CHAPTER - IV.

SECTION-A. : BREAKDOWN OF GASES BY HIGH FREQUENCY ELECTRIC FIELD IN A TRANSVERSE MAGNETIC FIELD (Pressure range 1 to 6 mm. of mercury)

SECTION-B. : BREAKDOWN OF GASES BY HIGH FREQUENCY ELECTRIC FIELD IN A TRANSVERSE MAGNETIC FIELD (Pressure range .05 mm. to 1.5 mm. of mercury)

SECTION - A.

INTRODUCTION.

The condition for the breakdown of a gas excited by high frequency electromagnetic waves depends mainly upon factors such as the pressure of the gas, the dimension of the discharge tube and the frequency of excitation. The two dominant factors by which electrons are lost are diffusion and mobility and if the gas is an electron attaching one, then by electron attachment also. It has been found that when the pressure of the gas is of the order of a few microns and the length of the discharge tube is large compared to the mean free path of the electrons, both the mobility and diffusion are the dominent factors by which electrons are lost. On the other hand, when the gas pressure is high and the frequency of excitation lies in the microwave region, the electrons are lost mainly by diffusion. The experimental values of the breakdown voltage are consistent with those calculated theoretically taking the above electron removal processes into consideration. The method of calculating the breakdown voltage from theoretical consideration has been developed by Herlin and Brown (1948) in the case of high pressure and high frequency where the dominent cause for the electron removal process is diffusion. Starting from a molecular model, an alternative method of calculation has been developed by Kihara (1952). He has considered both the mobility and diffusion as electron removal processes and in a number of papers published from this laboratory, (Sen & Ghosh 1963, Sen & Bhattacherjee 1965, 1966, 1967) experimental results obtained have been compared with the theory developed by Kihara. It has been found that when the pressure is of the order of a few microns and the frequency of excitation is of the order of a few megacycles/sec; both the diffusion and mobility are the major electron removing processes. The discrepancy observed between the experimental results and those calculated from Kihara's theory has been attributed to the uncertainty in the values of the molecular constants introduced by Kihara. As the mechanism of breakdown depends upon the pressure as well as upon the frequency of excitation, it is worthwhile to investigate which process is mainly responsible for electron removal under the present experimental setup. Further in this paper an attempt will be made to incorporate the effect of attachment in Kihara's theory.

The breakdown of a gas excited by a radiofrequency voltage in presence of a magnetic field either longitudinal or transverse has been studied previously. Mention may be made of the work by Townsend and Gill (1937) who carried out experiments in air for two frequencies namely 48 and 30 Mc/sec and the range of pressure varying from a few microns to .24 m.m. of mercury. Lax, Allis and Brown (1950) performed experiments on the breakdown voltage of a gas in a microwave field in presence of a transverse magnetic field. The gas used was helium containing a small admixture of mercury vapour and they obtained breakdown curves for different values of the pressure. Ferritti and Veronesi (1955) performed experiments for frequencies ranging from 10 to 30 Mc/sec in air, the magnetic field varying from 0 to 600 gauss. They used cylindrical electrodes and observed a lowering of breakdown potential in presence of the magnetic field. The breakdown of a discharge in air and nitrogen excited by a radiofrequency voltage of frequency between 7 to 10 Mc/sec and the pressure varying from 10 to 300μ in presence of a transverse magnetic field varying from 0 to 80 gauss has been studied by Sen and Ghosh (1963). Assuming that mobility and diffusion are both responsible for removal of electrons and utilising Kihara's theory, the authors have found good agreement with experimental results. In the present paper the effect of a higher magnetic field from 300 to 1800 gauss applied transversely has been studied and the paper reports the results in case of hydrogen, air, oxygen and carbondioxide. Attempt will first be made to explain the results with the theory developed by Herlin and Brown (1948) and then to compare the results with Kihara's theory (1952) after introducing in the theory the effects produced by the magnetic field.

EXPERIMENTAL ARRANGEMENT.

