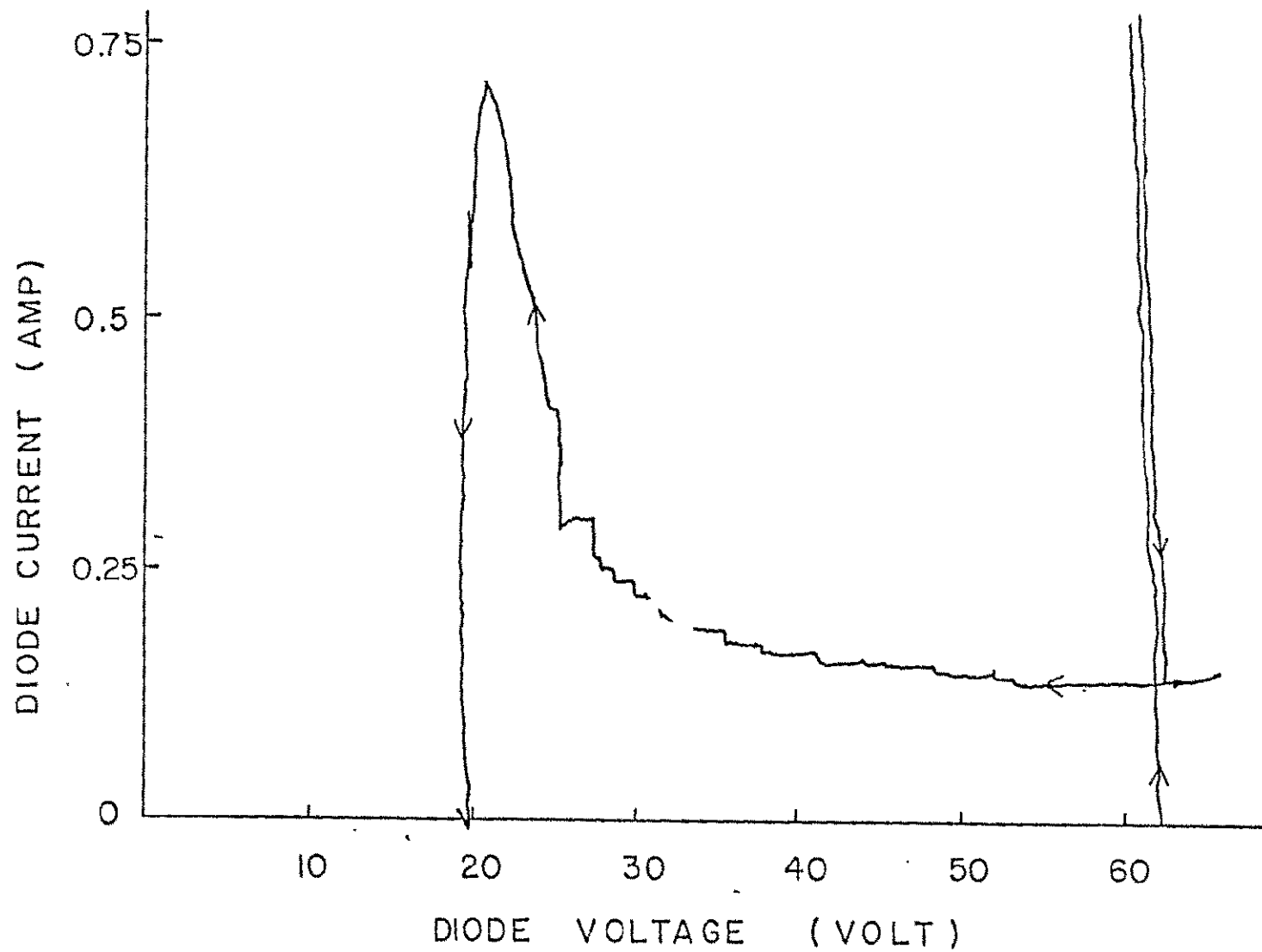
Fig. 6   I-V characteristic curve showing step increase in current.

line intensity (arbitrary unit)

3577Å(40V)

3915Å(40V)

3915Å(30V)

3915Å(20V)
4555Å(10V)

collector

emitter

interelectrode spacing

Fig. 7. Spatial distribution of cesium and nitrogen radiation.

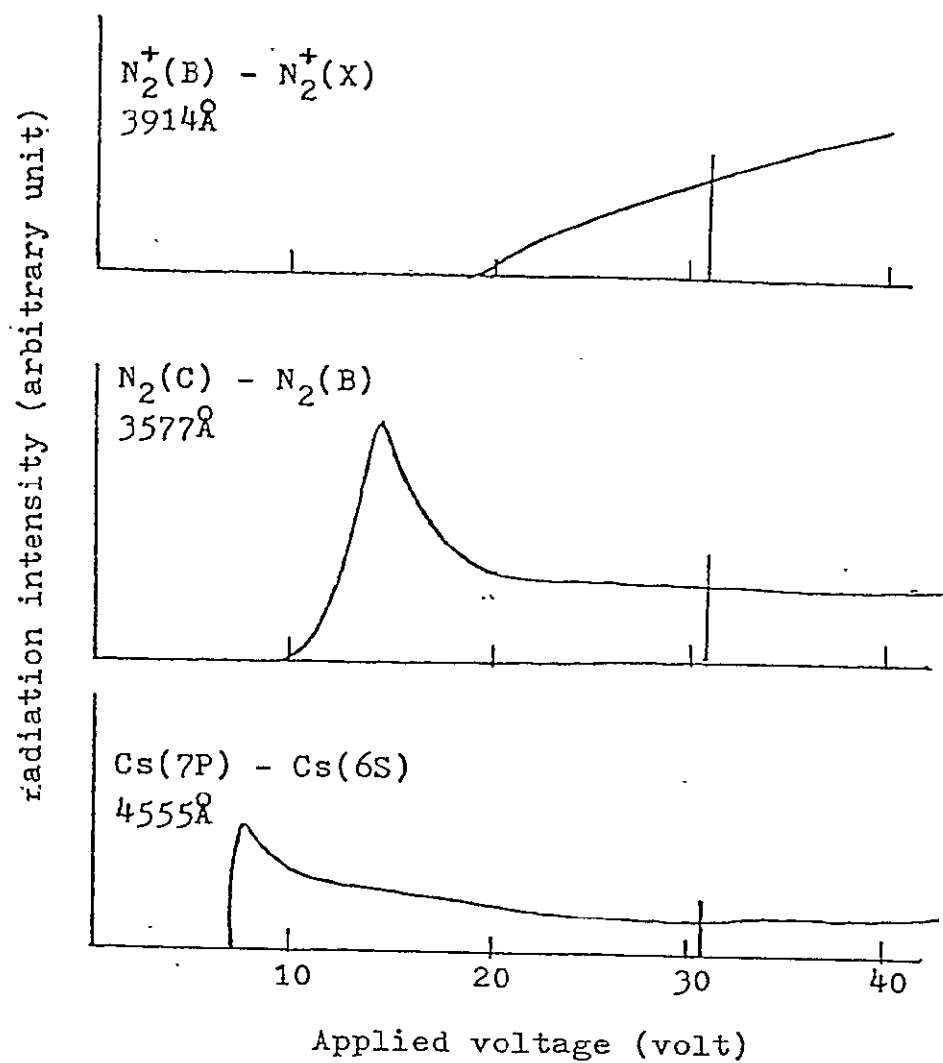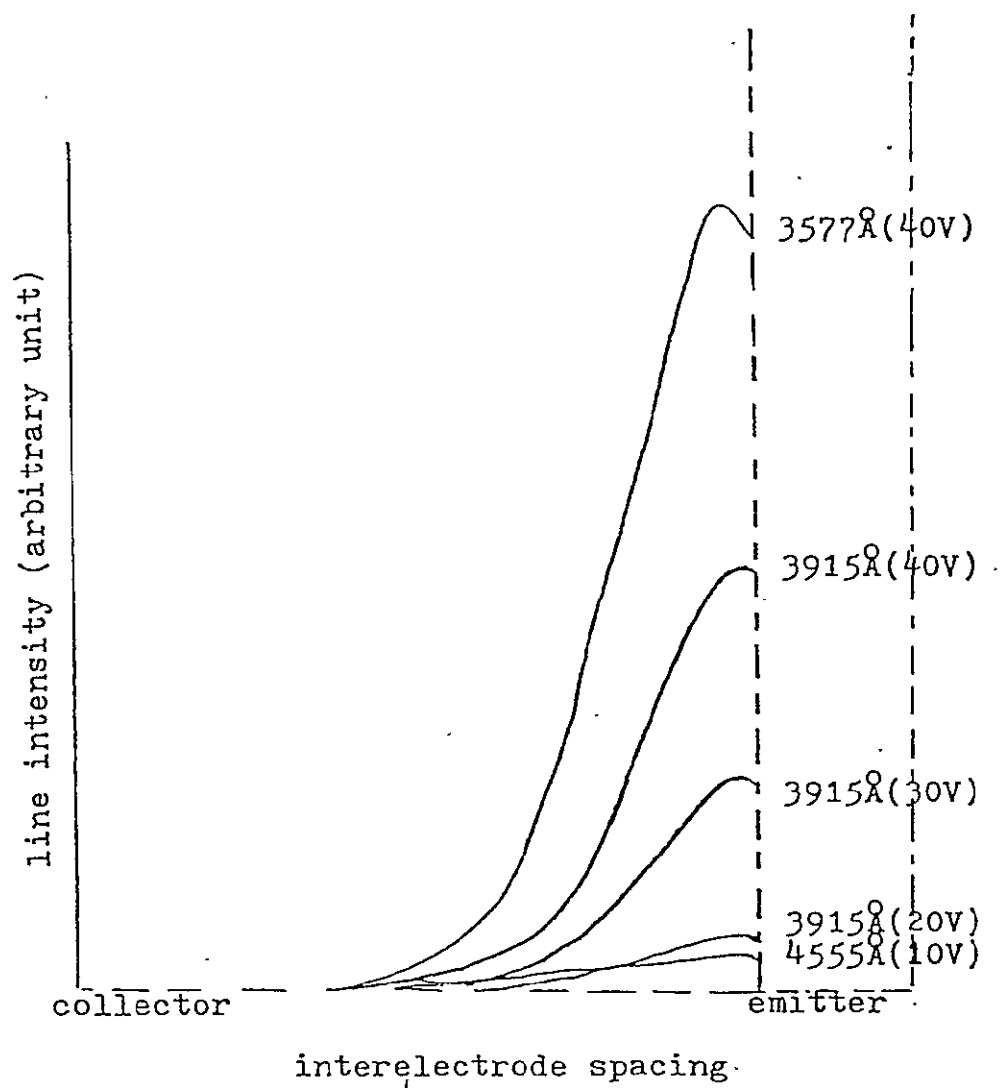cross section of cesium excitation is much larger than that of nitrogen, excitation [6,7]. And no electron has enough energy to excite the nitrogen to the electronically excited states. Nitrogen acts as a quenching agent, taking energy away from the cesium atoms with no return. The I-V characteristic behaves as a pure cesium discharge.

