# CHAPTER VIII

## MEASUREMENT OF PLASMA PARAMETERS IN AN ARC PLASMA BY PROBE METHOD

### 8.1. INTRODUCTION

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. The measurement of plasma parameters such as electron density $n_e$ and electron temperature $T_e$ by single probe Langmuir method is well known. It is also one of the standard methods of measuring plasma parameters directly without complicated circuits. 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 $\lambda_d$ 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 some of his research fellows 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 by 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 utilised 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 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. An experiment has been setup 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.

## 8.2. 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 the chap. 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. 2.13 (a), (Chapter II). The arc is produced by supplying power from a 250 V d.c. generator. The arc current has been varied from 2A to 5A 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. 2.13 (a), (Chapter 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.

### 8.2.1. MEASUREMENT OF $T_e$ AND $n_e$

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

$$I_e = I_{re} \exp\left(- \frac{e V_P}{K T_e}\right) \tag{8.1}$$

and

$$I_{re} = \frac{1}{4} A n_e \left(\frac{8 K T_e}{m \pi}\right)^{1/2} \tag{8.2}$$

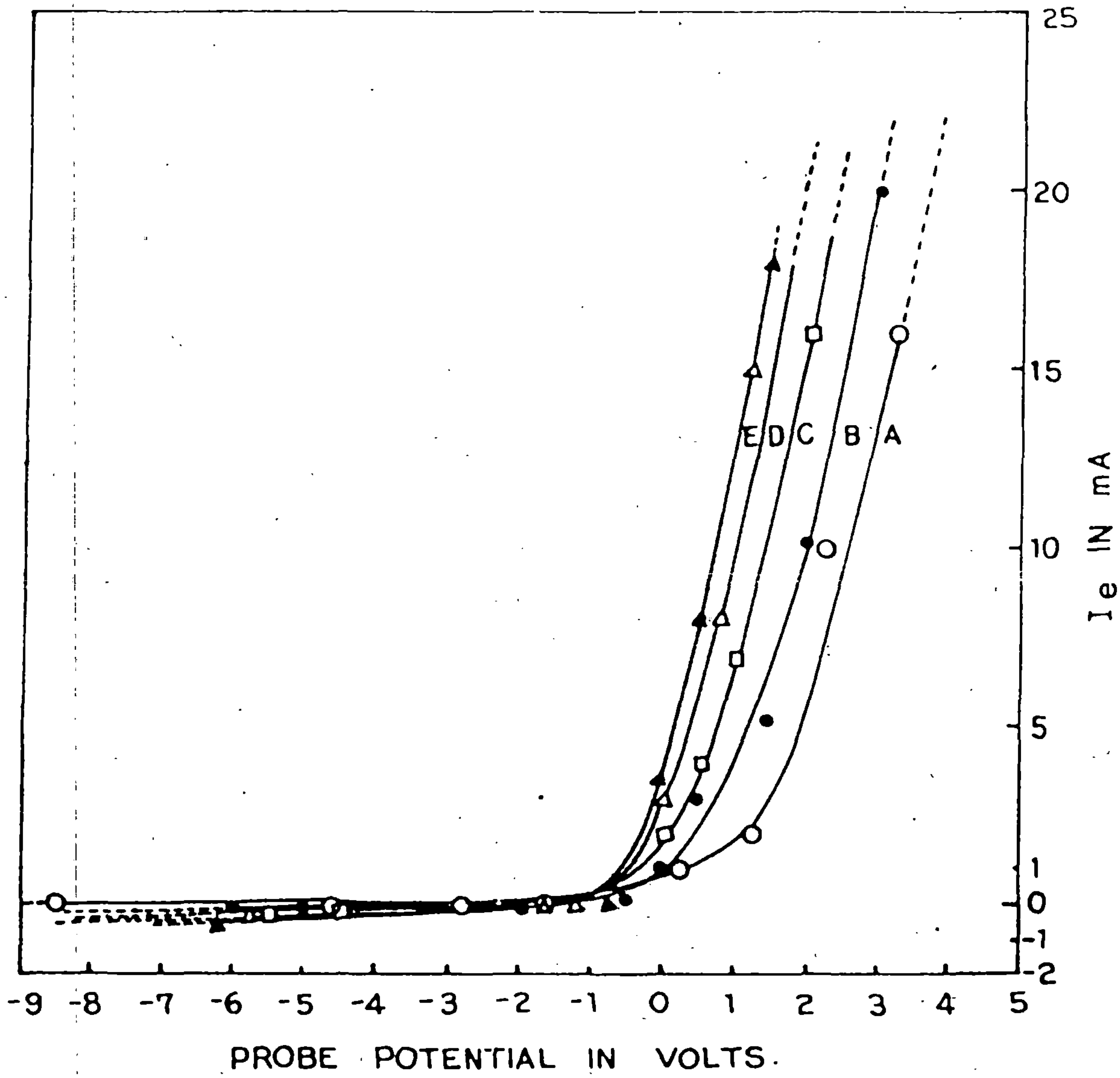
where the symbols have their usual significance. $A$ is the effective electron collecting area of the probe and $n_e$ is the unperturbed electron density. Assuming the distribution to be Maxwellian, $T_e$ is calculated by taking the slope of the Boltzmann line in a semilogarithmic plot of $I_e$ versus $V_p$ according to equation (8.1). 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 when extrapolated backwards with the Boltzmann 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 equation (8.2).