The method of measurement of breakdown voltage has been described in chapter III. The discharge tube is cylindrical, of length 0.4 cm and radius 1.4 cm fitted with two external electrodes and distance between the two electrodes being 0.4 cm. for all the gases studied. The radiofrequency voltage has been supplied from a tuned plate tuned grid oscillator, the frequency of the oscillator varying from 10 Mc/sec to 30 Mc/sec, the frequency used to excite the discharge being 17.6 Mc/sec, and the output of the oscillator can be continuously varied from 0 to 500 volts. The r.m.s. output voltage has been measured with a vacuum tube voltmeter. The pressure of the gas has been measured with a mercury manometer. The magnetic field has been supplied by an electromagnet, the lines of force being perpendicular to the length of the discharge tube and the magnetic field has been measured accurately with a calibrated fluxmeter. Keeping the magnetic field at a constant value, the pressure of the gas has been varied and breakdown voltage determined for various values of the gas pressure. The experiments have been repeated a large number of times and the results have been found to be consistent.

Preparation of gases :

Hydrogen was prepared by the electrolysis of a warm concentrated solution of barium hydroxide in a hard glass U tube fitted with nickel electrodes in which hydrogen was liberated at the cathode. The gas is dried by passing over broken pieces of potassium hydroxide followed by purified phosphorous pentoxide.

Pure oxygen is evolved at the anode in the electrolysis of barium hydroxide solution. It is passed over red hot platinum to remove traces of hydrogen and dried with pure phosphorous pentoxide.

Pure carbon dioxide has been obtained by the action of dilute sulphuric acid, boiled to free it from air, on pure sodium carbonate. The evolved gas is first passed through water to remove traces of acid and is then dried by passing through silica gel and phosphorus pentoxide.

RESULTS AND DISCUSSION.

The (E/p) values for different gases have been plotted against $p\Lambda$ in figure (10) for hydrogen, in figure (11) for air, in figure (12) for oxygen and in figure (13) for carbondioxide where Λ is the diffusion length. The curves indicate that the values of (E/p) gradually decrease with increasing values of $p\Lambda$ within the range of pressure investigated. In order to ascertain which process is dominant under the present experimental setup as the cause of electron removal, the following points have been taken into consideration.

(a) As has been stated by Brown (1959) the validity of the diffusion theory assumes that the measurements of breakdown are always taken in vessels whose dimensions are small compared to the wavelength of the exciting power because in that case the uniform field assumption is always valid. In our present experimental setup, the wavelength of the exciting radiation is 17.04 meters and the length of the discharge tube is 10.4 cm and radius 1.4cm. Consequently the uniform field assumption which is necessary for the diffusion theory to be valid is satisfied.

(b) The values of mean free path of electrons for various gases have been given by Townsend (1947) and are entered in table I.

TABLE - I.

Gas	L in cm.
Hydrogen	.02 - .04
air	.03
oxygen	.03 - .06
Carbondioxide	.004 - .06