As the system has higher and higher nitrogen to cesium pressure ratio, the voltage needed to excite and ionize cesium is also higher because of the pressure of nitrogen. As soon as the cesium picks up energy from the electrons and becomes ionized, and produces a low density plasma between the electrodes as in the low pressure ratio case, the potential drop within the electrodes immediately adjusts itself such that most of the applied voltage appears in the form of a steep emitter sheath. Thermionic electrons then are accelerated through this high potential drop, and collide with the abundant nitrogen, and electronically excite and ionize them. As the voltage increases or decreases the thermionic electrons will pick up corresponding energy across the sheath. These electrons then colloide with nitrogen molecules, and the nitrogen radiation responds correspondingly. Comparing the nitrogen radiation response to applied voltage with the cross section of electronic collision excitation response to the electron energy, we will find the similarity between the two as shown in Figure 8 [8,9].

Interesting things happen when the applied voltage across the discharge chamber is reduced further; at such low voltage, the energy these thermionic electrons picked up is not enough to excite nitrogen electronically; however, the energy is the right range for excitation of nitrogen vibrational state [10]. Such excitation has a peak cross section around 2.1 ev, and tapers off
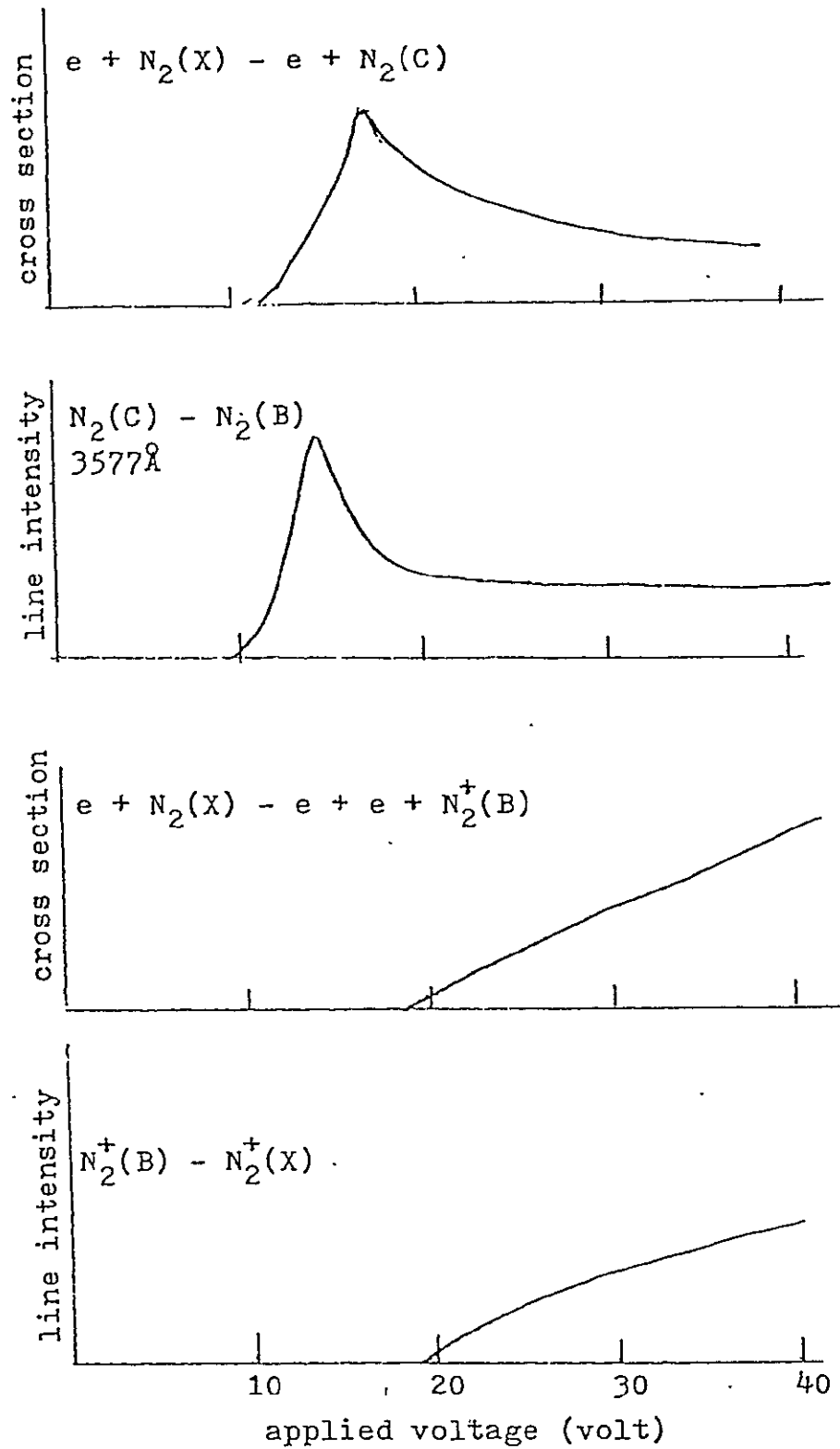
Fig. 8   Nitrogen radiation and electronic excitation cross section response to voltage.
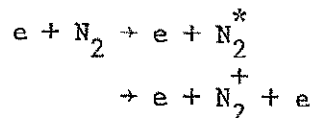
at lower and higher energy. The reduction of the applied voltage also
reduced the gas temperature. The vibrational states distribution is a
very sensitive function of gas temperature. Lower gas temperature tends
to enhance higher vibrational state population [11] as shown in Figure 9.
As the applied voltage is reduced, more and more high vibrationally
excited states of nitrogen are generated. These highly excited nitrogen
then collide with cesium and pass the energy to excite or ionize the
cesium atoms. As a result, the discharge current increases. The gas
temperature changes due to the decrease of applied voltage and is estimated
at having a relaxation time of one second for present geometry and density.
It is this long relaxation time that shows up in the discharge I-V char-
acteristic curve as the slow response of the current change to the imposed
voltage change. Further reduction of the applied voltage leads to
insufficient support of self-sustained discharge; thus the current drops
to zero.

The proposed energy transfer reactions in such a system are:

