CHAPTER III

MEASUREMENT OF PLASMA PARAMETERS IN AN ARC PLASMA BY PROBE METHOD

3.1. Introduction

A single probe method has been used to measure the electron temperature and electron density in an arc plasma in mercury vapour for arc current varying from 2 A to 5 A and for three background pressures namely 0.075, 0.10 and 0.13 torr. Langmuir's method for determination of electron density n_e and electron temperature T_e is well known and this is also a standard and simple method of measuring plasma parameters directly. In zero magnetic field the theory of the probe rests on the assumption that a parameter $\xi = r_p / \lambda_d$ introduced by Chen, Etievant and Mosher (1968) where r_p is the radius of the probe and λ_d is the Debye shielding length for repelled species should be greater than 5 (five). This should hold good in order that Langmuir's orbital theory for the determination of electron density and electron temperature by the single probe method can be regarded as valid. However, the limitations as well as the validity of these assumptions have been discussed by a large number of workers. In this regard a detailed discussion has been provided in the review article (Chapter I). In this laboratory Sadhya, Jana and Sen (1979) measured the electron density and electron temperature in a glow discharge in hydrogen, oxygen, nitrogen and air and investigated their variation in transverse and longitudinal magnetic fields by single probe method and the results were quantitatively explained by developing necessary mathematical formulation. It was further shown that the results obtained by probe method were in agreement with the results obtained by other methods, such as microwave and spectroscopic methods.

For the last few years Sen, S.N. and his research fellows, in this laboratory have taken up systematic investigation of the properties of arc plasma in order to develop a generalised theory as to the occurance of an arc plasma and bringing out the salient changes as regards the transition of glow discharge to arc plasma.

The measurement of electron temperature and its variation with an axial magnetic field in an arc plasma has been investigated by a spectroscopic method in detail [Sadhya and Sen (1980)] . Since a large collection of data regarding plasma parameters and their variation in a perturbing field is necessary to build up the theory for the occurance of arc plasma it is worthwhile to investigate whether the Langmuir single probe method can be utilized for measurement of arc plasma parameters. This will not only enable us to obtain the necessary data but will also extend the validity of Langmuir probe theory from the glow discharge to the arc plasma region. We report here the results of measurements of electron temperature and electron density in a mercury arc plasma for a range of arc current.

Another property that is of importance is the mechanism by which charged particles are lost by the ambipolar diffusion process . As experiment has been set up to measure the resultant diffusion voltage in an arc plasma for different arc currents. The method has been utilised by Sen, Ghosh and Ghosh (1983), in evaluation of electron temperature in glow discharge. The process of diffusion is basically connected with the radial distribution function of charged particles and an expression for the radial distribution function of the electrons in an arc plasma has been provided by Ghosal, Nandi and Sen (1978), the experimental results will be discussed in the light of the above theories.

3.2. Experimental Arrangement and Measurement

The method of measurement of electron temperature and electron density is the same as was used earlier and described in the paper by Sadhya, Jana and Sen (1979). In Chapter II the detailed experimental procedure for measurement of electron temperature and electron density has been given. Here, however, measurement has been carried out in a mercury arc plasma produced within a cylindrical glass tube of inner radius 1.31 cm with two mercury pool electrodes 38 cm apart. The schematic diagram of this experimental set up has been given in fig. 2.9 (a), (Chapt. II). The arc is produced by supplying power from a 250 V d.c. generator. The arc current has been varied from 2 A to 5 A by a regulated rheostat in series. Measurement has been taken for three background air pressures, namely 0.075 torr, 0.10 torr and 0.13 torr. A cylindrical tungsten wire of 0.014 cm radius within a glass capsule with a bare tip of 0.10 cm length is utilised as the probe which is placed at a distance of 14 cm from the anode. The probe current measurement circuit has been shown in Fig. 2.9 (a) (Chapt. II). The probe was supplied with d.c. bias voltage from dry battery through a potentiometer. For change over from ion current to electron current externally polarity reversal has been made with the help of band-switch. The circuit has been connected to the anode of the arc tube and the probe voltage which is relatively negative with respect to anode has been varied in steps from 0.2 - 5 volts. The probe current has been measured as a function of probe potential.

3.2.1. Measurement of T_e and n_e

According to Langmuir the relation between the probe current and probe voltage is given by

$$I_e = I_{re} \exp\left(- \frac{eV_p}{KT_e}\right) \quad \ldots(3.1)$$

and

$$I_{re} = \frac{1}{4} A n_e \left(\frac{8KT_e}{m\pi}\right)^{1/2} \cdots (3.2)$$

where the symbols have their usual significance. A is the effective electron collecting area of the probe and n_e is the unperturbed electron density. Assuming the distribution to be Maxwellian, T_e is calculated by taking the slope of the Boltzmann line in a semi-logarithmic plot of I_e versus V_p according to eqn. (3.1). Actually it is observed that the probe current never saturates. The rise of current with increasing positive potential is expected due to growth of effective collecting area of the probe as the sheath expands. Linear extrapolation of the curves has been made in such a way that the Boltzmann line is drawn through more points of less positive potential where the distribution is expected to be Maxwellian in accordance with the suggestion of Schott (1968). The other line is drawn in such a manner that it passes averaging the points deviated from being on the line of semilog plot points. The intersection of this line with the Boltzman line indicates the point of space potential (i.e. plasma potential) and the current corresponding to the space potential is taken as the saturation electron current which is utilised for calculating electron density from eqn. (3.2).

3.2.2. Method of measuring diffusion voltage in the arc plasma

An arc tube with internal radius 1.10 cm. was used for measurement of diffusion voltage. The separation between the two mercury pool electrodes was 4.0 cm. Two cylindrical probes of length 0.8 cm and radius 0.014 cm are placed parallel to one another one along the axis $r = 0$ and other at a distance of 0.6 cm from the axis. The output voltage at the probes was measured by a V.T.V.M. having an internal impedance of 100 MΩ. A low pass filter circuit has been utilised at the output of the probes to prevent oscillations generated in the arc from reaching the V.T.V.M. The output voltage between the probes which measures the diffusion voltage has been measured for arc currents varying from 2.0 A to 5.0 A for three values of pressures namely 0.075 torr, 0.10 torr and 0.13 torr.

3.3. Results and discussion

The variation of probe current with probe potential has been plotted for arc currents 2.0, 2.5, 3.0, 4.0 and 4.5 A for pressure 0.075 torr in Fig. 3.1, for 2.0, 2.5, 3.0, 4.0 and 4.5 A for pressure 0.1 torr in Fig. 3.2 and for 2.0, 2.5, 3.0 and 4.0 A for pressure 0.13 torr in Fig. 3.3. From these results the variation of log I_e against the probe potential has been plotted for the three different pressures for the various values of the arc currents in Fig. 3.4, 3.5 and 3.6. As is expected the variation of log I_e against the probe potential is linear for a certain range of probe potential and from the slope of the curves the corresponding electron temperature has been calculated utilizing eqn. (3.1). From figs. 3.1, 3.2 and 3.3, it is seen that the probe current does not show saturation and the saturated electron current has been calculated by a method as suggested by Schott (1968). The electron density has been