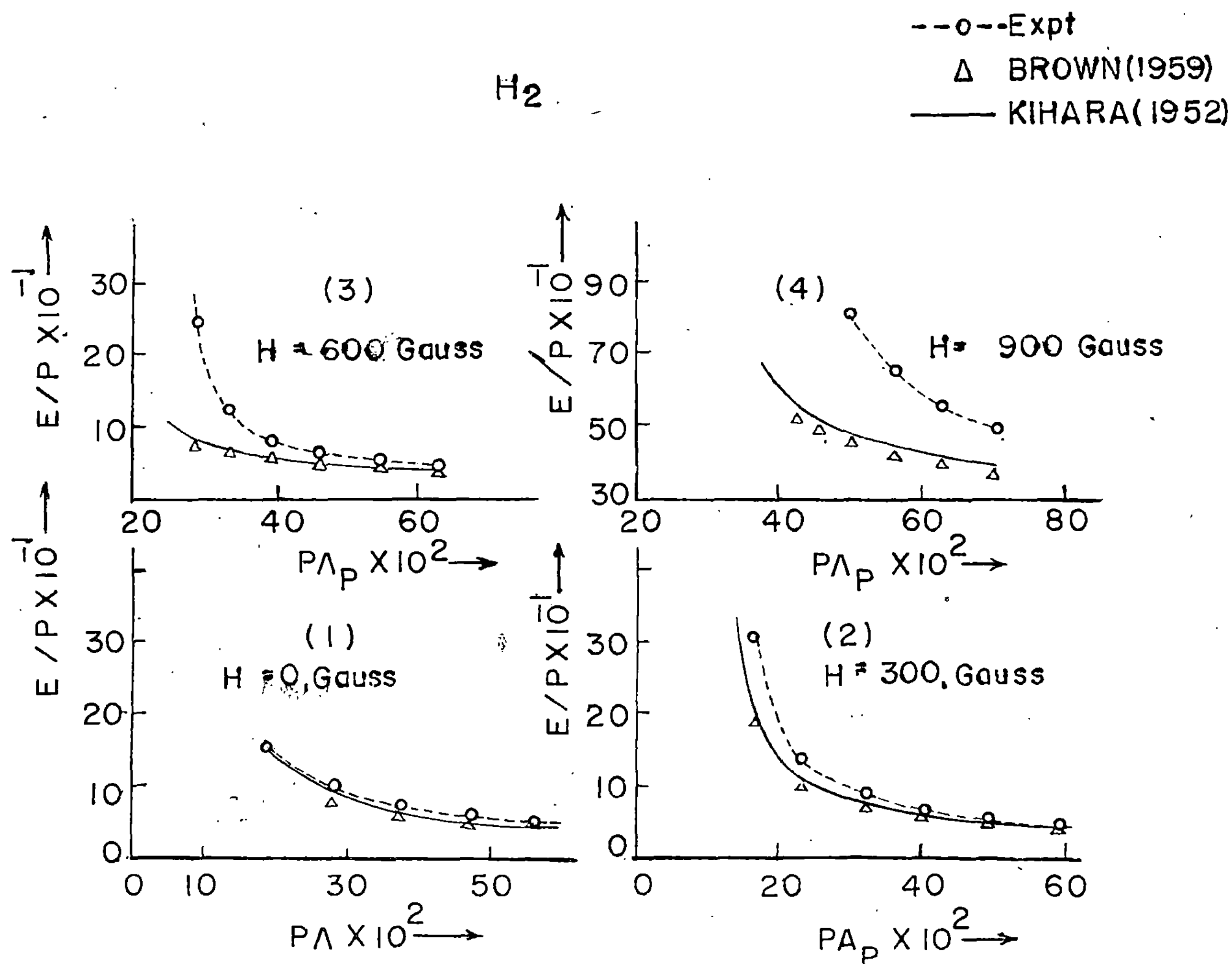

--o--Expt
Δ BROWN(1959)
—— KIHARA(1952)
H2
(3)
H = 600 Gauss
E/P X10⁻¹
PΛp X10²
(4)
H = 900 Gauss
(1)
H = 0 Gauss
PΛ X10²
(2)
H = 300 Gauss
PAp X10²