8.2.2. 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 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 pressure namely 0.075 torr, 0.10 torr and 0.13 torr.

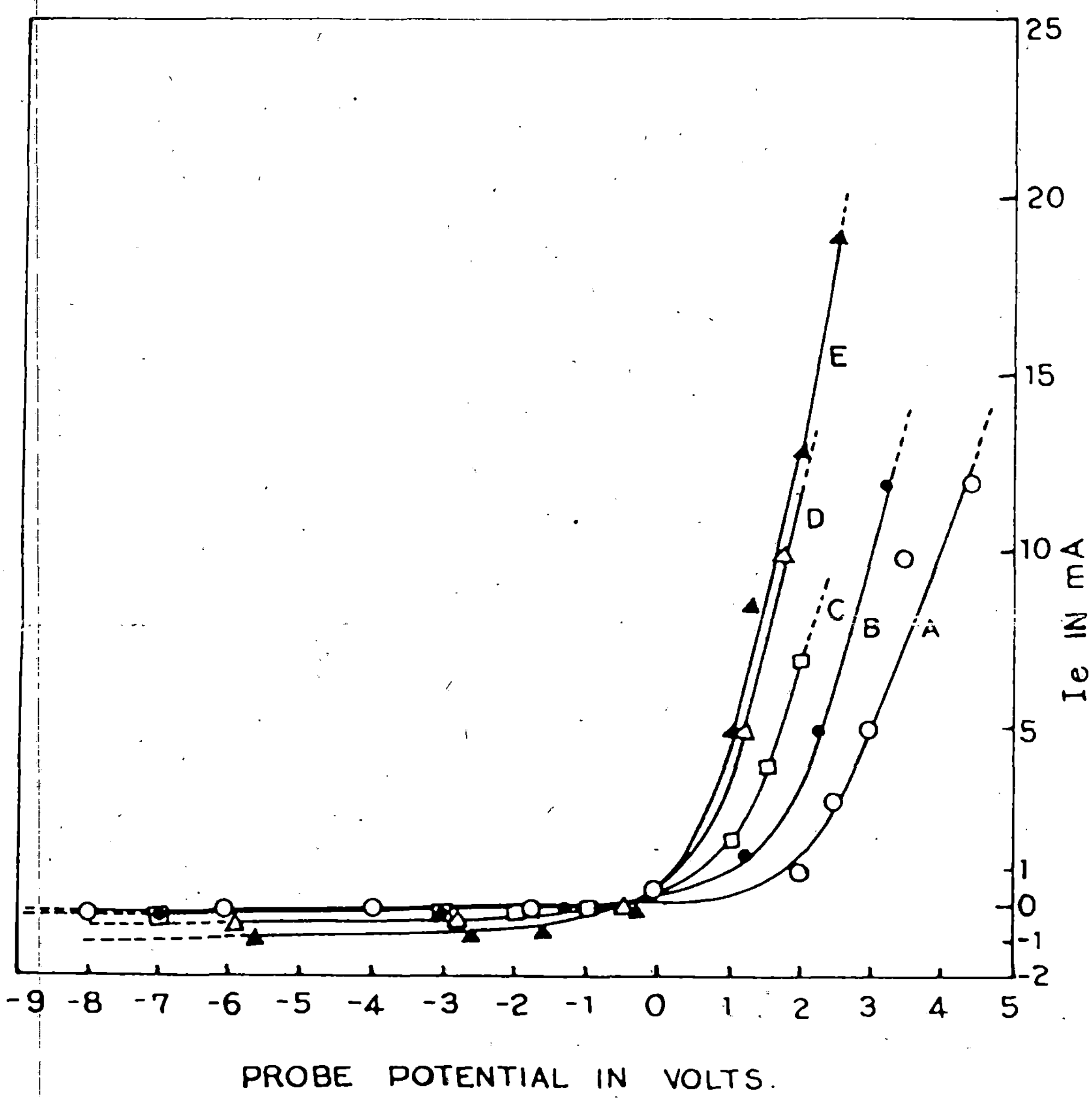
## 8.3. RESULTS AND DISCUSSION

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. 8.1, for 2.0, 2.5, 3.0, 4.0 and 4.5 A for pressure 0.1 torr in Fig. 8.2 and for 2.0, 2.5, 3.0 and 4.0A for pressure 0.13 torr in Fig. 8.3. 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. 8.4, 8.5, and 8.6. 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 utilising eqn.(8.1). From figs. 8.1, 8.2, and 8.3 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 (1968). The electron density has been



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 VOLTS.


Fig.8·1.