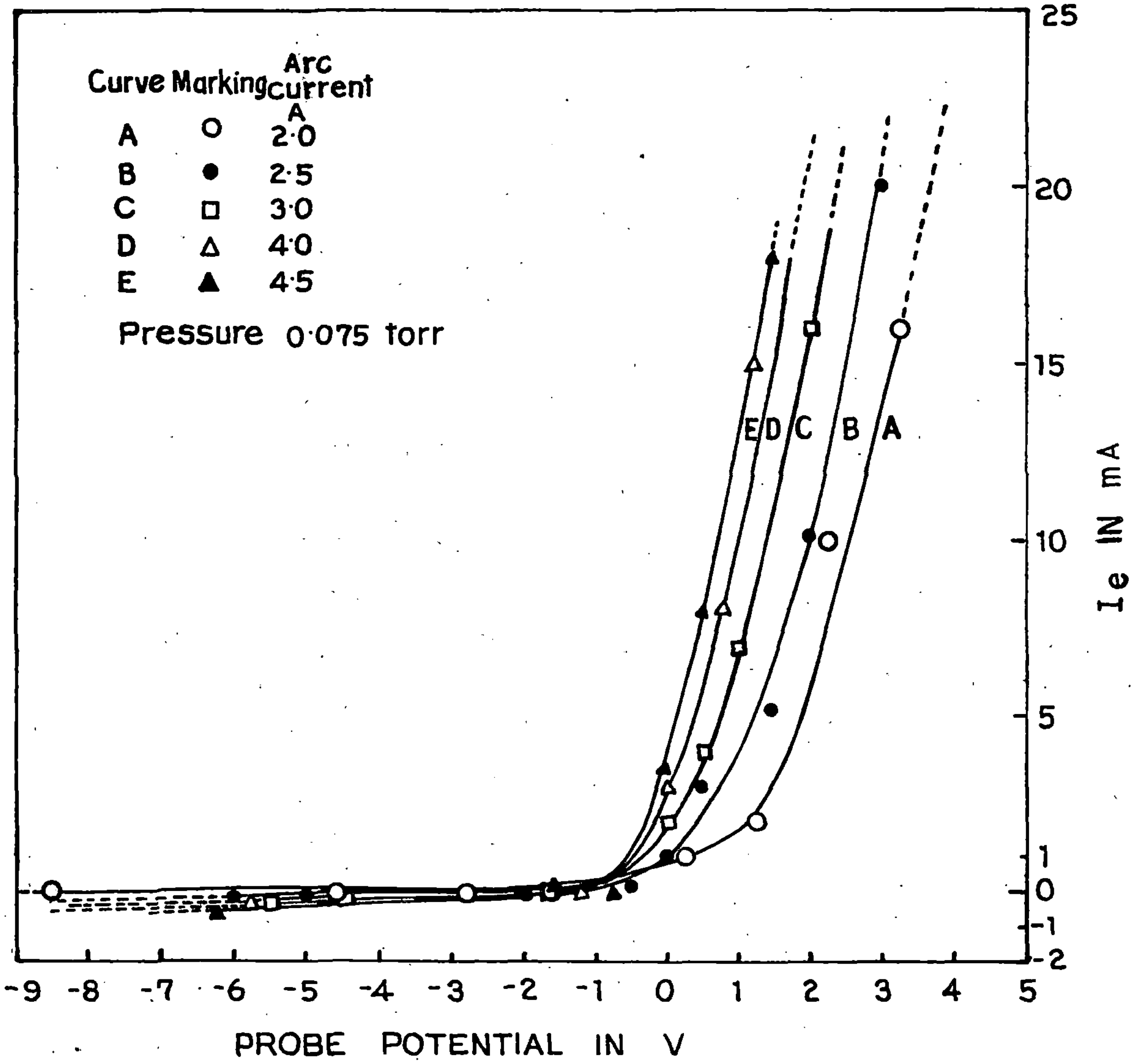

Curve Marking Arc current A
A ○ 2·0
B ● 2·5
C □ 3·0
D △ 4·0
E ▲ 4·5
Pressure 0·075 torr
E D C B A
25
20
15
10
5
1
0
-1
-2
Ie IN mA
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
PROBE POTENTIAL IN V

FIG. 3·1

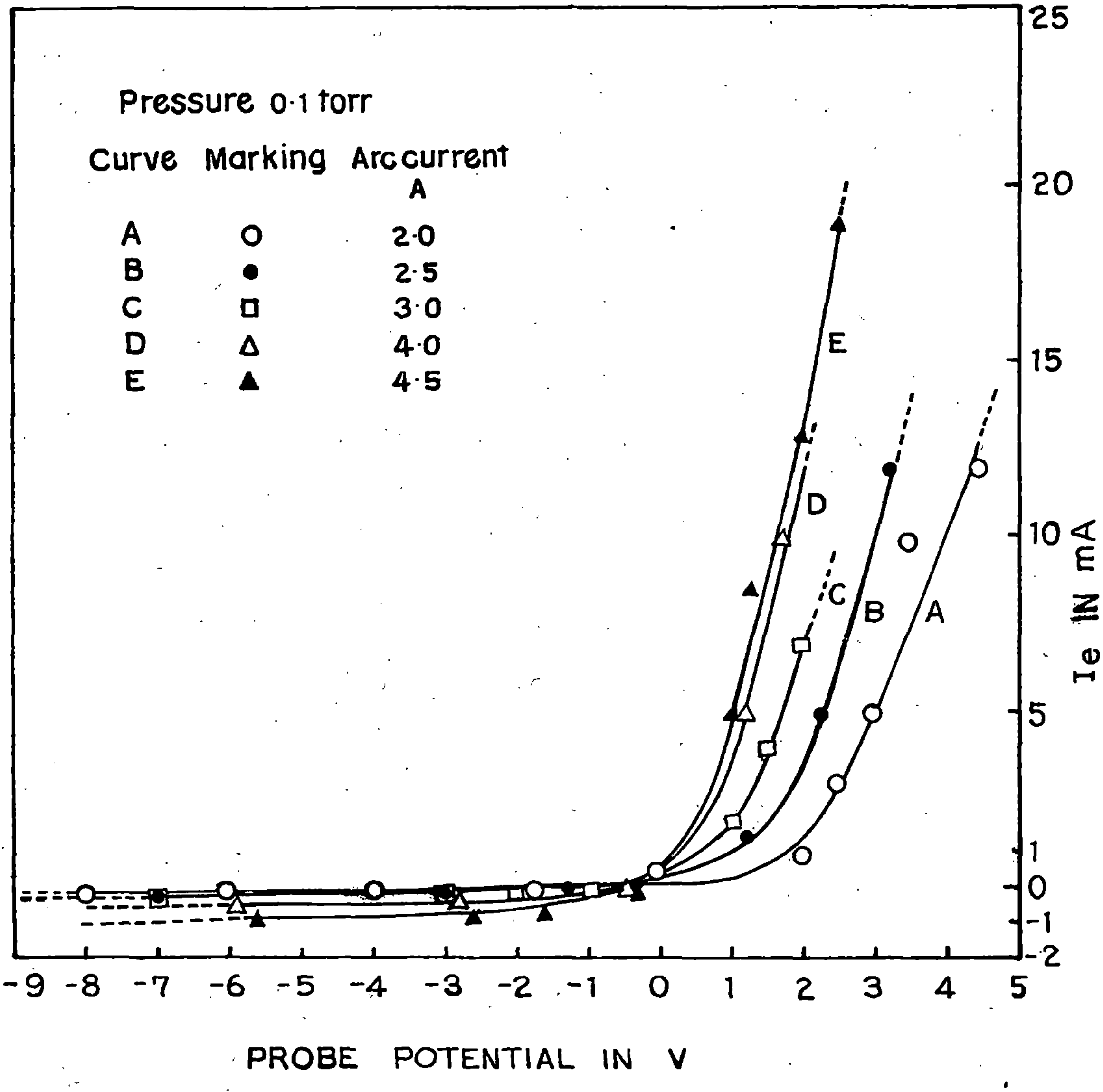

Pressure 0·1 torr
Curve Marking Arc current A
A ○ 2·0
B ● 2·5
C □ 3·0
D △ 4·0
E ▲ 4·5
A
B
C
D
E
25
20
15
10
5
1
0
-1
-2
Ie IN mA
-9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5
PROBE POTENTIAL IN V

FIG 3·2.

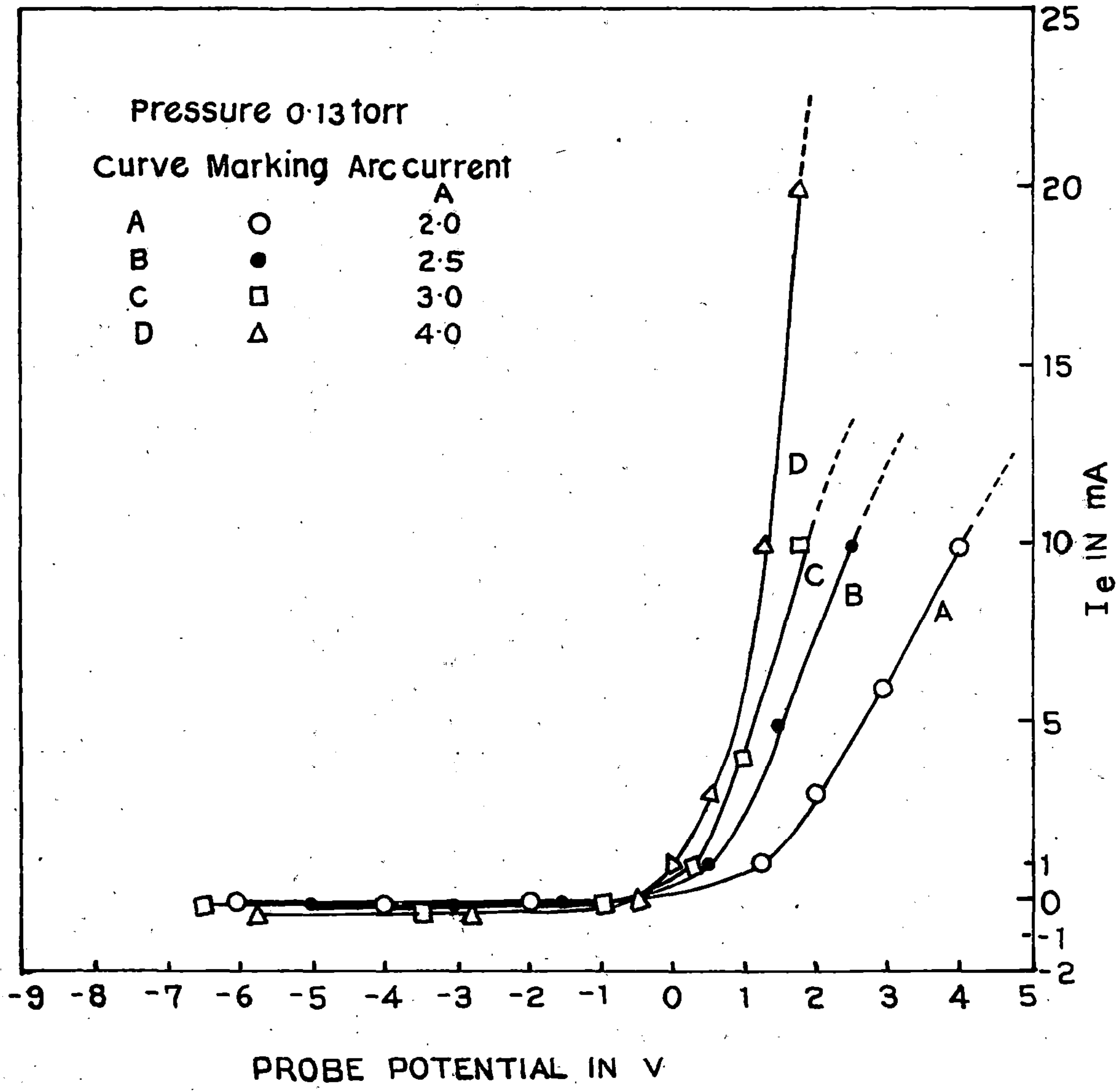

Pressure 0·13 torr
Curve Marking Arc current A
A ○ 2·0
B ● 2·5
C □ 3·0
D △ 4·0
A
B
C
D
-9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5
PROBE POTENTIAL IN V
25 20 15 10 5 1 0 -1 -2
Ie IN mA