Fig-10

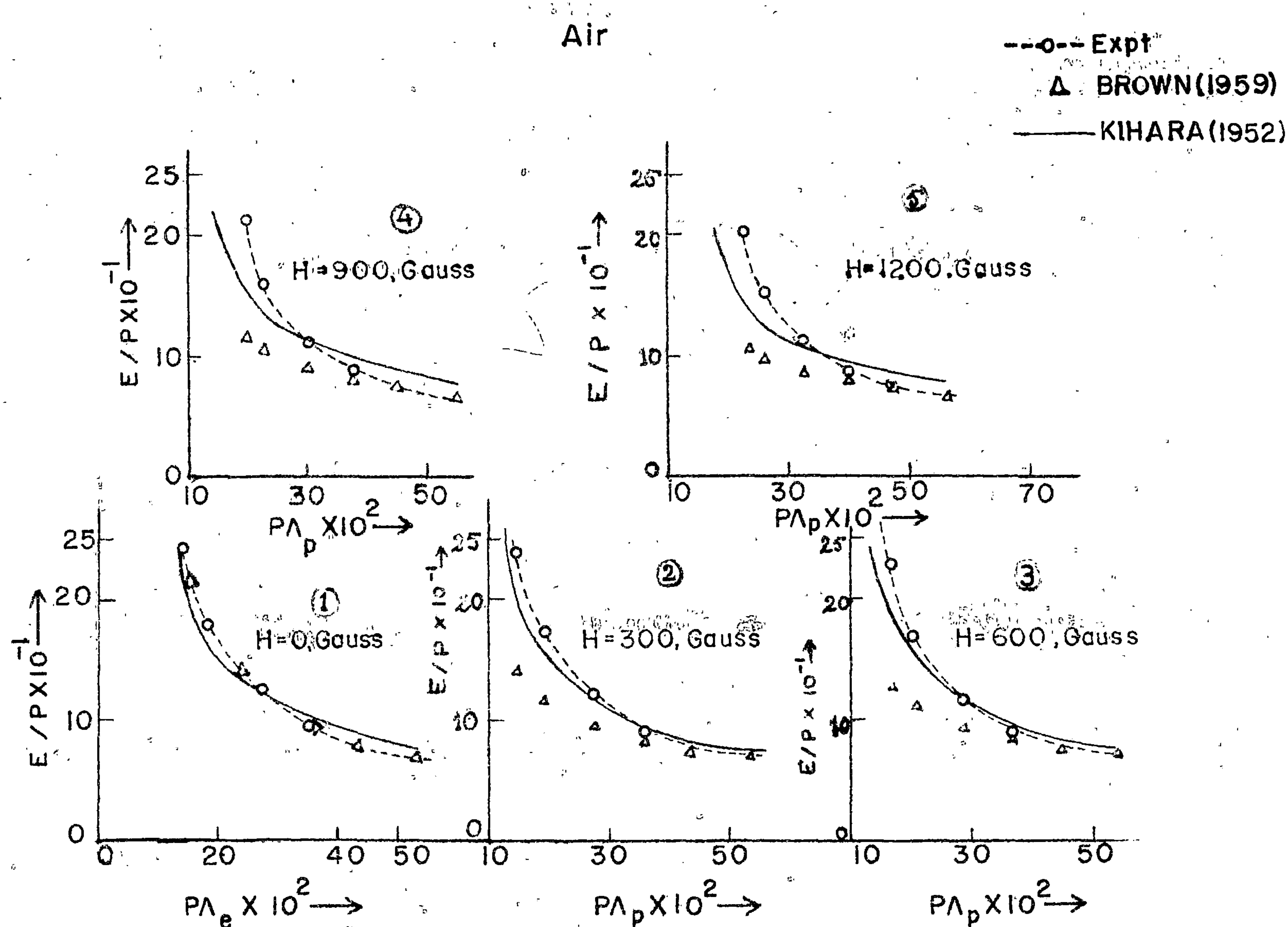

Air
--o-- Expt
Δ BROWN(1959)
—— KIHARA(1952)
④ H=900, Gauss
⑤ H=1200, Gauss
① H=0, Gauss
② H=300, Gauss
③ H=600, Gauss
E/P X 10⁻¹ →
PΛp X 10² →
PΛe X 10² →