base line
$$e + Cs \rightarrow Cs^* + e$$
$$\rightarrow Cs^+ + e + e$$

high voltage
$$e + N_2 \rightarrow e + N_2^*$$
$$\rightarrow e + N_2^+ + e$$
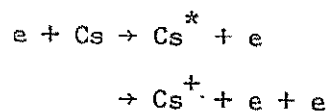
low voltage
$$e + N_2 \rightarrow e + N_2^*$$
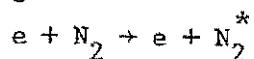
NE transition
$$N_2^* + Cs \rightarrow N_2 + Cs^*$$
$$\rightarrow N_2 + Cs^+ + e$$
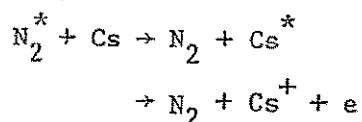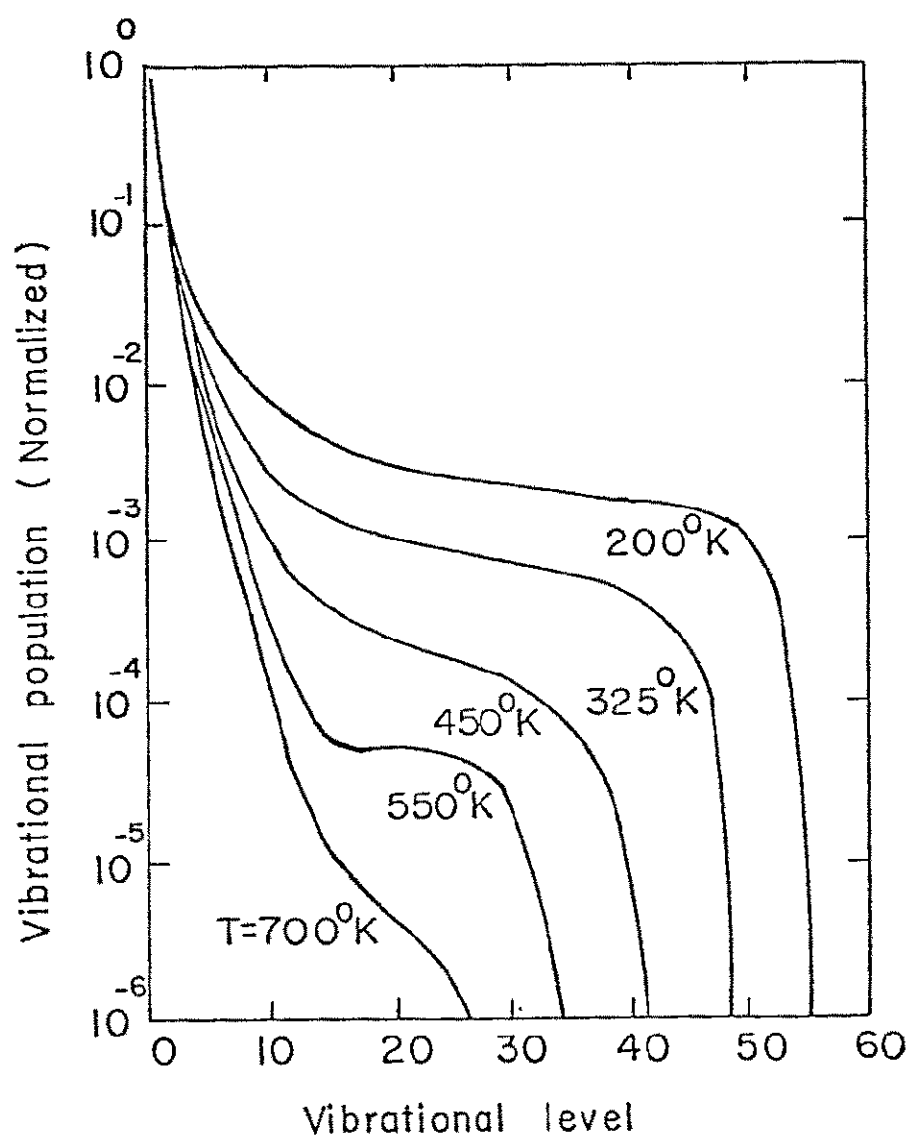
Fig. 9 N_2 vibrational population distribution.

It is evident that some external source of energy must be directed into the interelectrode spacing to produce cesium ions. The energy consumption of this source can then be interpreted as an equivalent plasma arc voltage drop. The performance of the overall system of electrodes and plasma should result into considerable reduction of losses in order to achieve a viable converter.

We intend to investigate the potential of applying microwave power in the interelectrode spacing of the converter as an external ion generation source [12]. Such a plasma generation scheme would be very attractive because of the simplicity of application (electrodeless), high flexibility in adjustment of the operation parameters (frequency and power), and high efficiency in the generation of microwave power from line power (better than 50%). Moreover, it allows for continuous as well as pulsed operation and the possibility of utilizing resonant cavity configurations to introduce the microwave power which may lead into lower losses. Also clearly minimal disturbance would result to the emitter and collector surfaces. This is very important in view of the fact that to date these surfaces have been optimized in performance more or less independently of the thermionic plasma.

II. PLASMA SUSTENANCE BY THE RESONANT APPLICATION OF MICROWAVE POWER

1. Introduction

The thermionic energy converter is very attractive for space power applications in a variety of space vehicles. The primary requirements in such applications are high power to weight ratio and reliable performance. Recently though, the focus of utilization of the thermionic converter has shifted from space to terrestial applications where efficiency and cost are the dominant considerations. In the search of cost reduction, the use of stainless steel or other alloys is favored over refractory metals which are expensive in all facets of construction. The penalty paid is that the emitter temperature now attainable is about 1600°K, which is considerably smaller than the range of 1800-2000°K utilized with refractory metals. The associated collector temperature desired falls in the range of 800°K. These lower temperatures are a better match to conventional power generators utilizing the steam cycle, a fact which makes the thermionic converter one of the attractive candiates in topping applications.

It is clear that we are demanding a strikingly large reduction of the emitter temperature in comparison to the space generation converters. The direct result of this emitter temperature reduction is a considerable reduction in the conductivity of the plasma. This is very undesirable in thermionic converters where high efficiency and high power density are required. It is thus important to devise a high efficiency ion generation scheme for the advanced converter in order to reduce the plasma resistivity. This must be accomplished without disturbing the quality of the performance of the emitter and the collector electrodes.

2. <u>Experimental apparatus</u>   The basic task of the experimental apparatus is to provide for the application of microwave power into the interelectrode spacing of a thermionic converter. Several techniques have been used in the past to couple microwave power into a plasma load. The two most common and successful have been to either locate the plasma column along the axis of a resonant cylindrical cavity [13] or to introduce it into a waveguide in a direction perpendicular to the broadside of the rectangular guide[14]. Both methods have been successfully employed in this work in the range 1-3 GH_z. It is important that proper coupling provisions be made in order to match the microwave transmission line to the plasma load so as to make accurate microwave power consumption measurements at the load possible.

The demountable cesium thermionic converter diode and the vacuum components used in this experiment are shown in Figure 10. The collector of the thermionic converter is a stainless steel disc one inch in diameter while the emitter is made of a tungsten swirl filament 0.040" diameter of the same apparent diameter as the collector. The emitter-collector separation varies between one inch in the cavity coupling arrangement to one half inch in the waveguide insert configuration. Both electrodes are housed in a pyrex glass envelope which serves to confine the plasma away from the walls of the cavity or the waveguide. The glass housing is connected to a cesium reservoir on the one hand and to the pumping system through a bakable valve on the other. The pumping system consists of a mechanical pump, a sorption cryogenic pump, and a 20 ℓ/sec ion pump operating in sequence; this particular combination has demonstrated the best capability of achieving the highest vacuum with the lowest concentration of active residual gases. The converter diode and the cesium reservoir are baked out at 250°C and the emitter outgassed for more than
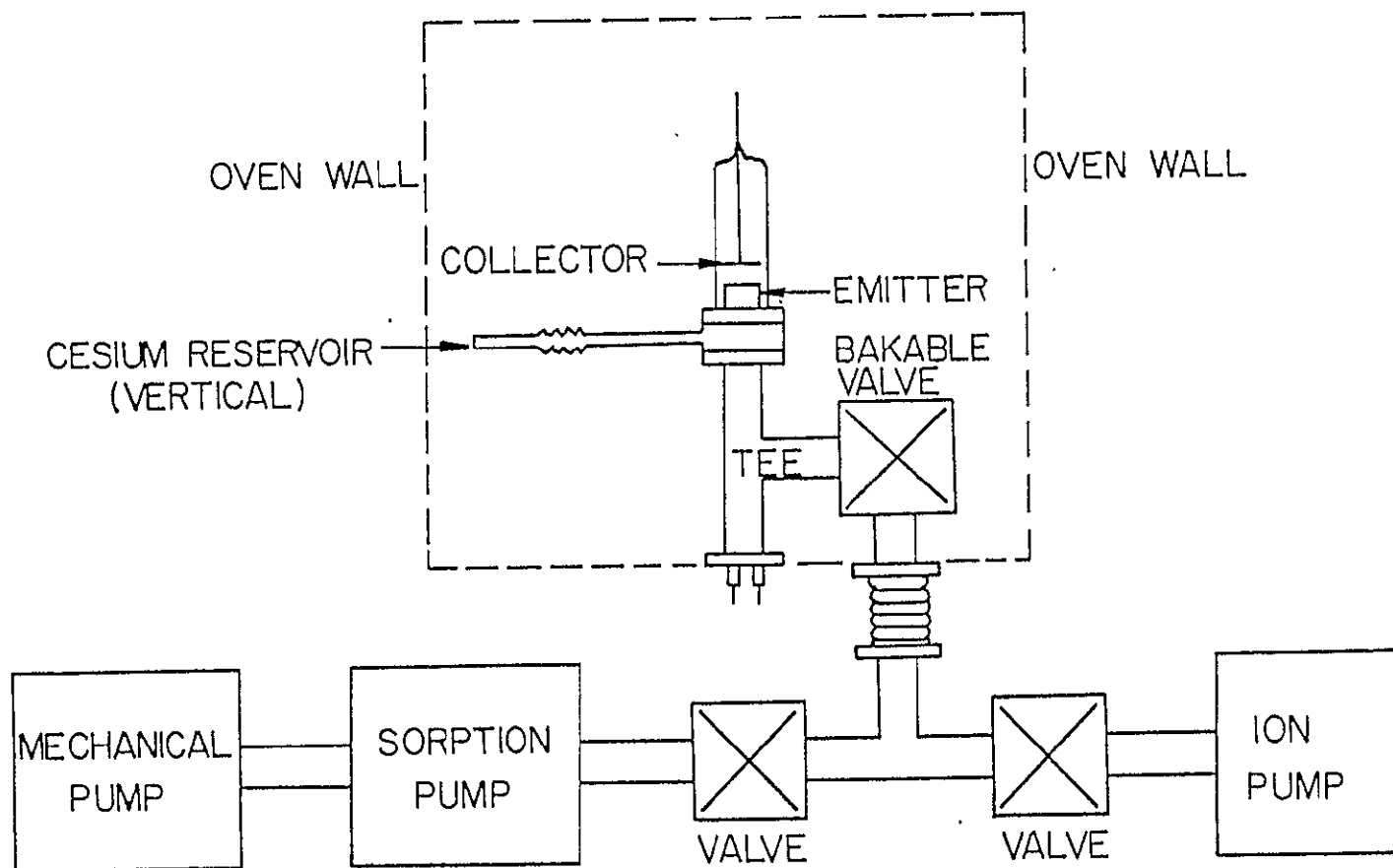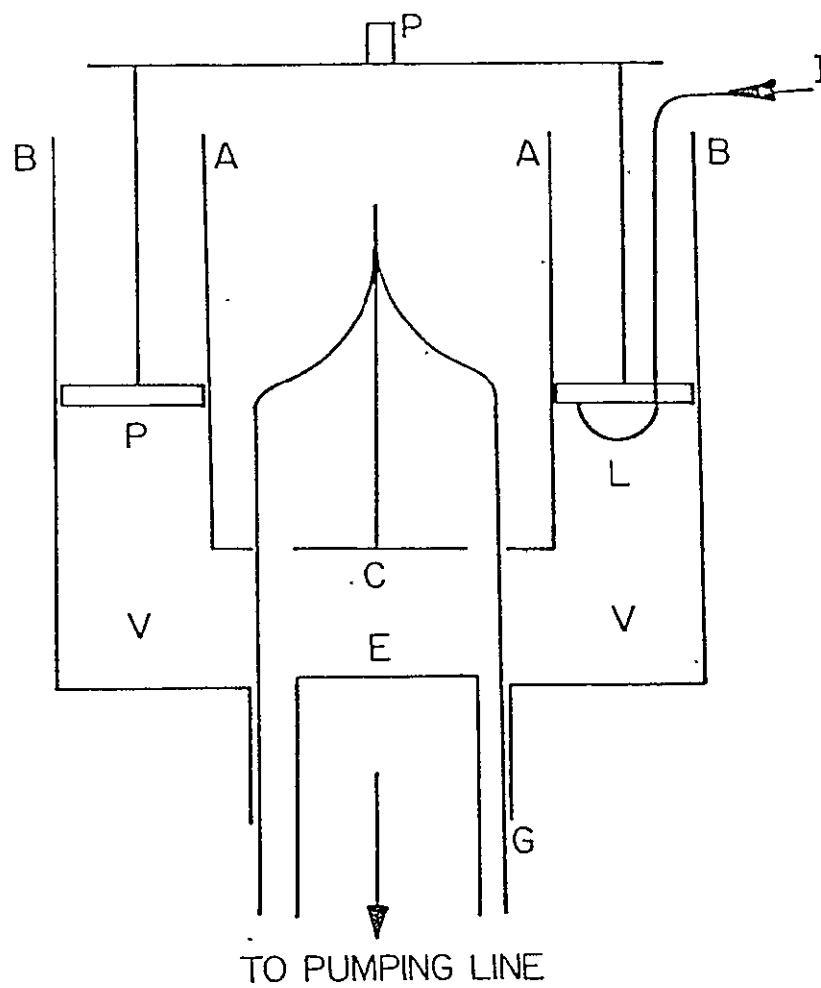
Fig. 10   Schematic diagram of the microwave thermionic system.