FIG. 3·3

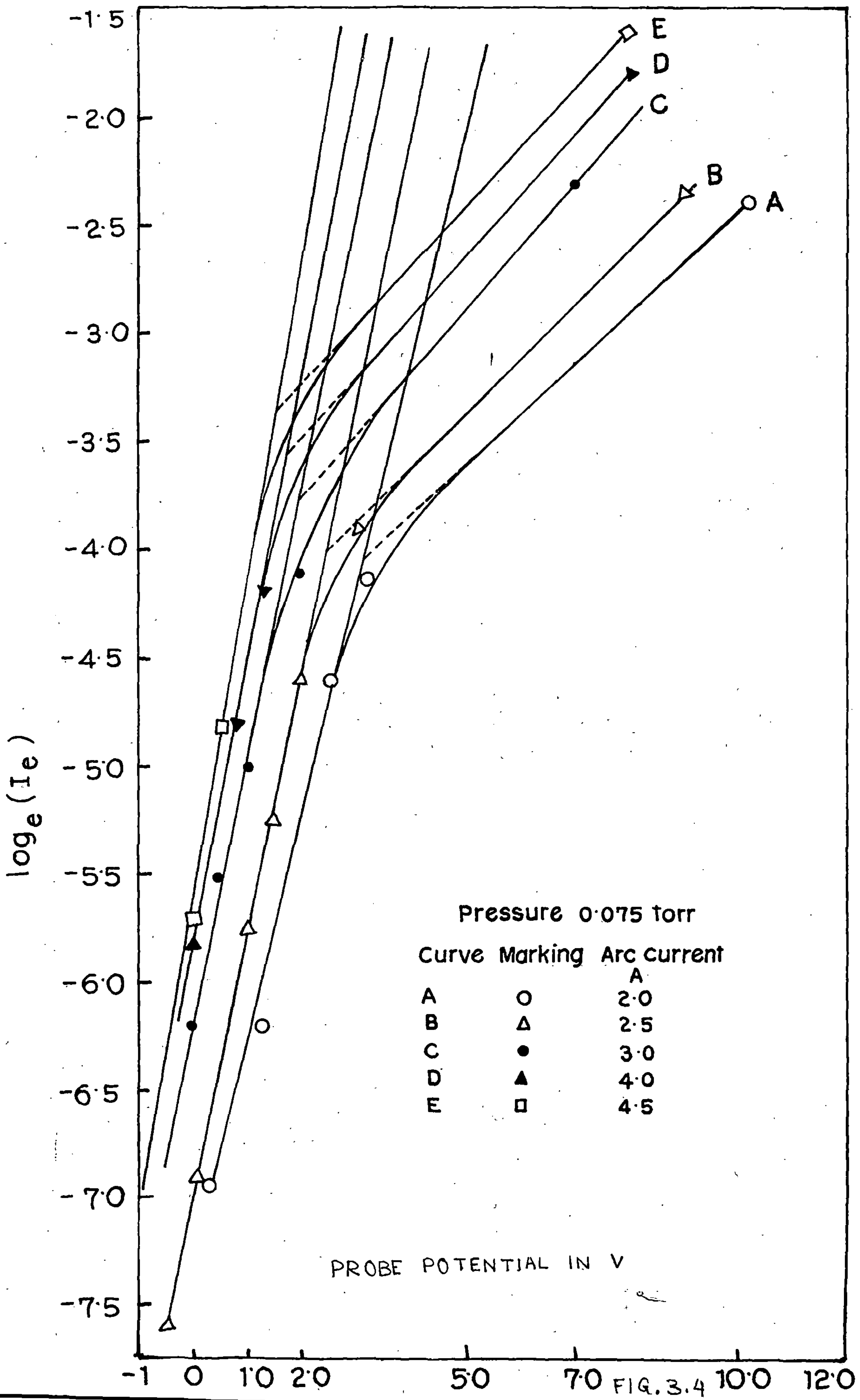
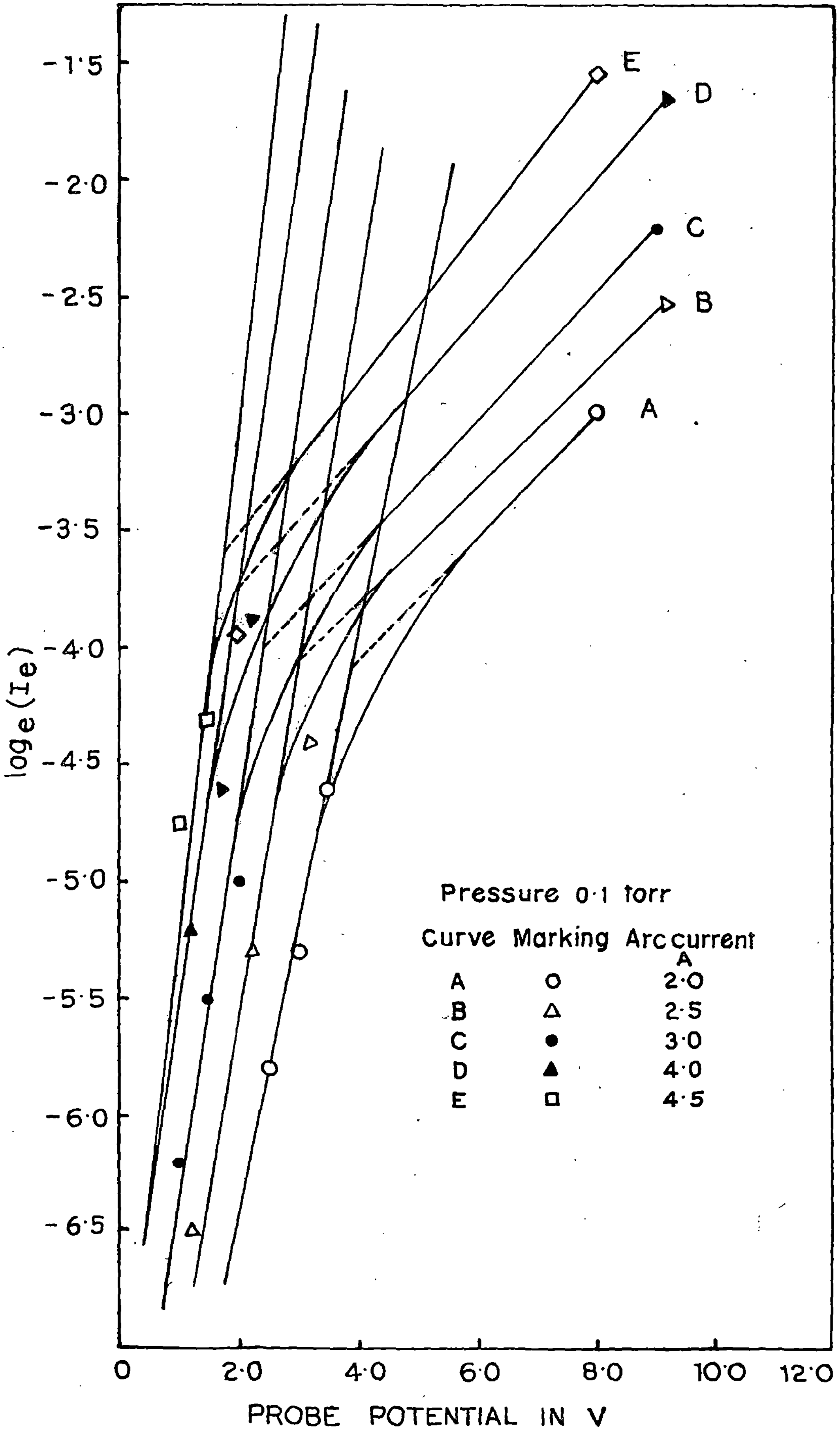
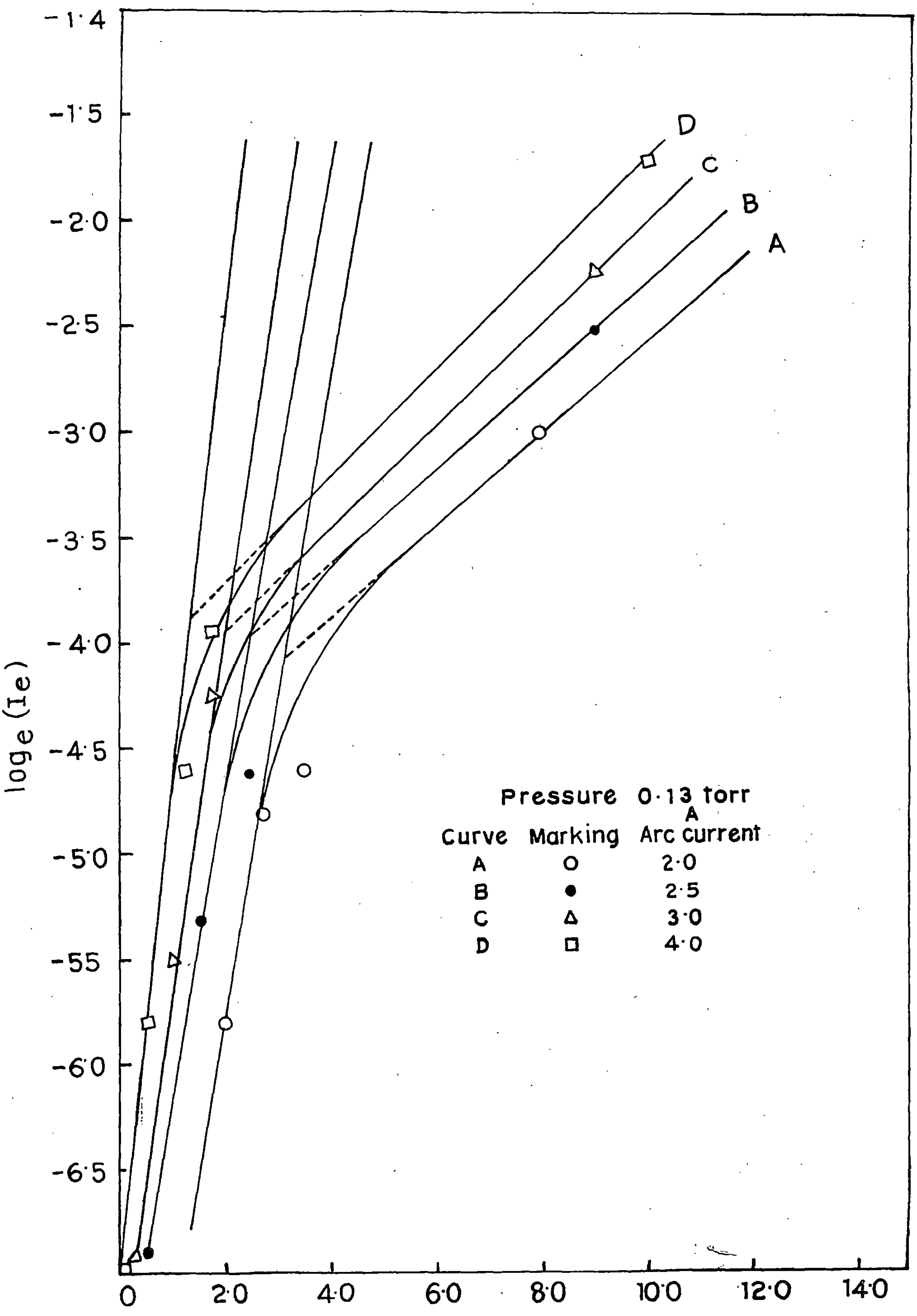