Fig-11

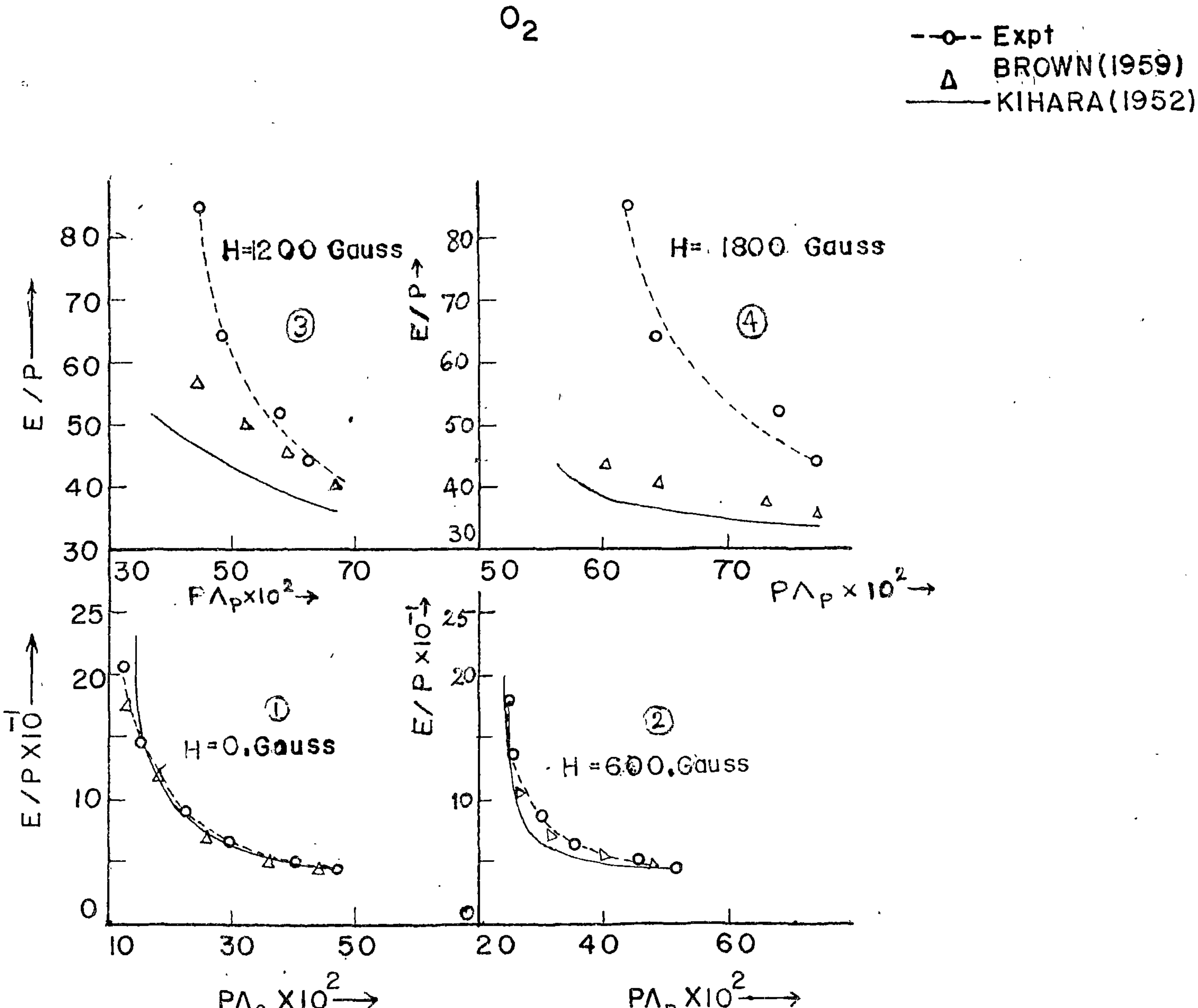
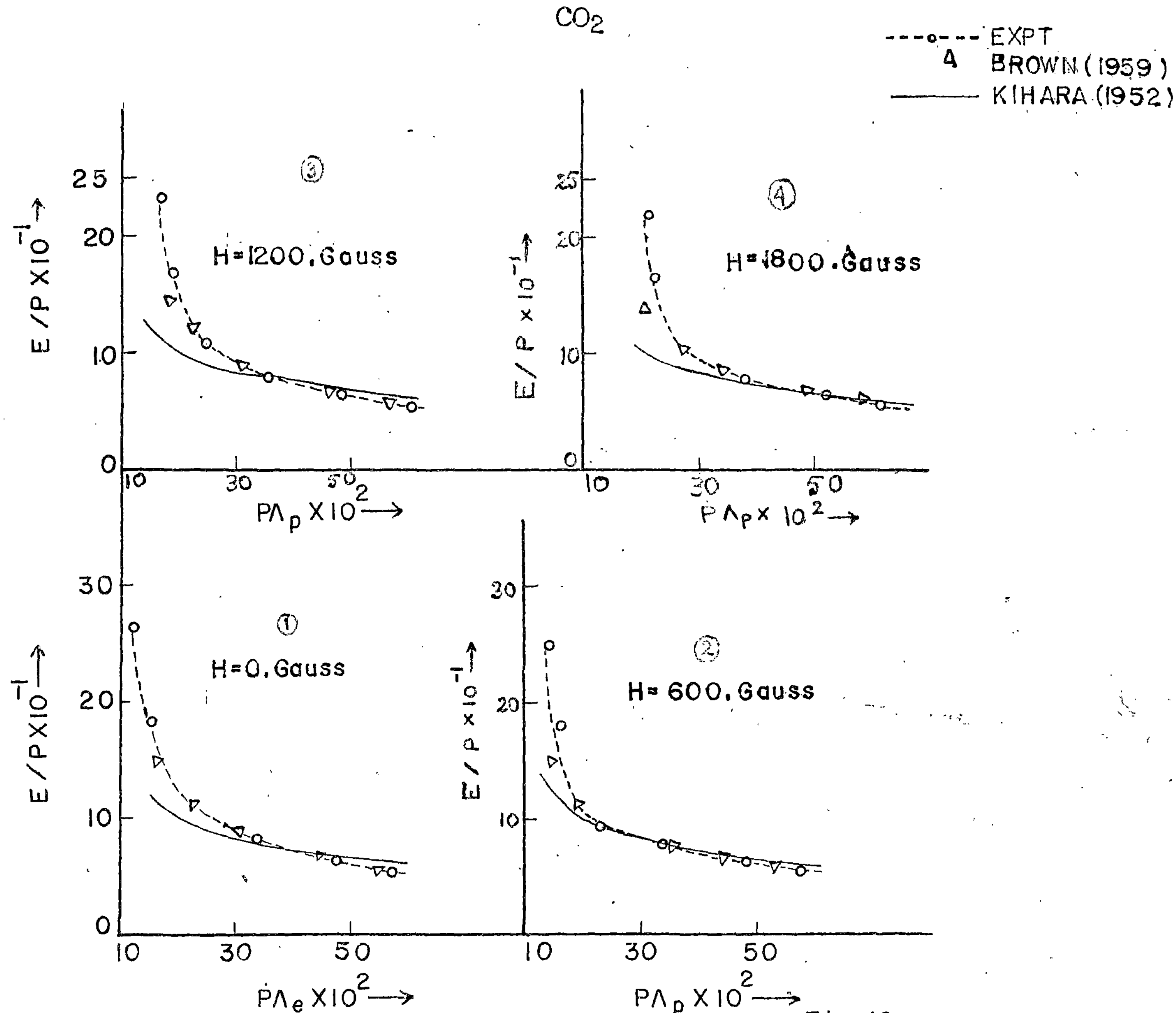