25
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Ie IN mA
E
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-9
-8
-7
-6
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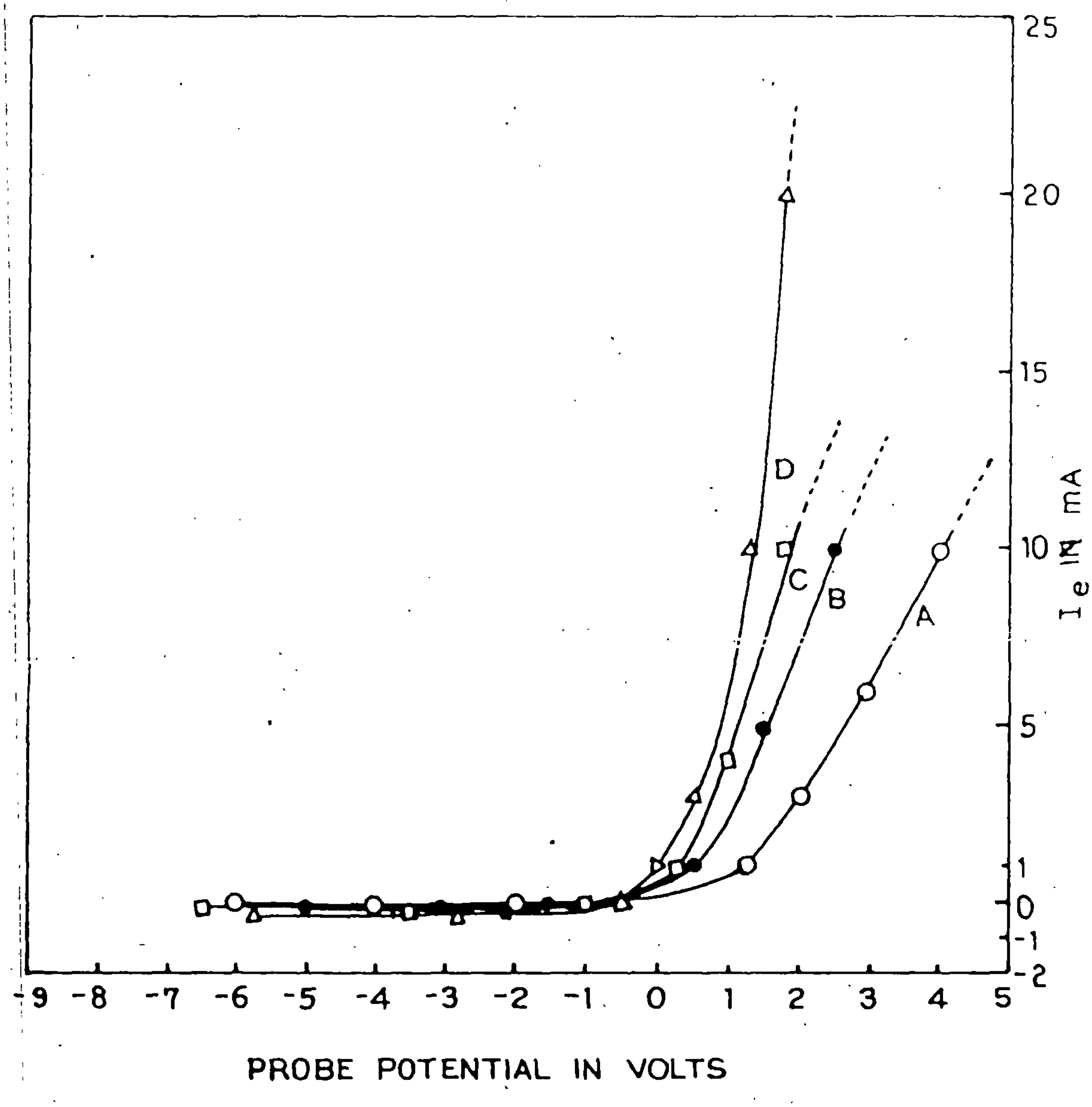
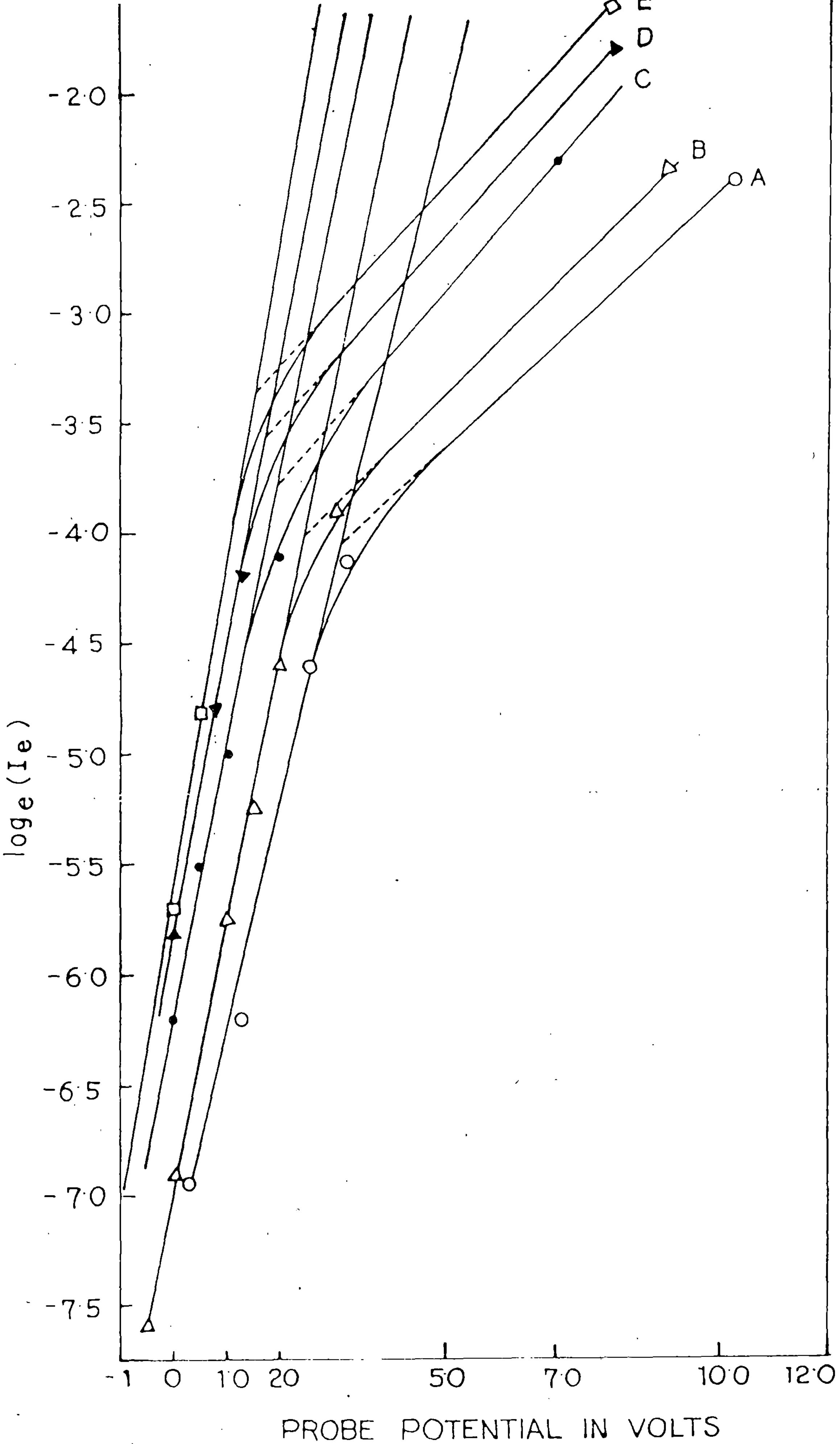
-4
-3
-2
-1
0
1
2
3
4
5
PROBE POTENTIAL IN VOLTS.