-1·5
-2·0
-2·5
-3·0
-3·5
-4·0
-4·5
-5·0
-5·5
-6·0
-6·5
-7·0
-7·5
$\log_e(I_e)$
-1
0
1·0
2·0
5·0
7·0
10·0
12·0
PROBE POTENTIAL IN V
A
B
C
D
E
Pressure 0·075 torr
Curve Marking Arc current
A
A ○ 2·0
B △ 2·5
C ● 3·0
D ▲ 4·0
E □ 4·5

FIG. 3.4



-1·5
-2·0
-2·5
-3·0
-3·5
-4·0
-4·5
-5·0
-5·5
-6·0
-6·5
loge(Ie)
0
2·0
4·0
6·0
8·0
10·0
12·0
PROBE POTENTIAL IN V
E
D
C
B
A
Pressure 0·1 torr
Curve Marking Arc current A
A ○ 2·0
B △ 2·5
C ● 3·0
D ▲ 4·0
E □ 4·5

FIG. 3·5.



-1·4
-1·5
-2·0
-2·5
-3·0
-3·5
-4·0
-4·5
-5·0
-55
-6·0
-6·5
loge (Ie)
D
C
B
A
Pressure 0·13 torr
Curve Marking A Arc current
A ○ 2·0
B ● 2·5
C △ 3·0
D □ 4·0
0
2·0
4·0
6·0
8·0
10·0
12·0
14·0
PROBE POTENTIAL IN V

FIG. 3·6

calculated from eqn. (3.2). The results are entered in columns (4) and (5) of Table 3.1. Langmuir (1925) while studying the scattering of electrons in mercury arc discharge deduced an expression for the arc current density given by

$$I = 5{\cdot}76 \times 10^{-10} \frac{n_e \lambda E}{\sqrt{T_e}} \quad \ldots (3.3)$$

where n_e is the electron density, λ the mean free path of electron, T_e is the electron temperature and E is the axial electric field per cm. From this expression it is evident that at a particular pressure the quantity $IT_e^{1/2}/n_eE$ should be constant for different arc currents for different pressures. The results are entered in column 7 of table 3.1. It is evident that the values calculated for $IT_e^{1/2}/n_eE$ show a fair degree of consistency justifying the validity of eqn. (3.3) for the arc current.

From the eqn. (3.3) it is evident that the mean free path of the electron can be calculated for different values of pressures. Taking the mean value of $IT_e^{1/2}/n_eE$ as entered in column (8) of Table 3.1, the value of λ has been calculated and results entered in table 3.2, column (3). From col.(4)

it is evident that $P\lambda$ is almost a constant for three different pressures and we can calculate $L = .P\lambda$ the mean free path of the electron at a pressure of 1.0 torr in the mercury vapour. There is no direct method for measurement of mean free path of the electron in the gas. The mean free path of molecule from kinetic theory of gases is $1/\sqrt{2}N\pi\sigma^2$ where N is the number of molecules per unit volume and σ is the molecular diameter. In case of mercury this cames out to be 3×10^{-3} cm. at 1.0 torr.

The mean free path of an electron has been found by classical reasoning to be $4\sqrt{2}\,\lambda$ and this expression has the correct order of magnitude. However, the electronic mean free path becomes a function of the energy of electron due to Ramsauer and Townsend effect.

The variation of open circuited diffusion voltage with arc current as measured has been plotted in fig. 3.7 for three pressures namely 0.075 torr, 0.10 torr and 0.13 torr. It is observed that the diffusion voltage becomes a minimum for a certain value of arc current at a particular pressure and this decreases with the increase of pressure. In a previous paper Sen, Ghosh and Ghosh (1983) have measured diffusion voltage in a glow discharge and have obtained the variation of electron temperature with a transverse magnetic field. In glow discharge the radial distribution of charged particles