24 hours while pumping until a residual pressure of the order of 10^{-8} Torr

is reached. We then close the bakeable valve and activate the cesium reservoir.

The cesium pressure in the experimental chamber is determined by the

reservoir temperature which is established by an independent oven controlled

to $\pm0.1°C$. All other parts of the vacuum system in the cesium atmosphere

are kept at a temperature at least 50°C higher than the reservoir temperature

by another oven in order to avoid cesium cold spots. Temperature measurements

are made at several judicious locations by chromel-alumel thermocouples.

The microwave cavity used[15] is of the reentrant type, as shown in

Figure 11a, because of its easily accessible size in our frequency range,

and the simplicity of construction and operation of its tuning elements.

The cavity is made of two concentric cylindrical conductors of 1 7/8" and

3" ID respectively. The two end walls bear a hole of 1 7/8" through which

the glass tubing housing of the converter is inserted. The emitter and the

collector surfaces thus effectively cover the hole copening as far as the

microwave field in the cavity is concerned. A plunger arrangement as

shown can be used to change the position of one of the end walls between

the cylindrical conductors to adjust the cavity tuning of the resonant

frequency.

An alternative arrangement to using a cavity, shown in Figure 11b,

is to introduce the thermionic converter directly into a waveguide. We

align the axis of the converter diode to be perpendicular to the broad

side of this waveguide and thus parallel to the local microwave electric

field lines in the guide in the TE_{10} mode. This scheme has been very

successful in terms of operational ease and measurement accuracy of the

consumed microwave power.

(a)
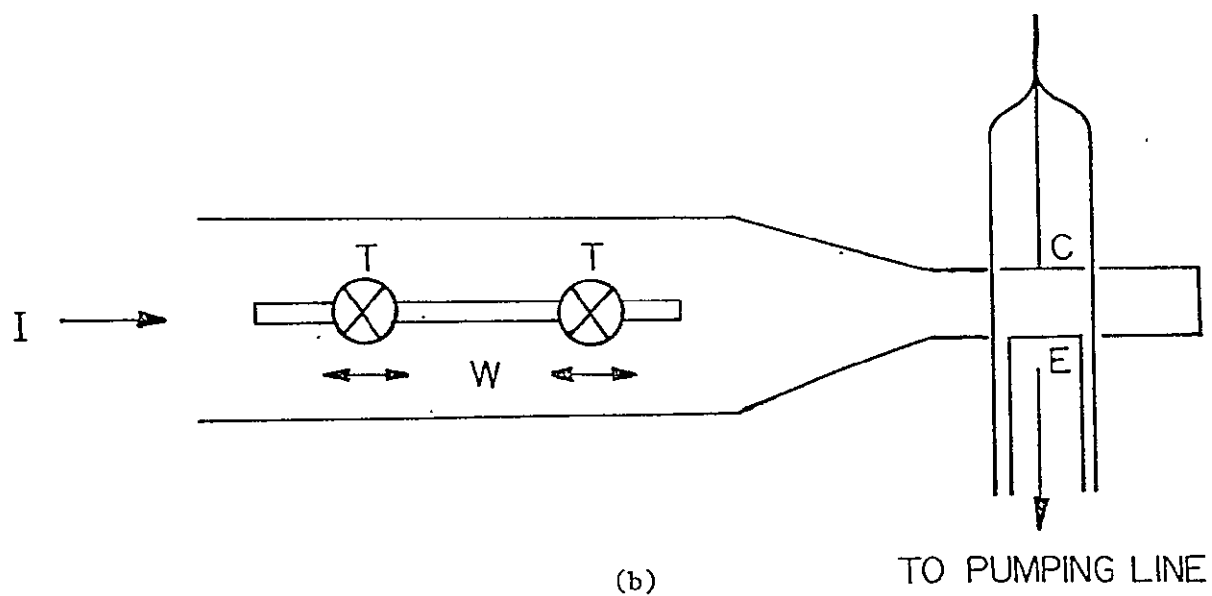
(b)

Fig. 11   a) Schematic diagram for the microwave cavity.

b) Schematic diagram for the microwave cavity inserted into

a waveguide.