Fig. 8·2.



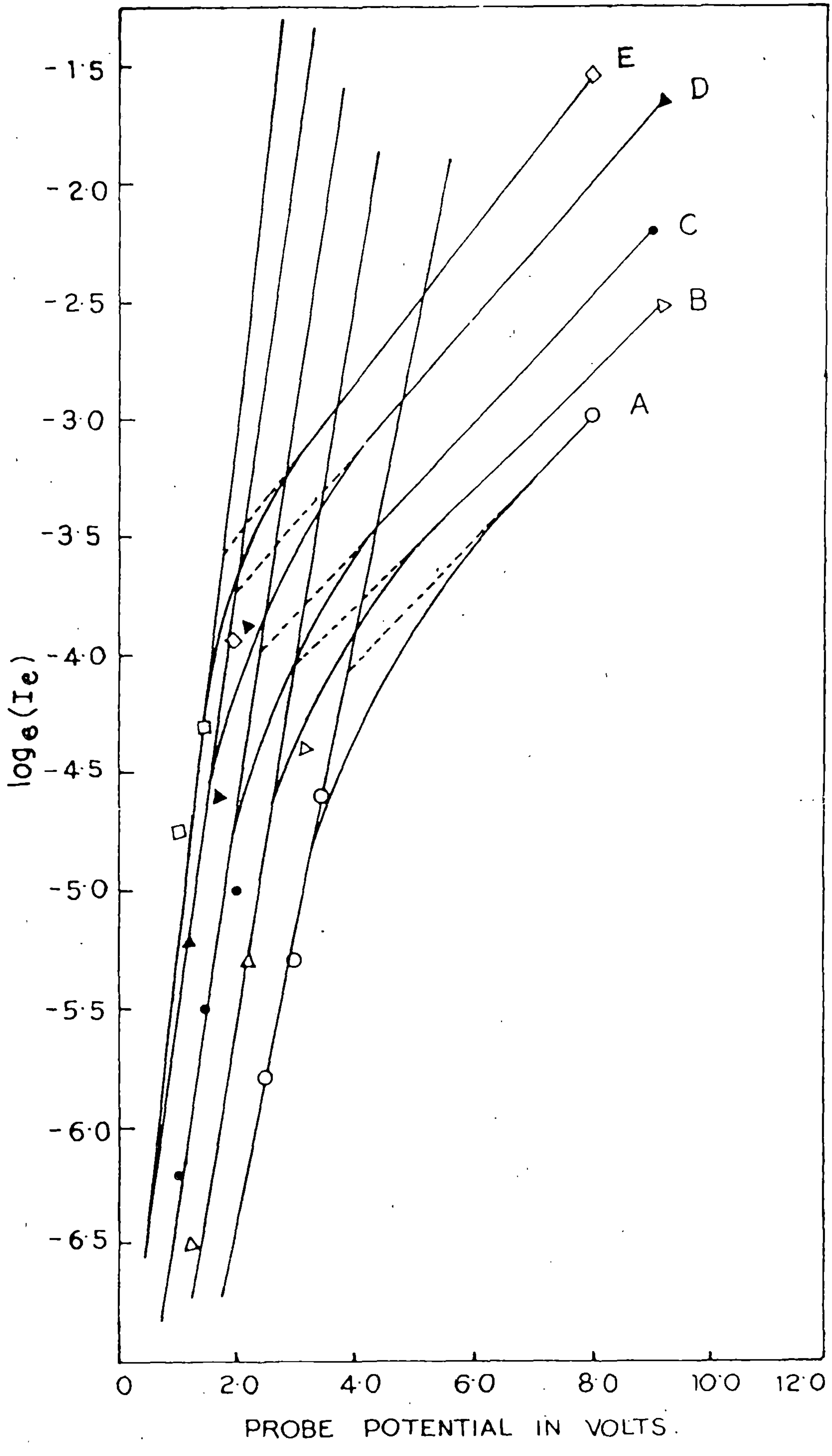
25
20
15
10
5
1
0
-1
-2
-9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5
D
C
B
A
Ie IN mA
PROBE POTENTIAL IN VOLTS


Fig.8·3.