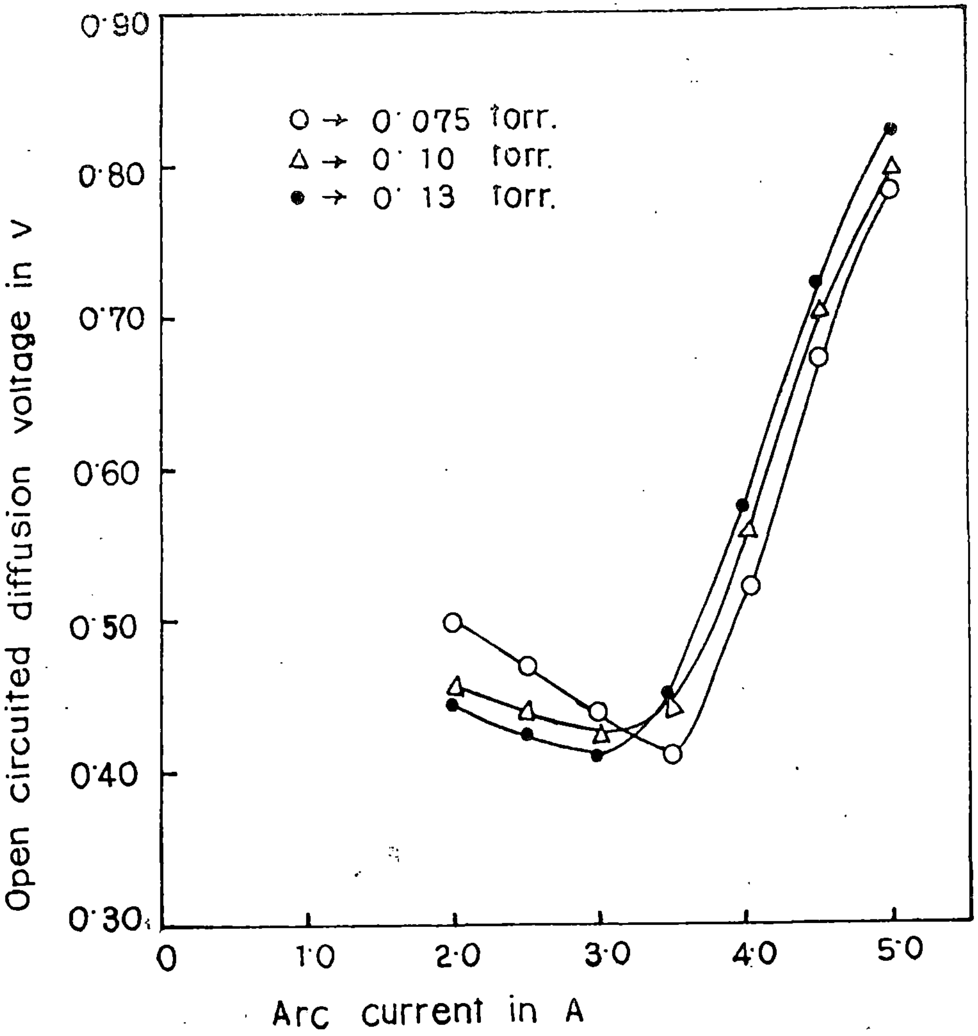

O → 0·075 torr.
Δ → 0·10 torr.
● → 0·13 torr.
Open circuited diffusion voltage in v
0·90
0·80
0·70
0·60
0·50
0·40
0·30
0
1·0
2·0
3·0
4·0
5·0
Arc current in A

FIG. 3·7.

Table 3.1

Back-ground air pressure in Torr.	Arc current in amp.	Mercury vapour pressure in torr	Electron temperature in ^{o}K	Electron density x 10^{-12} cm^{-3}	Arc drop in volts	$\frac{I T_e^{1/2}}{n_e E}$ x10^{10}	Average $\frac{I T_e^{1/2}}{n_e E}$ x 10^{10}
0.075	2.0	0.2342	11487.3	0.6967	42	0.5159	0.5352
	2.5	0.2752	10131.0	0.7803	41	0.5534	
	3.0	0.3032	9572.8	0.9812	39	0.5406	
	4.0	0.3342	9041.6	1.2964	38	0.5448	
	4.5	0.3658	8521.9	1.5608	36	0.5213	
0.1	2.0	0.2343	8195.6	0.7856	44	0.3694	0.3875
	2.5	0.2752	7593.5	0.8580	43	0.4159	
	3.0	0.3032	6066.9	1.0092	42	0.3890	
	4.0	0.3342	5839.4	1.3208	41	0.3980	
	4.5	0.3658	5532.1	1.5766	39	0.3655	
0.13	2.0	0.2343	7785.8	0.8473	47	0.3124	0.3321
	2.5	0.2752	7079.2	0.9336	46	0.3453	
	3.0	0.3032	5696.9	1.0948	44	0.3313	
	4.0	0.3342	4800.0	1.3704	42	0.3395	

Table 3.2.

Background pressure in torr	$\frac{I T_e^{1/2}}{n_e E}$ $\times 10^{10}$	λ cm	$P\lambda = L$ cm
0.075	0.5352	9.294×10^{-2}	6.971×10^{-3}
0.1	0.3875	6.728×10^{-2}	6.728×10^{-3}
0.13	0.3321	5.765×10^{-2}	7.494×10^{-3}

density has been assumed to be Besselian. It has however, been shown by Ghosal, Nandi and Sen (1978) that the radial distribution function for the azimuthal conductivity for an arc plasma is given by

$$\sigma(r) = \sigma(o)\left[1 - \left(\frac{r}{R}\right)^2\right]^n \quad \ldots(3.4)$$

where σ_o is the axial conductivity, $\sigma(r)$ is the conductivity at a distance r from the axis of the tube R is the tube radius of the arc and n is a constant which has been shown to be

$$n = \left[\frac{R^2}{a} - 2\right]$$

where 'a' is an experimentally determined quantity which varies with arc current. This distribution function can very well represent the radial charged particle distribution in an arc plasma. It has been shown by Sen, Ghosh and Ghosh (1983) that the diffusion voltage V_R is

$$V_R = -\int \frac{dn_e}{n_e} \quad \frac{KT_e}{e} \quad \dots (3.5)$$

and since the electron density is proportional to the conductivity we get from equation (3.4)

$$n_e = n_o \left[1 - \frac{r^2}{R^2} \right]^n$$

and from eqn. (3.5)

$$V_R = -\frac{nKT_e}{e} \int \frac{\left(- \frac{2r}{R^2} \right)}{\left(1 - \frac{r^2}{R^2} \right)} \, dr$$

Let $Z = \left(1 - \frac{r^2}{R^2} \right)$

then $$V_R = -\frac{nKT_e}{e} \int \frac{dZ}{Z}$$

$$= -\frac{nKT_e}{e} \log Z + C$$

eqn. at

$$r = 0 \,,\; V_R = 0 \text{ and } C = 0$$

Hence

$$V_R = - \frac{n\,KT_e}{e} \log \frac{R^2 - r^2}{R^2}$$

$$= \frac{2n\,KT_e}{e} \log \frac{R}{\sqrt{R^2 - r^2}} \qquad \ldots (3.6)$$

The values of electron temperature for the arc current for which diffusion voltage has been measured can be obtained from the first part of the present paper. Some values for n were obtained by Ghosal, Nandi and Sen (1978), but a measurement of n for a wider range of current has been carried out in this laboratory by the present author and variation in the value of n with arc current is plotted in fig. 3.8. Hence it is numerically possible to calculate the values of V_R for different arc currents at different pressures from eqn. (3.6). The results are entered in Table 3.3. It is observed that though the theoretically calculated values are higher than the corresponding experimental results, the minimum voltage occurs at the same value of arc current in both the cases. The value of the current at which the diffusion voltage becomes a minimum also decreases with the increase of pressure as is observed experimentally.

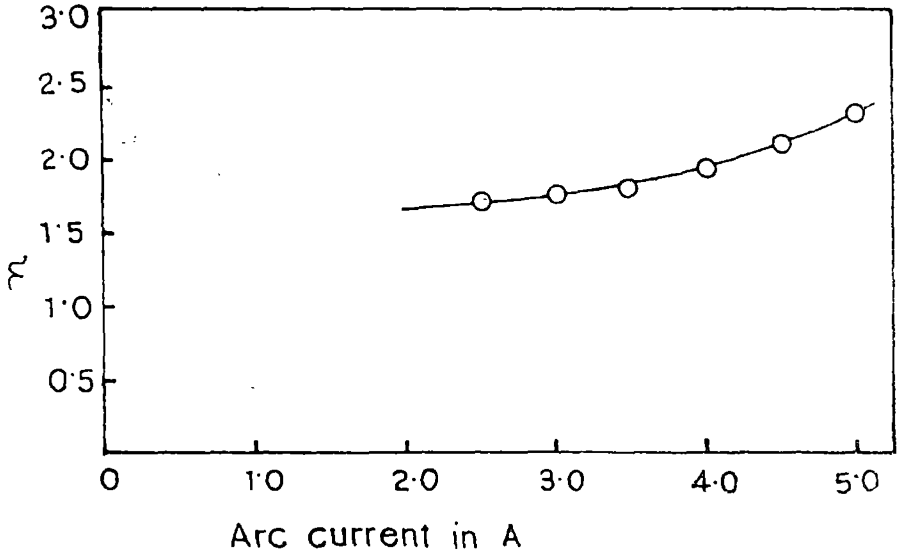


FIG. 3·8.

Table 3.3

Pressure in Torr	Arc current in Amps.	Diffusion voltage in volts	
		Experimental	Theoretical
0.075	2.0	0.498	0.575
	2.5	0.470	0.527
	3.0	0.438	0.506
	4.0	0.518	0.539
	4.5	0.670	0.544
	5.0	0.78	0.588*
0.10	2.0	0.458	0.410
	2.5	0.438	0.374
	3.0	0.435	0.349
	3.25	-	0.334*
	3.5	0.447	0.336*
	4.0	0.556	0.348
	4.5	0.700	0.353
	5.0	0.796	0.369*
0.13	2.0	0.446	0.390
	2.5	0.425	0.348
	3.0	0.410	0.307
	3.5	0.450	0.297*
	4.0	0.570	0.304
	4.5	0.719	0.313*
	5.0	0.823	0.334*

* from extrapolated values

The results are presented in table 3.4.

Table 3.4

Pressure in Torr	Arc current in Amp at which diffusion voltage is minimum
0.075	3.50
0.10	3.25
0.13	3.00

We can thus conclude that the distribution formula for azimuthal conductivity as proposed by Ghosal, Nandi and Sen (1978) gives results in quantitative agreement with experimental results. We have thus seen that the Langmuir probe method can also be utilised for the measurement of electron temperature and electron density just as in the case of glow discharge and the results are consistent with the values obtained by spectroscopic method (Sadhya and Sen, 1980). Langmuir's expression for arc current (eqn. 3.3) is verified and the results provide a means of calculating the electronic mean free path in the gas.