A sketch of the microwave transmission and measurement system is shown in Figure 12 . The microwave signal is generated by either a 1-2 GH$_z$ or a 2-4 GH$_z$ sweep oscillator and is then amplified by a travelling wave tube amplifier (TWT) providing output power in the range of 20 watts. A pair of directional couplers is used to measure the incident and reflected power. The reflected signal level is also measured by a power meter and can be displayed on an oscilloscope. The slotted line and the tuner are used to measure and adjust the impedence matching of the microwave line to the plasma load. The resonant frequency and the Q of the empty cavity change substantially when the cavity is loaded by the plasma. It is difficult under these circumstances to initiate and sustain a microwave discharge without tedious adjustments. We thus find it necessary to start the discharge by DC applied voltage, raise the current to the desired operating level, and then turn on the microwave power, tune the cavity and adjust the coupling in the microwave line for the best impedance match and finally slowly turn off the applied DC power while keeping the microwave power to the plasma load constant.
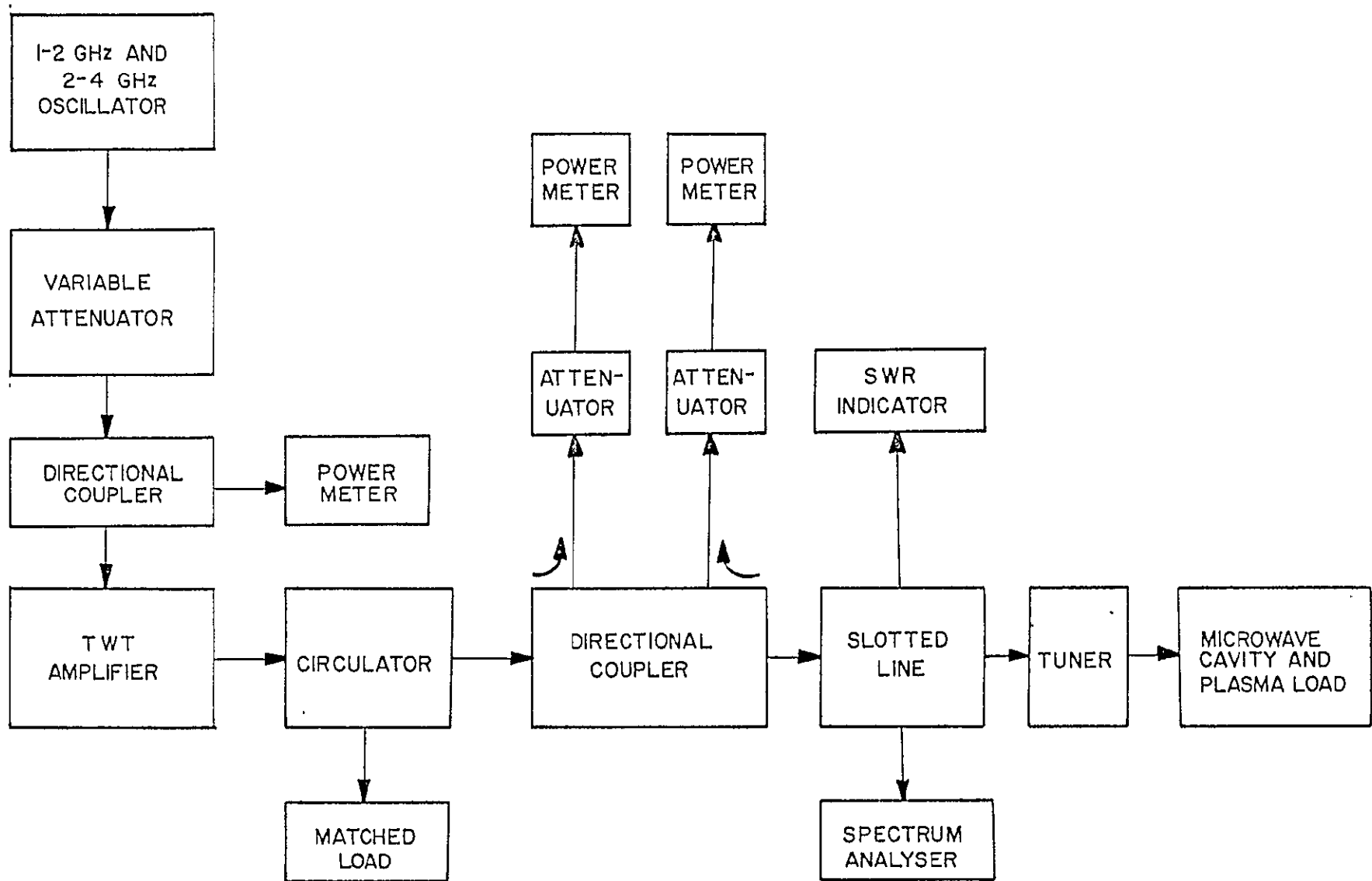
Fig. 12   Block diagram of the microwave transmission and measurement system.

3. <u>The Experimental Results.</u> The performance of a thermionic converter or diode can be improved substantially by lowering the plasma arc drop. The quality of the performance of a converter diode can be deduced from its I-V characteristic curve. The transition point (the "knee") of an I-V characteristic curve of a thermionic diode is also the point of maximum performance of the diode at a certain emitter temperature. · The arc drop voltage of the diode measured at the transition is the potential drop across the interelectrode space required to produce just enough ions to balance the plasma losses. In order to maintain the plasma density level, the electron temperature of the plasma must be sufficiently high to produce ions as rapidly as they are lost by the diffusion to the electrodes and by volume recombination. So the reduction of the arc drop voltage of the diode when the plasma is sustained by microwave power can be measured by the shift of the output voltage at the transition point when we compare the I-V curves with or without applied microwave power.

The experiments were carried out under the following conditions:

1. The cesuim reservoir temperature ranges from 150°C to 200°C which corresponds to a relatively low cesium pressure from 0.01 to 0.1 Torr.

2. The emitter temperature is about 1300°K, which implies an emitter current density of the order of or less than, 1 amp/cm^2.

3. The microwave power level consumed by the thermionic converter plasma varied from 0 to 5 watts.

It is immediately evident that the thermionic diode is not operated at the optimum performance region or in the positive power quadrant This is not important in this work since our interest lies in the understanding of the plasma properties of the thermionic converter distinct from the emitter and collector surfaces.

We measured the I-V characteristic either on the oscilloscope or an X-Y recorder. Both quasi-DC and rectified 60 cycle AC electrical power was applied to ingite or discharge the cesium plasma.

We expected that the application of microwave power would raise the plasma density and temperature and thus significantly alter the characteristic I-V curves. Numerous curves were obtained, but it was found that the important features of the results could be demonstrated by a detailed analysis of the I-V traces obtained at microwave power levels of 0, 1 and 2 watts.

If we study the I-V curves shown in Figure 13a we observe a most dramatic effect displayed by the ignition traces (i.e., increasing voltage) of the thermionic converter. When no microwave power is applied we get, as expected, the usual I-V curves characterized by a breakdown voltage as signified by the knee of the curve. However, upon application of microwave power the knee of the I-V curve disappears completely, and no breakdown voltage is indicated anymore. Indeed, we observe current conduction at zero voltage and even at negative applied voltage indicating that there is conversion of microwave power in DC electrical output power.

The return traces of the I-V curves (decreasing applied voltage) shown in Figure 13b also show important differences revealed in the amount of current that can be carried by the plasma under the same applied voltage; considerably more current can be carried when microwave power is applied and this current enhancement is greatest at the low current levels. The high current ranges are affected very little and in fact the value of the saturation current is not changed at all.

Moreover, it was also found that the knee of the ignition I-V curves indicating the presence of a breakdown voltage was not affected at all at applied microwave power levels below 0.5 watts, then it continuously shifted to lower voltages as the power increased from about 0.5 to 1 watt; and
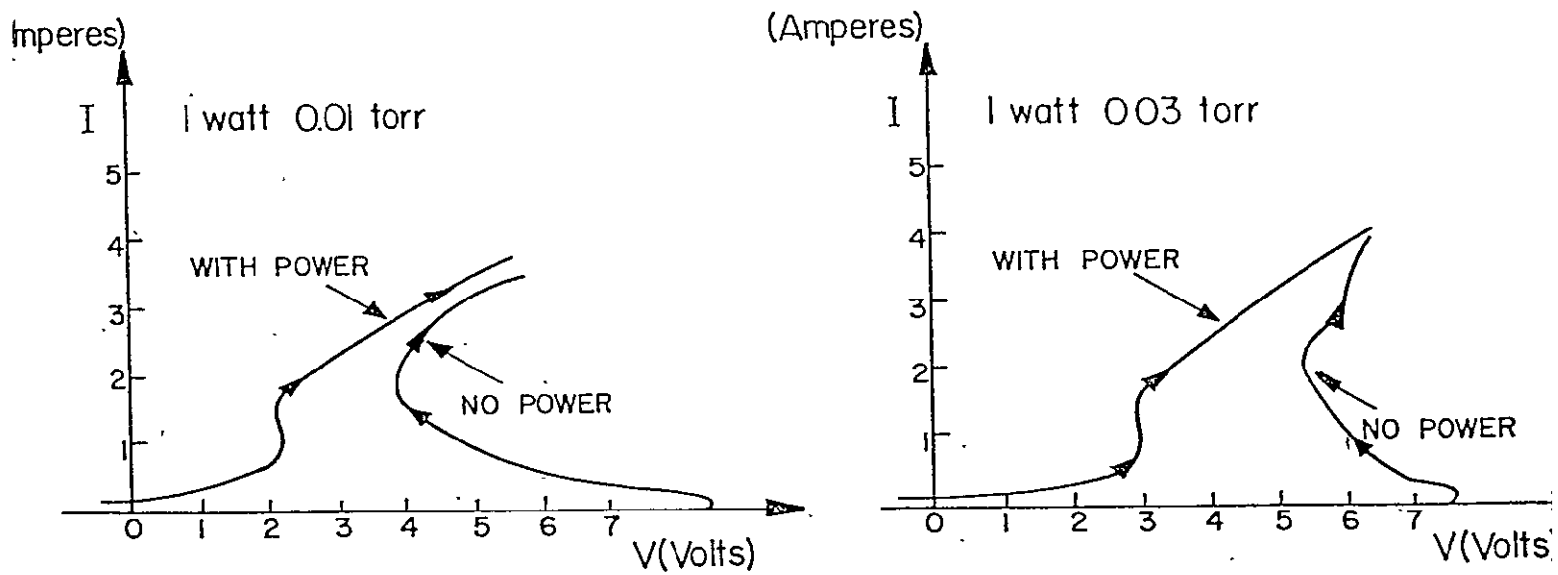
(a)
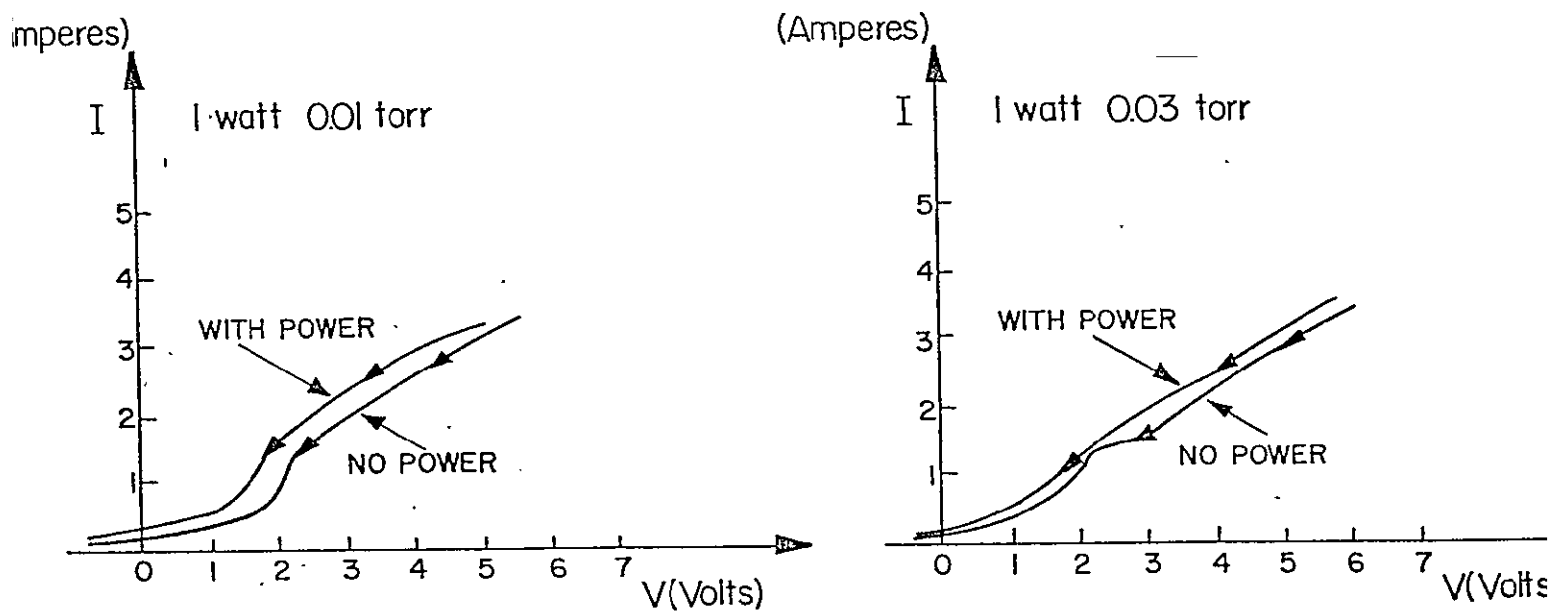
(b)