O2
Expt
BROWN(1959)
KIHARA(1952)
H=1200 Gauss
③
H= 1800 Gauss
④
E/P
E/P
FΛp×10²
PΛp×10²
E/P×10⁻¹
E/P×10⁻¹
①
H=0 Gauss
②
H=600 Gauss
PΛe×10²
PΛp×10²

Fig-12



CO2
EXPT
BROWN (1959)
KIHARA (1952)
③
H=1200, Gauss
E/P X10^-1
PΛp X10^2
④
H=1800. Gauss
E/P x 10^-1
PΛp x 10^2
①
H=0, Gauss
E/P X10^-1
PΛe X10^2
②
H= 600, Gauss
E/P x 10^-1
PΛp X10^2

Fig-13

Where L denotes the electronic mean free path at a pressure of 1 m.m. The values of λ_e, the electronic mean free path will be smaller at higher pressures. Since the length of the discharge tube is 10.4 cm, and radius = 1.4 cm it is observed that $\lambda_e < d$ or r where d is the length and r is the radius of the discharge tube.

(c) The collision frequency $\nu_c = v_r/\lambda_e$ where v_r is the random velocity. From the measurements made in this laboratory on the radiofrequency conductivity of ionised gases, (Gupta & Mandal 1967) the random velocity of electrons is of the order of 10^8 cm/sec for most of the gases studied here and hence for a pressure of 1 m.m. of mercury the collision frequency will be of the order of 10^9 and as the frequency of the applied field is 17.6 Mc/sec, the collision frequency is greater than the applied frequency and at higher pressure it will be still greater. Within the limits of experimental conditions in which diffusion theory adequately explains the breakdown behavior, one of the phenomenological changes that occurs is the transition from many collisions per oscillation to many oscillations per collision. Within our present experimental setup for the range of pressure investigated $\nu_c \gg \omega$ where ω is the angular frequency of the applied r.f. field. Hence we shall only deal with the case in which the electron suffers large number of collisions per oscillation.