The not too satisfactory agreement between the diffusion voltage calculated and experimentally observed results may be attributed to some uncertainty in the value of n but the occurance of minima as observed experimentally at the same calculated value of the arc current at three pressures lends support to the validity of distribution function as proposed by Ghosal, Nandi and Sen (1979). The importance of the experiment is that the electron temperature can be measured accurately without perturbing the plasma by only measuring the open circuited diffusion voltage.

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Measurement of plasma parameters in an arc plasma by a single probe method

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A single probe method has been used to measure the electron temperature and electron density in an arc plasma in mercury vapour for arc current varying from 2 to 5 A and for three background pressures of 0.075, 0.1 and 0.13 torr. Langmuir's expression [*Phys Rev* (*USA*), 26 (1925) 585] for arc current has been found to be valid within the range of arc current investigated and the results have been utilized to calculate the mean free-path of the electron in mercury vapour. The open circuited diffusion voltage in the arc plasma has also been measured for the same range of current and voltage. Utilizing the radial distribution function of conductivity as introduced by S K Ghosal, G P Nandi and S N Sen [*Int J Electron* (*GB*), 44 (1978) 409] an analytical expression for the diffusion voltage has been calculated which can satisfactorily explain the observed results. The validity of the probe method for measurement of plasma parameters in an arc plasma has been discussed.

1 Introduction

The measurement of plasma parameters such as electron density and electron temperature by single probe Langmuir method is well known. In zero magnetic field, the theory of the probe rests on the assumption that the parameter $\xi = r_p/\lambda_d$ introduced by Chen *et al.*[1], where r_p is the radius of the probe and λ_d is the Debye shielding length, for repelled species, should have a value greater than 5. This should hold good in order that Langmuir's orbital theory for the determination of electron density and electron temperature by the single probe method can be regarded as valid. Sadhya *et al.*[2] measured the electron density and electron temperature in a glow discharge in hydrogen, oxygen, nitrogen and air and investigated their variation in transverse magnetic fields by the single probe method and the results were quantitatively explained by developing necessary mathematical formulation. It was further shown that the results obtained by the probe method were in agreement with the results obtained by other methods, such as microwave and spectroscopic methods.

For the last few years we have taken up a systematic investigation of the properties of arc plasma in order to develop a generalized theory as to the occurrence of an arc plasma and bringing out the salient changes as regards the transition of glow discharge to arc plasma. The measurement of electron temperature and its variation with an axial magnetic field in an arc plasma has been investigated by a spectroscopic method in detail by Sadhya and Sen[3]. Since a large collection of data regarding plasma parameters and their variation in a perturbing field is necessary to build up the theory for the occurrence of arc plasma, it is worthwhile to investigate whether the Langmuir single probe method can be utilized for measurement of arc plasma parameters. This will not only enable us to obtain the necessary data but will also indicate whether Langmuir's oribital theory can be extended for measurement in case of arc plasma as well. We report here the results of measurement of electron temperature and electron density in a mercury arc plasma for different background air pressures and the corresponding mercury vapour pressures for different arc currents.

Another important property that is of importance is the mechanism by which charged particles are lost from a plasma. One of the main factors is the loss by the ambipolar diffusion process. When the process of diffusion becomes ambipolar, a steady radial voltage develops due to charge separation which is defined as diffusion voltage. An experiment has been set up to measure the resultant diffusion voltage in an arc plasma for different arc currents. The method has been utilized by Sen *et al.*[4] in evaluation of electron temperature in glow discharge. The process of diffusion is basically connected with the radial distribution function of charged particles and an expression for the radial distribution function of the electrons in an arc plasma has been provided by Ghosal *et al.*[5] The experimental results will be analyzed in the light of the above theories.

2 Experimental Arrangement and Measurement

The method of measurement of electron temperature and electron density is the same as was used earlier and described in the paper by Sadhya *et al.*[2] Here however, measurement has been carried out in a mercury arc plasma produced within a cylindrical glass tube of inner radius 1.31 cm with two mercury pool electrodes 38 cm apart. The arc is excited by supplying power from a 250 V dc generator where the arc current has been varied from 2 to 5 A by a regulated rheostat in series. Measurement has been taken for three background air pressures (0.075, 0.1 and 0.13 torr). The corresponding values of mercury vapour pressure for different arc currents are entered in Table 1. A cylindrical tungsten wire of 0.014 cm radius within a glass capsule with a bare tip of 0.1 cm length is utilized as the probe which is placed at a distance of 14 cm from the anode.

2.1 Measurement of T_e and n_e

In order to justify the validity of Langmuir's probe theory in the present experimental set-up, the vapour pressure of mercury was determined as in an earlier paper by Sadhya and Sen[3] by noting the temperature of the wall for different arc currents. The results are entered in the third column in Table 1. The Debye shielding length λ_d is of the order of 10^{-3} cm for these pressures and since the radius of the probe is 0.014 cm, the criteria (Chen *et al.*[1]) that $\xi = r_p/\lambda_d$ should be greater than 5 is satisfied. Further the electronic mean free-path of mercury vapour at an average pressure of 0.3 torr is 7.6×10^{-2} cm and the radius of the probe is 1.4×10^{-2} cm and hence $r_p < \lambda_e$, which also satisfies the criteria for Langmuir's probe theory. According to Langmuir, the relation between the probe current and probe voltage is given by:

$$I_e = I_{re} \exp\left(-\frac{eV_p}{kT_e}\right) \qquad \ldots (1)$$

and

$$I_{re} = \frac{1}{4} A n_e \left(\frac{8kT_e}{m\pi}\right)^{1/2} \qquad \ldots (2)$$

where the symbols have their usual significance. A is the effective electron collecting area of the probe and n_e is the unperturbed electron density. Assuming the distribution to be Maxwellian, T_e is calculated by taking the slope of the Boltzmann line in a semilogarithmic plot of I_e versus V_p according to Eq. (1). Actually it is observed that the probe current never saturates. The rise of current with increasing positive potential is expected due to growth of effective collecting area of the probe as the sheath expands. Linear extrapolation of the curves has been made in such a way that the Boltzmann line is drawn through more points of less positive potential where the distribution is expected to be Maxwellian in accordance with the suggestion of Schott[6]. The other line is drawn in

Table 1—Variation of electron temperature and electron density at different arc currents for different pressures

Background air pressure torr	Arc current A	Mercury vapour pressure in torr	Electron temp. K	Electron density $\times 10^{-12}$ cm^{-3}	Arc drop V	$IT_e^{1/2}/n_eE$ $\times 10^{10}$	Average $IT_e^{1/2}/n_e$ $\times 10^{10}$
0.075	2.0	0.2343	11487.3	0.6967	42	0.5159	0.5352
	2.5	0.2752	10131.0	0.7803	41	0.5534	
	3.0	0.3032	9572.8	0.9812	39	0.5406	
	4.0	0.3342	9041.6	1.2964	38	0.5448	
	4.5	0.3658	8521.9	1.5608	36	0.5213	
0.1	2.0	0.2343	8195.6	0.7856	44	0.3694	0.3875
	2.5	0.2752	7593.3	0.8580	43	0.4159	
	3.0	0.3032	6066.9	1.0092	42	0.3890	
	4.0	0.3342	5839.4	1.3208	41	0.3980	
	4.5	0.3658	5532.1	1.5766	39	0.3653	
0.13	2.0	0.2343	7785.8	0.8473	47	0.3124	0.3321
	2.5	0.2752	7079.2	0.9336	46	0.3453	
	3.0	0.3032	5696.9	1.0948	44	0.3313	
	4.0	0.3342	4800.0	1.3704	42	0.3395	

such a manner that it passes averaging the points deviated from being on the line of semilog plot points. The intersection of this line when extrapolated backwards with the Boltzmann v line indicates the point of space potential and the current corresponding to this space potential is taken as the saturation electron current which is utilized for calculating electron density from Eq. (2).

2.2 Method of Measuring Diffusion Voltage in the Arc Plasma

A mercury arc with internal radius 1.1 cm was used for measurement of diffusion voltage. The separation between the two mercury pool electrodes was 41 cm. Two identical cylindrical probes of length 0.8 cm and diameter 0.01 cm are placed parallel to each other, one along the axis $r=0$ and the other at a radial distance 0.6 cm from the axis. The output voltage at the probes was measured by a VTVM having an internal impedance of 100 MΩ. The voltage across the two probes is the diffusion voltage and has been measured for arc currents varying from 2 to 5 A for three values of background air pressure namely 0.075, 0.10 and 0.13 torr.