Fig. 13   a) The ignition current voltage characteristics under two cesium

pressures with and without microwave power.

b) The return current voltage characteristics under two cesium

pressures with and without microwave power.

completely disappeared when the level of 1 watt was reached. In order to appreciate the effects of varying the applied microwave power level we show in Figure 14 a family of ignition and return curves at cesium pressure P = 0.01 Torr. At higher microwave power levels only small changes occur mostly in the lower current region. In these lower ranges the current carried at the same voltage rises as a function of the applied microwave power; in particular at zero voltage the transmitted current increases indicating that more microwave power is converted into DC power.
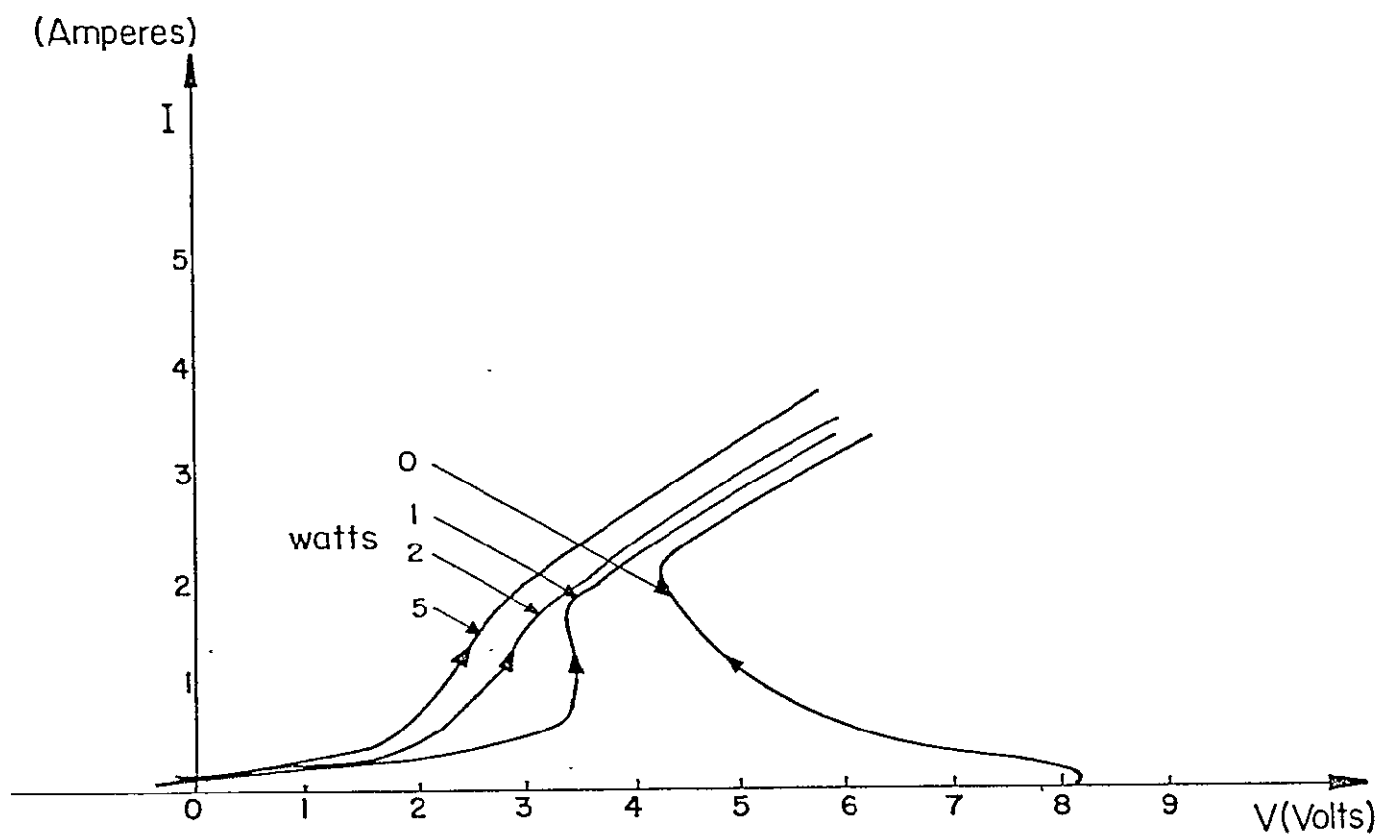
(a)
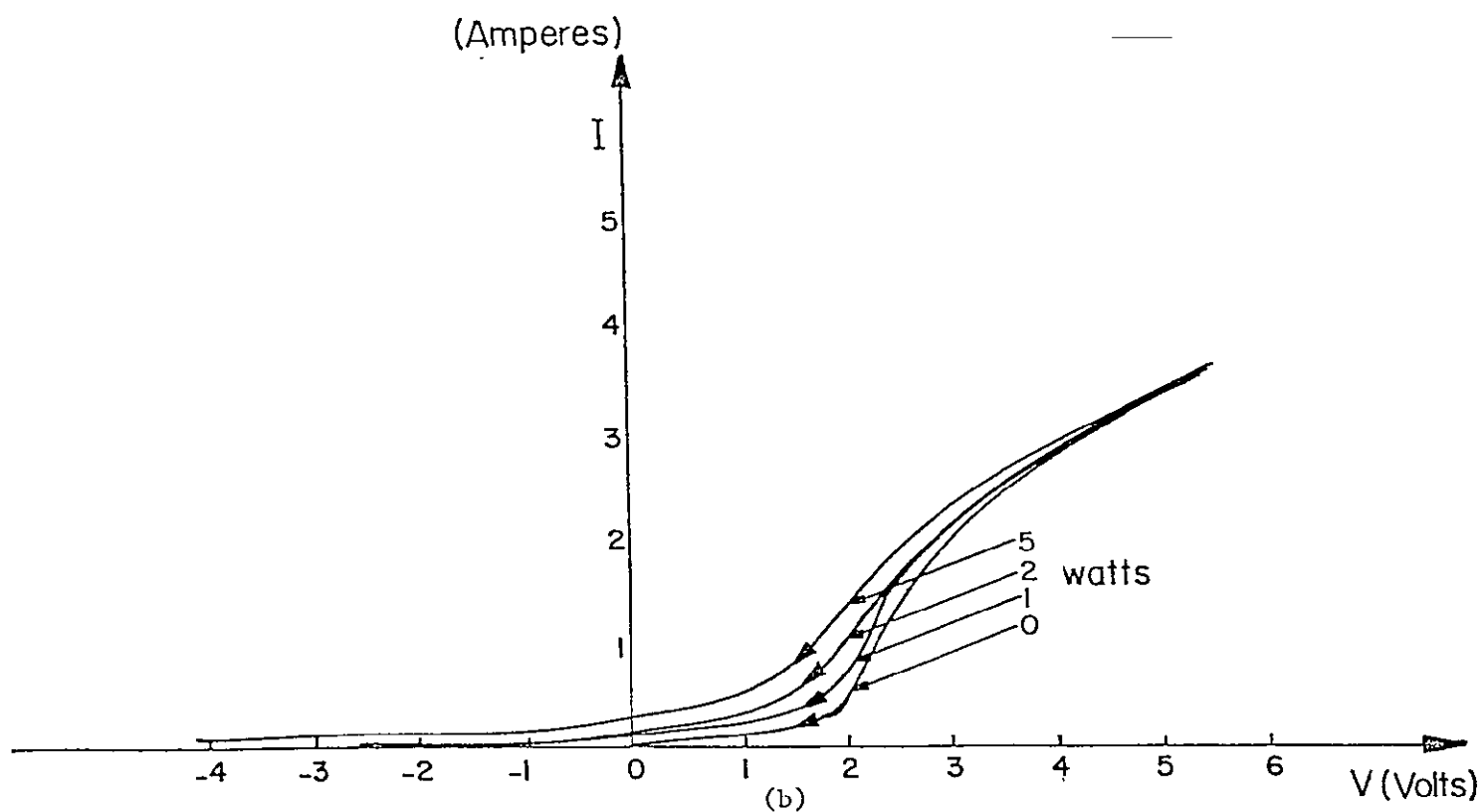
(b)