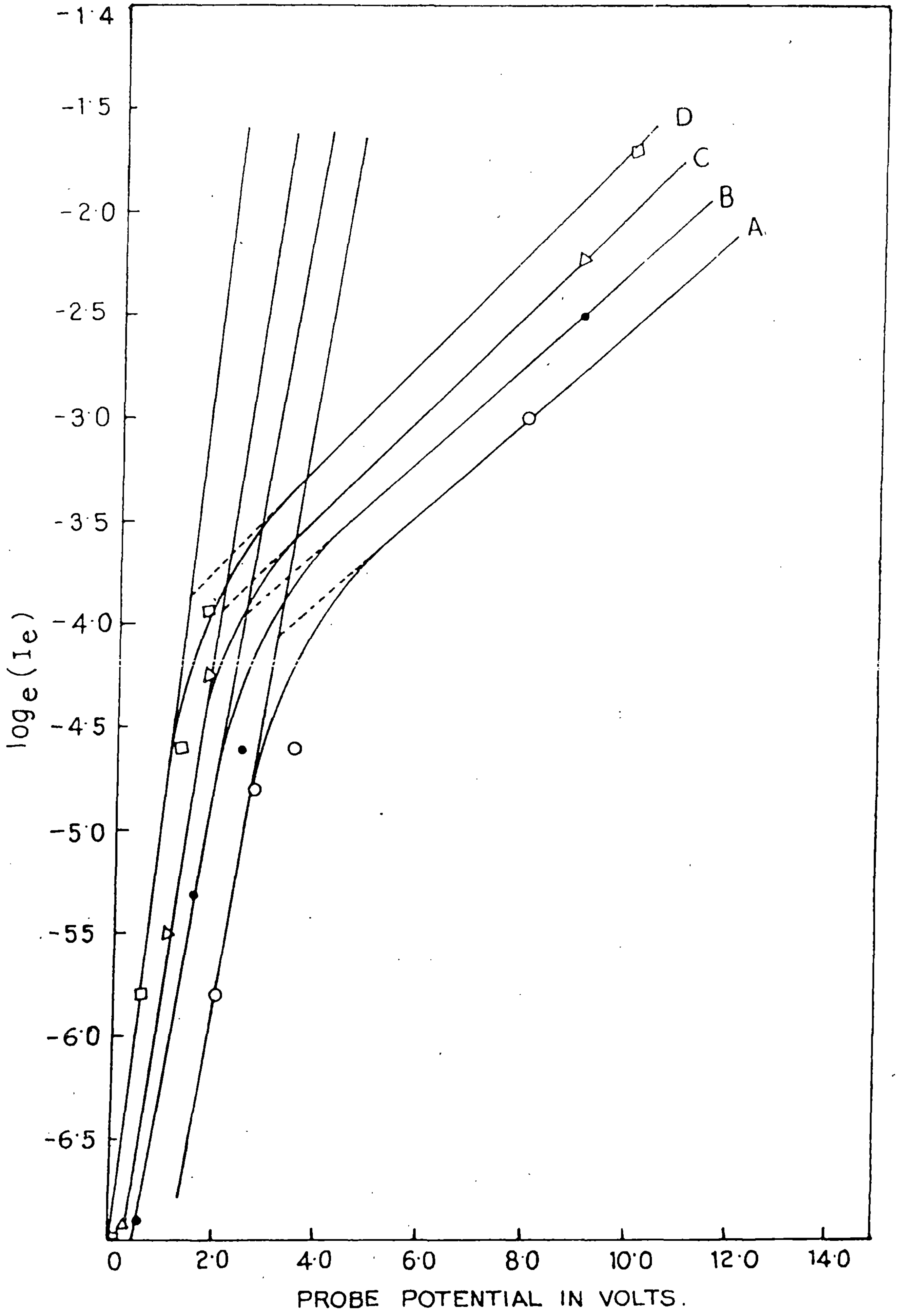
E
D
C
B
A
-2·0
-2·5
-3·0
-3·5
-4·0
-4·5
-5·0
-5·5
-6·0
-6·5
-7·0
-7·5
$\log_e(I_e)$
-1
0
1·0
2·0
5·0
7·0
10·0
12·0
PROBE POTENTIAL IN VOLTS