3 Results and Discussion

The variation of probe current with probe potential has been plotted for arc currents 2, 2.5, 3, 4 and 4.5 A for a background pressure 0.075 torr in Fig. 1; for arc currents 2.0, 2.5, 3, 4 and 4.5 A for a pressure 0.1 torr in Fig. 2 and for arc currents 2.0, 2.5, 3.0 and 4.0 A for a pressure 0.13 torr in Fig. 3. From these results the variation of log I_e against the probe potential has been plotted for the three different pressures for the various values of the arc currents in Figs 4-6. As is expected, the variation of log I_e against the probe potential is linear for a certain range of probe potential and from the slope of the curves the corresponding electron temperature has been calculated utilizing Eq. (1). From Figs 1-3 it is seen that the probe current does not show saturation and as mentioned earlier the saturated electron current has been calculated by a method as suggested by Schott[6]. The electron density has been calculated from Eq. (2). The results are prsented in Table 1. Langmuir[7] while studying the scattering of electrons in a mercury arc discharge deduced an ex-

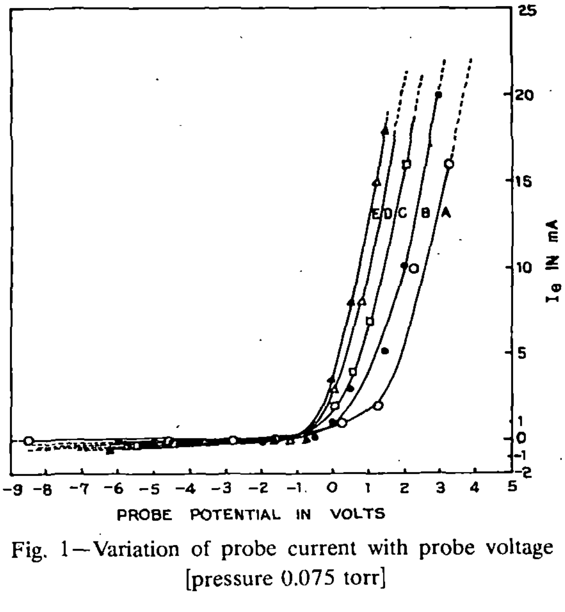

Fig. 1—Variation of probe current with probe voltage [pressure 0.075 torr]

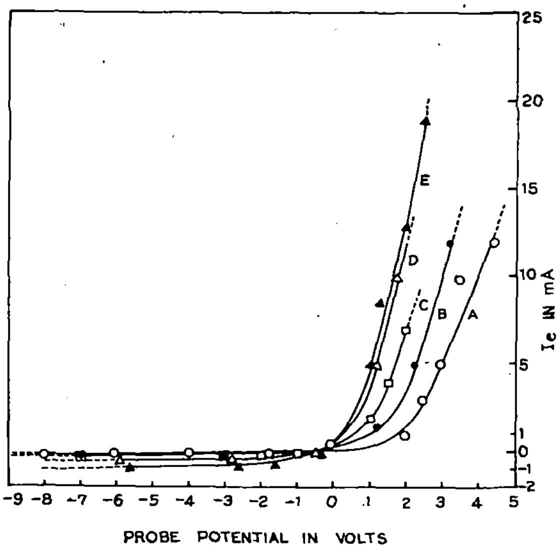

Fig. 2—Variation of probe current with probe voltage [pressure 0.1 torr]

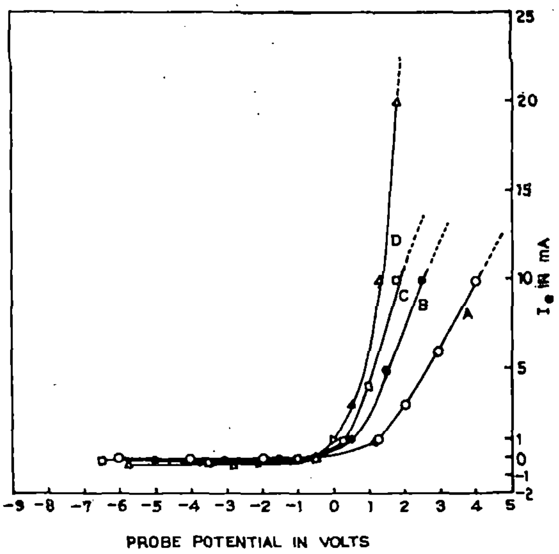

Fig. 3—Variation of probe current with probe voltage [pressure 0.13 torr]

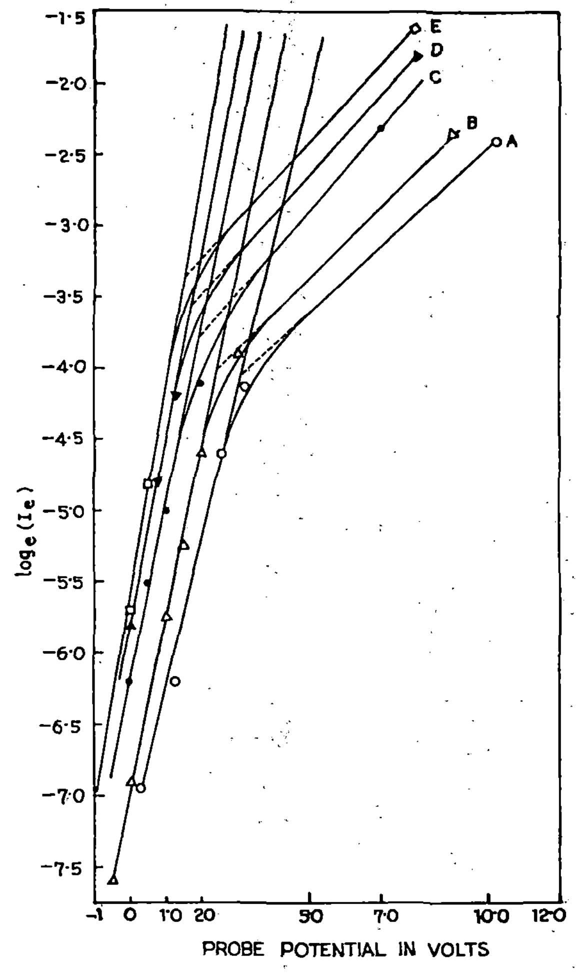

Fig. 4—Variation of log T_e with probe voltage [pressure 0.075 torr]

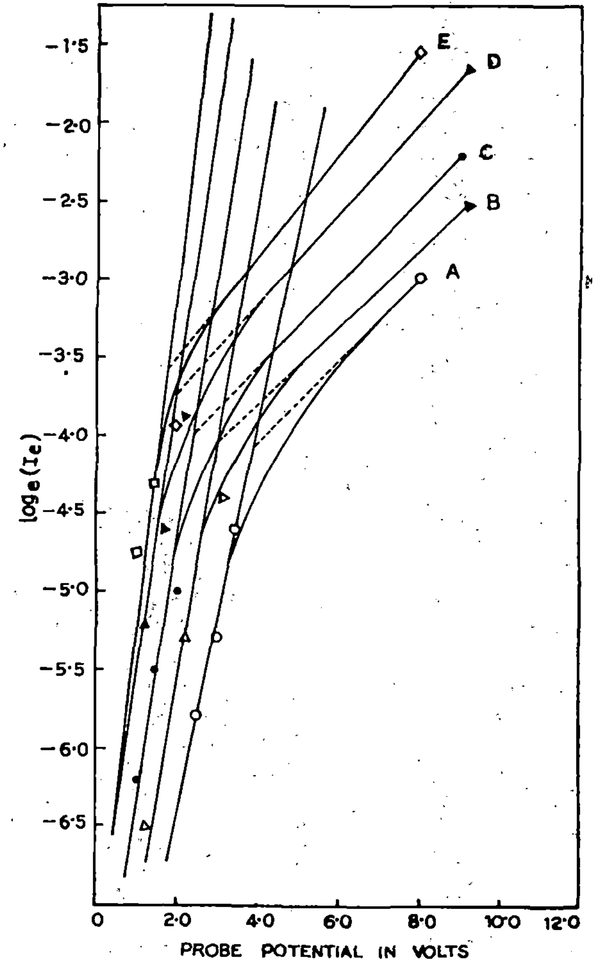

Fig. 5—Variation of log I_e with probe voltage [pressure 0.1 torr]

pression for the arc current density given by:

$$I = 5.76 \times 10^{-10}\,\frac{n_e \lambda_e}{T_e^{1/2}} \quad \ldots (3)$$

where n_e is the electron density, λ_e, the mean free-path of the electron, T_e, the electron temperature and E the axial electric field per cm. From this expression it is evident that at a particular pressure, the quantity $IT_e^{1/2}/n_e E$ should be a constant for different arc currents. Since both the electron temperature and electron density have been measured for different arc currents and corresponding voltage drop across the arc has been measured, the quantity $IT_e^{1/2}/n_e E$ can be calculated for different arc currents for different pressures. The results are entered in column 7 of Table 1. It is evident that the values calculated for $IT_e^{1/2}/n_e E$ show a fair degree of consistency justifying the validity of Eq. (3) for the arc current.