Fig. 14   The ignition (a) and return (b) I-V characteristics for varying

microwave power at cesium pressure P = 0.01 torr.

4. Analysis of the Results

A qualitative understanding of the above results can be gained by considering the potential energy diagrams for the converter in the presence or in the absence of applied microwave power. In Figure 15 we show an ignition curve in the absence of microwave power; three main regions can be distinguished characterized by different potential energy diagrams, the unignited mode, the obstructed region, and the saturation region. In the unignited mode no double sheath exists, while in the obstructed region the double sheath erected in front of the emitter dominates the behavior of the converter. The voltage must thus be raised to the breakdown value in order to overcome this motive peak. The double sheath disappears in the saturation region. When microwave power of a sufficiently high level is applied, no such breakdown voltage threshold is observed, which immediately indicates that no motive peak exists; the structure of the potential energy diagram under these conditions is very simple, as seen in Figure 16. An interesting method of evaluating the performance of the thermionic converter is provided by Lam [16] who summarizes the plasma arc drop in terms on a single parameter, the normalized plasma resistance R. According to this theory the converter arc drop V_d is related to the plasma resistance R by the equation

$$ j = \frac{1}{1 + \exp \dfrac{jR - V_d}{\tau}} \tag{1} $$

where j is the converter current and τ the plasma temperature; all $V_d, j, R,$ and τ are in normalized units given by:

$$ V_d = (\phi_E - \phi_c + \Delta X - V_o)/(kT_E/e) \tag{2a} $$
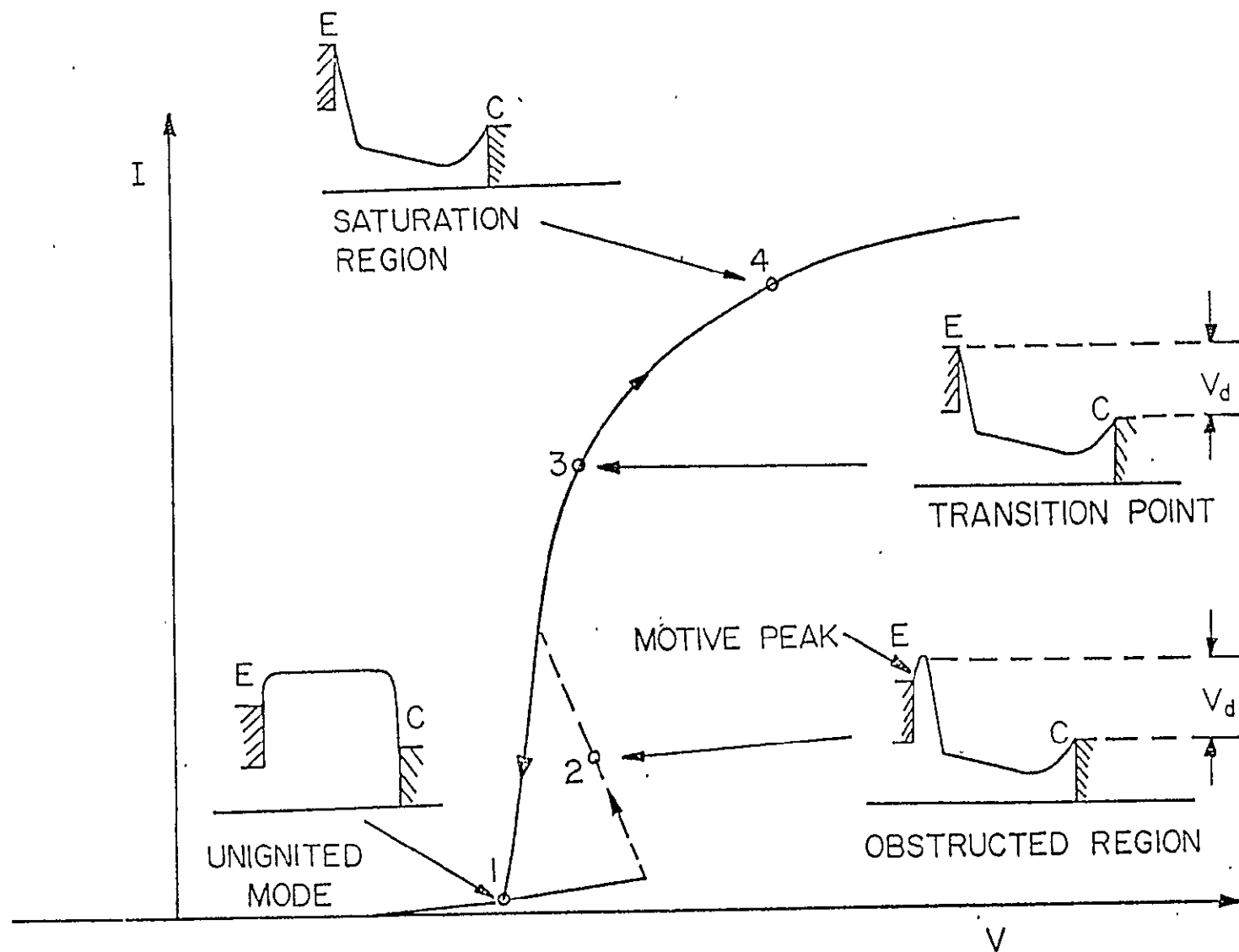
Fig. 15   The potential diagram for typical ignition current voltage

characteristics without microwave.
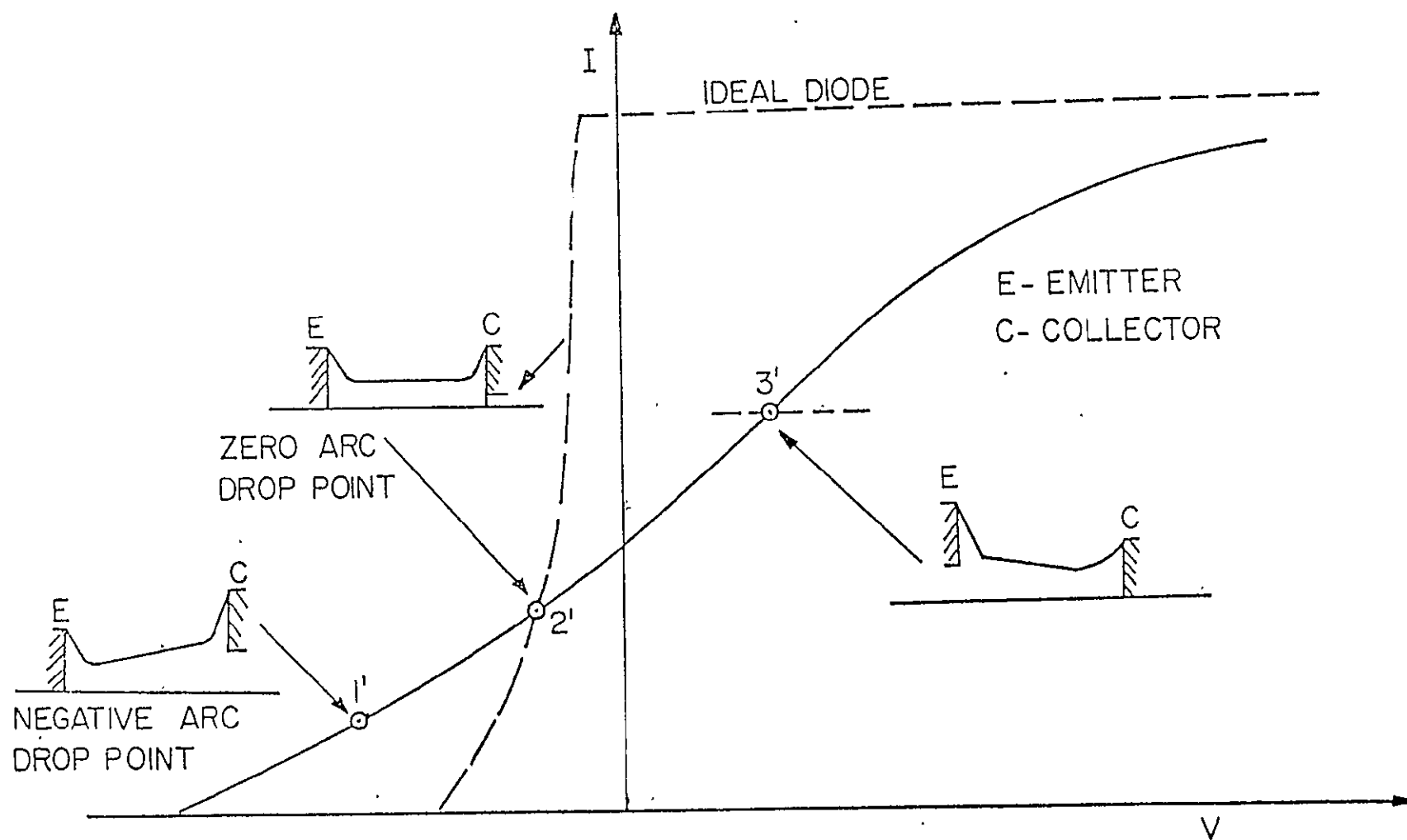
Fig. 16   The potential diagram for typical ignition current voltage