Fig.8·4



E
D
C
B
A
-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 VOLTS.


Fig 8·5.



-1·4
-1·5
-2·0
-2·5
-3·0
-3·5
-4·0
-4·5
-5·0
-55
-6·0
-6·5
$\log_e(I_e)$
0
2·0
4·0
6·0
8·0
10·0
12·0
14·0
PROBE POTENTIAL IN VOLTS.
D
C
B
A


Fig. 86.

calculated from eqn. (8.2). The results are entered in the third and fourth columns of the table 8.1. Langmuir (1925) while studying the scattering of electrons in mercury arc discharge deduced an expression for the arc current density given by

$$I = 5.76 \times 10^{-10} \frac{n_e \lambda E}{\sqrt{T_e}} \qquad (8.3)$$

where $n_e$ is the electron density, $\lambda$ 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 $I\,T_e^{1/2} / n_e E$ should be constant for different arc currents for different pressures. The results are entered in the sixth column of Table 8.1. Considering the uncertainty involved in the measurement of $n_e$ the values calculated for $I\,T_e^{1/2} / n_e E$ show a fair degree of consistency justifying the validity of eqn. (8.3) for the arc current.

From the eqn. (8.3) it is evident that the mean free path of the electron can be calculated for different values of pressures. Taking the mean value of $I\,T_e^{1/2}/n_e E$ as entered in the sixth column of Table 8.1, the value of $\lambda$ has been calculated and results entered in Table 8.2, column (3). From column (4) it is evident that $p\lambda$ is almost a constant for three different pressures and we can

Table 8.1

| Pressure in torr | Arc current in A | Electron temperature in $^oK$ | Electron density $\times 10^{-12}$ per c.c. | Arc drop in volts | $I T_e^{1/2} / n_e E \times 10^{10}$ | Average $I T_e^{1/2} / n_e E \times 10^{10}$ |
|---|---|---|---|---|---|---|
| | 2.0 | 11487.3 | 0.6967 | 42 | 0.5159 | |
| | 2.5 | 10131.0 | 0.7803 | 41 | 0.5534 | |
| 0.075 | 3.0 | 9572.8 | 0.9812 | 39 | 0.5406 | 0.5352 |
| | 4.0 | 9041.6 | 1.2964 | 38 | 0.5448 | |
| | 4.5 | 8521.9 | 1.5608 | 36 | 0.5213 | |
| | 2.0 | 8195.6 | 0.7856 | 44 | 0.3694 | |
| | 2.5 | 7593.5 | 0.8580 | 43 | 0.4159 | |
| 0.10 | 3.0 | 6066.9 | 1.0092 | 42 | 0.3890 | 0.3875 |
| | 4.0 | 5839.4 | 1.3208 | 41 | 0.3980 | |
| | 4.5 | 5532.1 | 1.5766 | 39 | 0.3653 | |
| | 2.0 | 7785.8 | 0.8473 | 47 | 0.3124 | |
| 0.13 | 2.5 | 7079.2 | 0.9336 | 46 | 0.3453 | |
| | 3.0 | 5696.9 | 1.0948 | 44 | 0.3313 | 0.3321 |
| | 4.0 | 4800.0 | 1.3704 | 42 | 0.3395 | |

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 $\sigma$ is the molecular diameter. In case of mercury this comes out to be $3 \times 10^{-3}$ cm at 1.0 torr.