From Eq. (3) it is evident that λ_e the mean free-path of the electron can be calculated for different values of background air pressure. Taking the mean value of $IT_e^{1/2}/n_e E$ as entered in column 8 of Table 1, the value of λ_e has been calculated and results entered in Table 2, column 3. From column 4 it is evident that $P\lambda_e$ is almost a constant for three different pressures and we can calculate $L = P\lambda_e$ the mean free-path of the electron at a pressure of 1 torr. The result is entered in the fourth column in Table 2. There is no direct method for measurement of mean free-path of the electron in the gas. The mean free-path of a molecule from kinetic theory of gases is $1/\sqrt{2}\,n\pi\sigma^2$ where N is the number of molecules per unit volume and σ is the molecular diameter. In case of mercury, this comes out to be 3×10^{-3} cm at 1 torr. The mean free-path of an electron has been found by classical reasoning to be $4\sqrt{2}\lambda$ and this expression gives the correct order of magnitude as obtained experi-

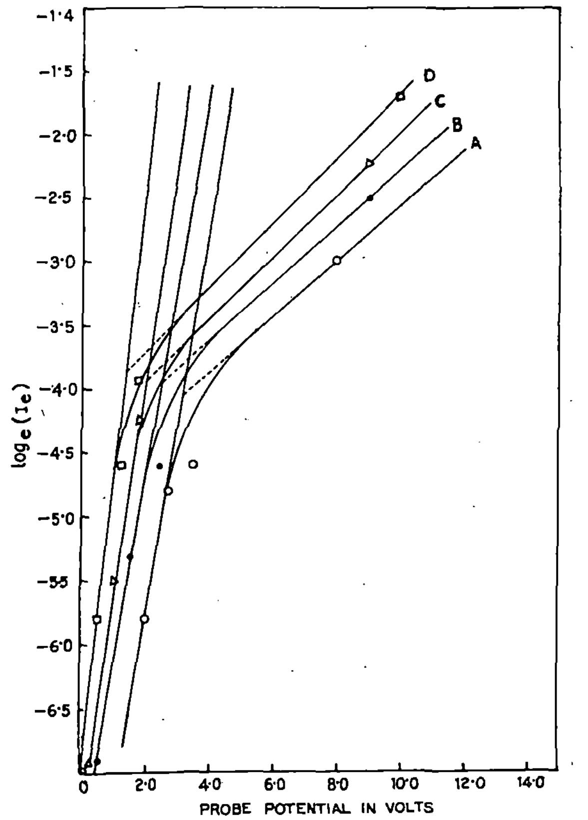

Fig. 6—Variation of log I_e with probe voltage [pressure 0.13 torr]

Table 2—Calculation of electronic mean free-path at different pressures

Background pressure torr	$IT_e^{1/2}/n_eE$ $\times 10^{10}$	$\lambda_e \times 10^{-2}$ cm	$P\lambda_e = L \times 10^{-3}$ cm
0.075	0.5352	9.294	6.971
0.1	0.3875	6.728	6.728
0.13	0.3321	5.765	7.494

mentally for mean free-path of the electron at a pressure of 1 torr. However, the electronic mean free-path becomes a function of the energy of electron due to Ramsauer and Townsend effect.

The variation of open circuited diffusion voltage with arc current as measured has been plotted in Fig. 7 for three background pressures namely 0.075, 0.1 and 0.13 torr. It is observed that the diffusion voltage becomes a minimum for a certain value of arc current at a particular pressure and this decreases with the increase of pressure (Table 3). In a previous paper (Sen *et al.*[4]) diffusion voltage has been measured in a glow discharge and the variation of electron temperature with a transverse magnetic field determined. In glow discharge, the radial distribution of charged particle density has been assumed to be Besselian. It has, however, been shown by Ghosal *et al.*[5] that the radial distribution function for the azimuthal conductivity for an arc plasma is given by:

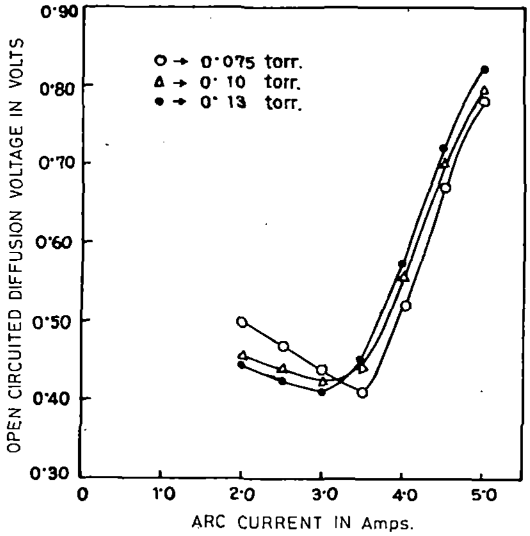

Fig. 7—Variation of diffusion voltage with arc current

Table 3—Experimental values of arc current at which diffusion voltage is minimum for different pressures

Pressure torr	Arc current in amp at which the diffusion voltage is minimum
0.075	3.5
0.1	3.25
0.13	3.0

$$\sigma(r) = \sigma_0 \left[1 - \left(\frac{r}{R}\right)^2\right]^n \qquad \ldots (4)$$

where σ_0 is the axial conductivity, σ the conductivity at a distance r from the axis, R the radius of the arc and n a constant[5] given by:

$$n = \left[\frac{R^2}{a} - 1\right]$$

where a is an experimentally determined quantity which varies with arc current. This distribution function can very well represent the radial charged particle distribution in an arc plasma. It has been shown by Sen *et al.*[4] that the diffusion voltage V_R is:

$$V_R = -\int \frac{dn_e}{n_e} \frac{kT_e}{e} \qquad \ldots (5)$$

and since the electron density is proportional to σ, we get from Eq. (4):

$$n_e = n_0\left[1-\left(\frac{r}{R}\right)^2\right]^n$$

and from Eq. (5)

$$V_R = -\frac{nkT_e}{e}\int \frac{-\frac{2r}{R^2}}{\left(1-\frac{r^2}{R^2}\right)}\,\mathrm{d}r$$

Let

$$Z = \left[1-\frac{r^2}{R^2}\right]$$

then

$$V_R = -\frac{nkT_e}{e}\int \frac{\mathrm{d}Z}{Z} = -\frac{nkT_e}{e}\log Z$$

$$V_R = -\frac{nkT_e}{e}\log\frac{R^2-r^2}{R^2}$$

$$= \frac{2nkT_e}{e}\log\frac{R}{\sqrt{R^2-r^2}} \qquad \ldots (6)$$

The values of the electron temperature corresponding to the arc currents for which diffusion voltage has been measured are reported in the earlier part of the present paper. Some values of n were obtained by Ghosal *et al.*[5], but a measurement of n for a wider range of current has been recently carried out in this laboratory and variation in the value of n with arc current is plotted in Fig. 8. Hence it is numerically possible to calculate the values of V_R for different arc currents at different pressures from Eq. (6). The results are presented in Table 4. It is observed that though the theoretically calculated values are higher than the corresponding experimental results, the minimum voltage occurs at the same value of current in both the cases. The value of the current at which the diffusion voltage becomes a minimum also decreases with increase of pressure as is observed experimentally. The discrepancy between the theoretically calculated and experimentally observed values of V_R may be due to the fact that both n and, T_e are functions of the radius of the arc tube. We can thus conclude that the distribution formula for azimuthal conductivity as proposed by Ghosal *et al.*[5] gives results in quantitative agreement with experimental results. We have thus seen that the Langmuir probe method can also be utilized for the measurement of electron temperature and electron density in an arc plasma just as in the case of glow discharge. It is not possible to calculate the percentage accuracy in these measurements but the results are consistent quantitatively with the values obtained by the spectroscopic method (Sadhya and Sen[3]). Langmuir's expression for arc current [Eq. (3)] is verified and the results provide

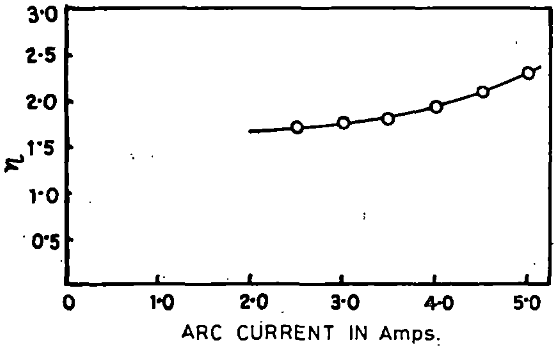

Fig. 8—Variation of n with arc current

Table 4—Experimental and calculated values of diffusion voltage at different arc currents for three different pressures

Pressure torr	Arc current A	Diffusion voltage in V	
		Exptl	Theor.
0.075	2.0	0.498	0.575
	2.5	0.470	0.527
	3.0	0.438	0.506
	3.5	0.412	0.495*
	4.0	0.518	0.539
	4.5	0.670	0.544
	5.0	0.78	0.588*
0.10	2.0	0.458	0.410
	2.5	0.438	0.374
	3.0	0.435	0.349
	3.25	—	0.334*
	3.5	0.447	0.336*
	4.0	0.556	0.348
	4.5	0.700	0.353
	5.0	0.796	0.369*
0.13	2.0	0.446	0.390
	2.5	0.425	0.348
	3.0	0.410	0.307
	3.5	0.450	0.297*
	4.0	0.570	0.304
	4.5	0.719	0.313*
	5.0	0.823	0.334*

*From extrapolated value

a means of calculating the electronic mean free-path in the gas.

The not too satisfactory agreement between the diffusion voltages calculated and experimentally observed results may be attributed to some uncertainty in the value of n but the occurrence of minima as observed experimentally at the same calculated value of the arc current at three pressures lends support to the validity of distribution function as proposed by Ghosal *et al.*[5]

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