characteristics with microwave.

where ϕ_E is the emitter work function, ϕ_c the collector work function, $\Delta\lambda$ the

voltage height of the emitter double sheath measured from the emitter, and

V_o is the output voltage. The value for V_d in volts has been normalized to

units of $\frac{kT_E}{e}$ where T_E is the emitter temperature, k the Boltzmann constant

and e the electronic charge. We further define the normalized current

density

$$j = J/J_E \qquad (2b)$$

where J is the converter diode current density and J_E is the emitter current

density. The normalized plasma resistance R is defined by the expression

$$\Delta X_{ohmic} = jR \qquad (2c)$$

where ΔX_{ohmic} is the normalized (again in units of kT_E/e) ohmic (momentum

scattering) contribution to the total plasma arc drop. The plasma electron

temperature T_e is also included in dimensionless form τ given by

$$\tau = T_e/T_E \qquad (2d)$$

In the obstructed region we have

$$J_E = J_R \exp(-\Delta\tilde{\chi}) \qquad (3)$$

where $\Delta\tilde{\chi} = \Delta\chi/(kT_E/e)$. If the emitter motive peak is suppressed, i.e., if $\Delta\chi = 0$,

then $J_E = J_R$. Without external heating, R cannot be determined experimentally be-

cause J_E and τ both change simultaneously below the transition point of the I-V

curve, where the emitter motive exists. This can be explained by Figure 15 which shows

the potential diagram between the electrodes at four points on the I-V curve.

At point 1, the plasma is unignited and the current density is very low. At

point 2, the plasma is in the negative resistance region where the plasma is not

completely ignited and the emitter motive peak still exists. At either point 1

or 2, the emitter net current density J_E cannot be determined because J_E is

a function of τ and $\Delta\tilde{\chi}$ which are both varying during the transition from

point 1 to point 3. It is only when point 3 is reached which is the transition

point or the "knee" of the I-V curve, that the plasma is completely ignited,

the emitter motive peak disappears, and $J_E = J_R$ becomes a constant. At

point 4 the plasma is in the saturation region. In Figure 16 we see the I-V curve

and the potential diagrams of the converter diode with microwave heating. The

"knee" of the I-V curve disappears and the plasma is sustained at high current

density when both AC and microwave power are applied while at low current density the

plasma is sustained only by microwave power. Because of the disappearance

of the emitter motive peak there is no sudden jump of the diode current and

$J_R = J_E$ = constant can be assumed. As a result, Eq. (1) can be used to

relate $j = (J/J_R)$ and V_d at a certain value of R and τ. The normalized

I-V characteristics of the diode with external heating are plotted as j versus

V_d. The best fit of these experimental I-V curves with respect to the para-

meters R and τ into the curves provided by Lam's theory can provide us with

the best values of R and τ. The normalized plasma resistance, R and the nor-

malized electron temperature τ, are tabulated in Table 1 with different

emitter temperatures. The cesium pressure is 0.08 Torr.

Table I

$T_E(^\circ K)$	935.	965	995	1025	1055	1085	1115	1180	1210	1240	1270	1300
R	10	10	15	20	25	25	25	25	30	30	50	50
τ	10	8	7	5	5	5	5	5	5	4	3	3

We find that at $T_E = 935°K$, R is equal to 10 and the best value of τ is also 10. At $T_E = 1055°K$, R increases to 25 and τ decreases to 5 which is almost constant until $T_E = 1180°K$. From $T_E = 1210°K$ to $1300°K$, R is greater than 30 and τ is less than 4. The table shows that as τ decreases, the plasma resistance increases, which is an indication that in order to reduce plasma resistance or arc drop, higher electron temperature is required.

5. Discussion.

We have seen a significant rise in the thermionic converter current level upon application of microwave power. In the experiments described in this work the improvement is limited to the lower current ranges due to the shielding effects of the plasma at the higher current values. At these high current ranges the plasma density is high and microwave propagation is cutoff if the frequency is not high enough. It is expected though that higher frequency microwave power would suffer no such limitations and would provide current enhancement at high current levels which would be of great interest in practical applications.

It is thus believed that microwave power shows great promise as a source of energy to sustain the cesium plasma in a thermionic converter. At the lower operating temperature of 1600°K the emitter in the advanced converter can no longer supply sufficient ionization levels. An external source of ion generation is needed which does not interfere with the emitter and collector electrodes. Externally supplied microwave power may prove to be the best agent to perform the task. It is attractive in many ways. There is considerable flexibility in that we may adjust both the power and the frequency of the applied microwave power to achieve the desired plasma condition. In supplying microwave energy we do not interfere with the interelectrode spacing by the insertion of extraneous electrodes. We may operate in the continuous mode in contrast to pulsed systems which would not be available for power generation during the pulse on condition. Furthermore the geometrical size of the emitter-collector distance envisioned is the correct order of magnitude to allow support of the plasma by microwave fields in a resonant mode. The energy expenditure of microwave power at a resonant plasma system is expected to be smaller in comparison to alternative energy sources. Moreover, the power

requirements in the applied microwave field seem rather modest – a few watts – easily available in present day technology even for large thermionic converters. Subsequent experiments should be performed with microwave power of high frequency, i.e., at 10 GH_z (X-band) and 20 GH_z (K-band). The technology of microwave power generation and transmission is well advanced with many off-the-shelf items available to utilize in our systems.

We have seen in our analysis of the experimental data a trend that tends to support Lam's theoretical treatment. More work is needed in this area to provide a comprehensive understanding of the plasma in the thermionic converter. The simplicity of a microwave supported plasma in an optimum diode could allow for easily interpreted data from which conclusions may be drawn about the proper plasma density level for highest overall efficiency. We thus believe that microwave power sustenance of a thermionic plasma in a resonant configuration is indeed a very attractive choice.

REFERENCES

1. A.C. Mitchell and N.W. Zemansky, <u>Resonance Radiation and Excited</u>
    <u>Atoms</u>, Cambridge Press, London 1961, p. 189.

2. D.R. Jenkins, <u>Proc. Roy. Soc.</u>, (London) <u>A</u> <u>303</u>, 453 (1968).

3. R. Hang, G. Rappenecker, and C. Schmidt, <u>Chem. Phys.</u> <u>5</u>, 255 (1974).

4. H.F. Krause, J. Frick and W.L. Fite, <u>J. Chem. Phys.</u>, <u>56</u>, 4593 (1972).

5. C.M. Sadowski, H.I. Shiff and G.K. Chow, <u>J. Photochem.</u>, <u>1</u>, 23 (1972).

6. S.C. Brown, <u>Basic Data of Plasma Physics</u>, MIT, 1966.

7. J.M. Houston, Report on Thermionic Conversion Specialist Conference,
    IEEE, Cleveland 1964, p. 300.

8. D. Rapp and P. Englander-golden, <u>J. Chem. Phys.</u>, <u>43</u>, 1461 (1965).

9. S.M. Kishko and M. Iu. Kuchinken, <u>Opt. Spect.</u> <u>6</u>, 378 (1959).

10. G.J. Shulz, <u>Phys.Review,</u> <u>125,</u> 229 (1962).

11. G.E. Calidoniz and R.D. Center, <u>J.Chem. Phys.</u>, <u>55</u>, 552 (1971).

12. H.S. Chi-, D.T. Shaw, C.N. Manikopoulos and C.H. Lee, 12th Intersociety
    Energy Conversion Engineering Conference, Sept. 1-5, 1977, Washington.

13. K.I. Thompson, <u>J. Appl. Phys.</u>, <u>34</u>, No. 6, 1622 (1963).

14. G. Cicconi, V.G. Molinari, and C. Rosatelli, <u>J. Appl. Phys.</u>, <u>12</u>,
    No. 5, 721 (1973).

15. K. Fujisawa, IRE Trans.Micr.Th. and Techn., 344, October (1958).

16. S.H. Lam, IEEE International Conference on Plasma Science, May 23-
    25, 1977, RPI, Troy, N.Y.