Table 8.2

| Pressure in torr | $\frac{I\, T_e^{1/2}}{n_e E} \times 10^{10}$ | $\lambda$ | $P\lambda = L$ |
|---|---|---|---|
| 0.075 | 0.5352 | $9.294 \times 10^{-2}$ | $6.971 \times 10^{-3}$ |
| 0.10 | 0.3875 | $6.728 \times 10^{-2}$ | $6.728 \times 10^{-3}$ |
| 0.13 | 0.3321 | $5.765 \times 10^{-2}$ | $7.494 \times 10^{-3}$ |

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

The variation of open circuited voltage with arc current as measured has been plotted in figure 8.7 for three pressures namely 0.075 torr, 0.10 torr and 0.13 torr.

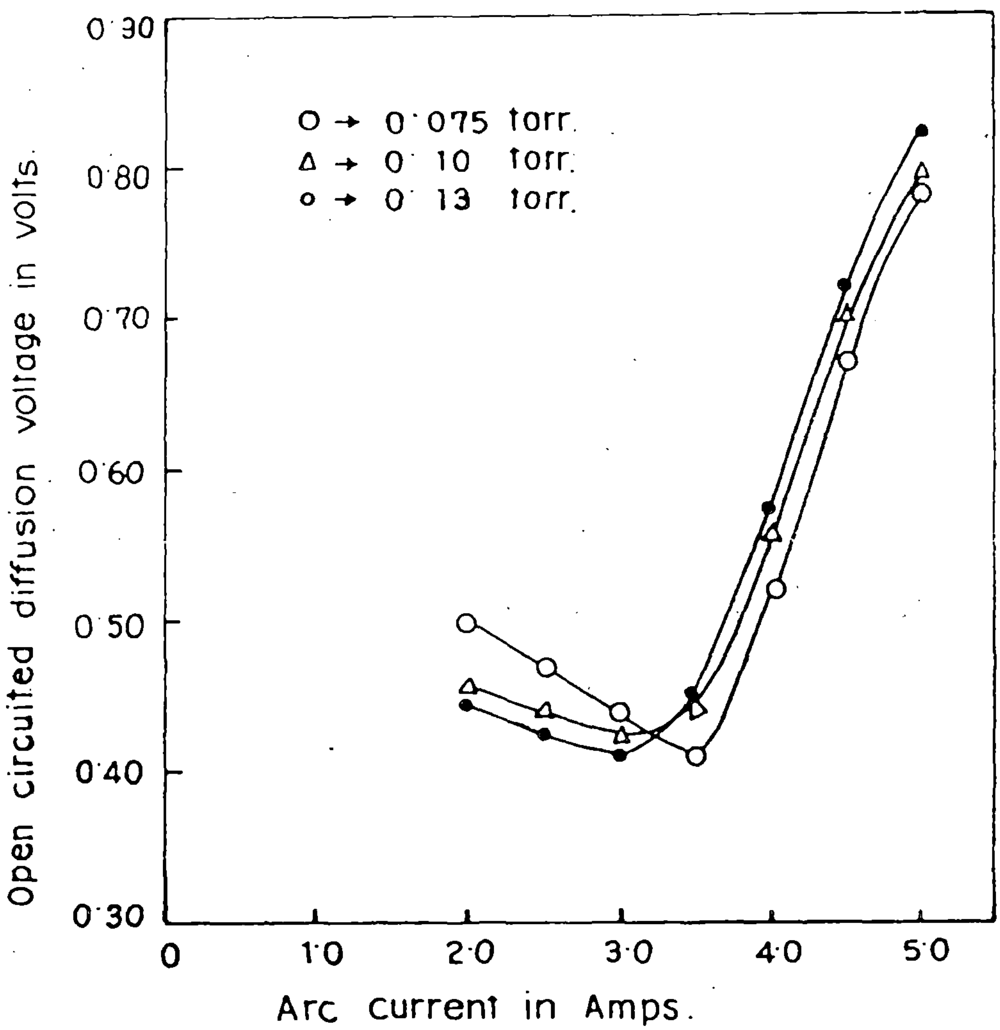

O → 0·075 torr.
Δ → 0·10 torr.
• → 0·13 torr.
Open circuited diffusion voltage in volts.
0·30
0·80
0·70
0·60
0·50
0·40
0·30
0
1·0
2·0
3·0
4·0
5·0
Arc current in Amps.

Fig.87.

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 transversemagnetic field. In glow discharge the radial distribution of charged particle 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

$$\sigma(r) = \sigma_0 \left[ 1 - (r/R)^2 \right]^n \qquad (8.4)$$

where $\sigma_0$ 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

$$n = \left[ R^2/a - 2 \right]$$

where a is an experimentally determined quantity which varies with arc current. In this regard same work has been carried out by the present author and discussed in the next chapter (Chapter IX). 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

$$V_R = -\int \frac{dn_e}{n_e} \frac{KT_e}{e} \qquad (8.5)$$

and since the electron density is proportional to the conductivity we get from equation (8.4)

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

and from equation (8.5)

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

Let $Z = (1 - r^2/R^2)$

then $V_R = - \frac{nKT_e}{e} \int \frac{dZ}{Z} = - \frac{nKT_e}{e} \log Z + C$ .

**Eqn.**

at $r = 0$, $V_R = 0 = 0 + C$

Hence, $V_R = - \frac{nKT_e}{e} \log \frac{R^2 - r^2}{R^2}$

$$= \frac{2nKT_e}{e} \log \frac{R}{\sqrt{R^2 - r^2}} \qquad (8.6)$$

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 figure 8.8. Hence it is numerically possible to calculate the values of $V_R$ for different arc currents at different pressures from equation (8.6). The results are entered in Table 8.3.

Table 8.3.

| Pressure in torr | Arc current in Amps. | Diffusion voltage in volts | |
|---|---|---|---|
| | | Experimental | Theoretical |
| | 2.0 | 0.498 | 0.575 |
| | 2.5 | 0.470 | 0.527 |
| | 3.0 | 0.438 | 0.506 |
| 0.075 | 3.5 | 0.412 | 0.495* |
| | 4.0 | 0.518 | 0.539 |
| | 4.5 | 0.670 | 0.544 |
| | 5.0 | 0.780 | 0.588* |
| | 2.0 | 0.458 | 0.410 |
| | 2.5 | 0.438 | 0.374 |
| | 3.0 | 0.435 | 0.349 |
| 0.10 | 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* |
| | 2.0 | 0.446 | 0.390 |
| | 2.5 | 0.425 | 0.348 |
| | 3.0 | 0.410 | 0.307 |
| 0.13 | 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

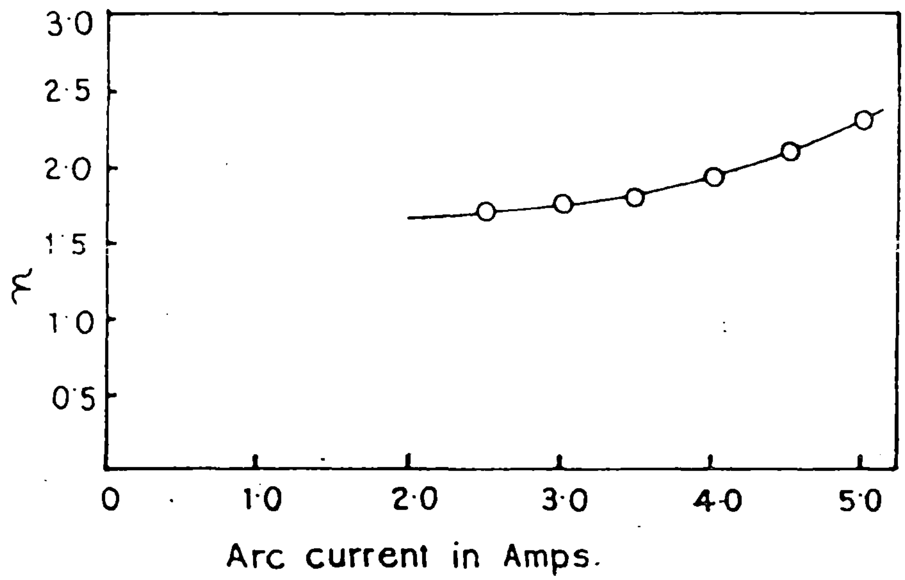



Fig. 8·8 .

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. The results are presented in Table 8.4.

Table 8.4

| 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. 8.3) 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 (1978). In fact the value of $n$ has been calculated at a particular back ground air pressure, but for better agreement it should be measured at all the required pressures as radial electron density profile has certainly some functional dependence on the pressure. It is also noteworthy that in the expression for $V_R$ (eqn. 8.6) one term involves logarithmic dependence on the separation distance between the two probes utilised for diffusion voltage measurement. So little inaccuracy in its measurement will change the result. However, it is the beauty of the experiment that with a prior knowledge of radial density distribution profile, the electron temperature can be measured much more accurately because eventually plasma condition will not suffer any perturbation while open circuited diffusion voltage will be measured.

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## CAPTION FOR FIGURES

Fig. 8.1 Variation of probe current with probe potential
A 2.0A, B 2.5A, C 3.0A, D 4.0A & E 4.5A;
Pressure = 0.075torr.

Fig. 8.2 Variation of probe current with probe potential.
A 2.0A, B 2.5A, C 3.0A, D 4.0A & E 4.5A;
Pressure = 0.10torr.

Fig. 8.3 Variation of probe current with probe potential.
A 2.0A, B 2.5A, C 3.0A & D 4.0A;
Pressure = 0.13torr.

Fig. 8.4 Variation of $\log I_e$ against the probe potential.
Details of curves as in fig. 8.1.

Fig. 8.5 Variation of $\log I_e$ against the probe potential.
Details of curves as in fig. 8.2.

Fig. 8.6 Variation of $\log I_e$ against the probe potential.
Details of curves as in fig. 8.3.

Fig. 8.7 Variation of diffusion voltage with arc current.

Fig. 8.8 Variation of 'n' with arc current.