(d) The amplitude of electron oscillation when collision is taken into consideration is given by

$$x = \frac{e E_p}{m \omega \sqrt{\omega^2 + \nu_c^2}} \quad \ldots(4.1)$$

where E_p is the electric field intensity. Putting an average value of E_p, ω and ν_c it is observed that the amplitude of oscillation is of the order of .32 cm at a pressure of 1 m.m. and for higher pressures the amplitude will be still smaller.

Under the above conditions, it is thus apparent that the electrons make many oscillations of small amplitude because the motion is restricted by collisions, and the cloud of electrons appears stationary (there being no drift motion) spreading outwards only by diffusion. Hence in the present case, the loss due to drift can be neglected. New charged particles are formed due to ionization collisions and only the loss due to diffusion predominates. The case is similar to that occuring in the case of microwave breakdown of gases and hence

$$\nu . n + D . \frac{d^2 n}{dx^2} = 0 \qquad \ldots(4.2)$$

where n = electron density ; ν = frequency of ionisation ; D = diffusion coefficient.
As the length of the discharge tube is small compared to its diameter, one dimensional treatment is valid and the solution of the equation with the usual boundary condition $n = 0$ at $x = \pm d/2$ where d denotes the length of the discharge tube, is given by

$$\nu / D = 1/\Lambda^2 \qquad \ldots(4.3)$$

where Λ is the diffusion length and for a cylinder of length d and radius r is given by

$$\frac{1}{\Lambda^2} = \left(\frac{\pi}{d}\right)^2 + \left(\frac{2.405}{r}\right)^2 \qquad \ldots(4.4)$$

As stated above, under the present experimental setup and the range of pressure investigated, the collision frequency is much larger than the frequency of the applied radiofrequency field and the electron suffers many collisions per oscillation of the field. As has been stated by Brown (1959), with the rise of pressure the electronic mean free path decreases and the energy gain per mean free path is proportional to the mean free path at constant E field. Hence to cause breakdown the field must increase inversely proportionally to the mean free path or directly proportional to pressure. He has thus concluded that at high pressures where the electrons make many collisions per oscillation, their behaviour is the same as in the case of d.c. discharge. Hence putting $\nu = \alpha \bar{K} E$ in equation (4.3) where α is the first Townsend coefficient and $\bar{K}$ the mobility coefficient we get

$$\frac{\alpha \bar{K} E}{D} = 1/\Lambda^2 \qquad \ldots(4.5)$$

as $\frac{\bar{K}}{D} = \frac{e}{KT_e}$ where T_e is the electron temperature

we get,

$$\left(\frac{\alpha}{P}\right) \frac{E e P}{K T_e} = 1/\Lambda^2 \qquad \ldots(4.6)$$

and from Townsend's equation

$$(\alpha/P) = A_0 \exp(-B_0 P/E)$$

$$\therefore A_0 \exp\left(-\frac{B_0 P}{E}\right) . \frac{E}{P} . \frac{e}{KT_e} . P^2 = 1/\Lambda^2 \qquad \ldots(4.7)$$

In case of low density plasmas encountered in low current electric discharges, the electron temperature T_e is $f(E/P)$. The thermal energy of an electron is determined by the difference between the work done by the electric field and the energy losses due to collision between electrons and atoms. It is evident that at higher field strength the electron will gain greater amount of energy between successive collisions. However with the increase of pressure there is an increase in energy losses due to collisions and therefore the electron temperature will decrease with increasing pressure. A mathematical expression involving T_e and (E/P) has been deduced by Von Engel (1955)

$$\frac{KT_e}{e} = \frac{L}{\sqrt{K}} \cdot (E/P) = \gamma \cdot (E/P) \quad \text{where } \gamma = \frac{L}{\sqrt{K}} \qquad \ldots(4.8)$$

where L is the mean free path of the electron in the gas at a pressure of 1 m.m. of Hg. and $k = \frac{2m}{M}$ where m is the mass of the electron and M is the mass of ion. Hence we get

$$A_0 \exp\left(-\frac{B_0 P}{E}\right) \cdot \frac{P^2}{\gamma} = 1/\Lambda^2$$

$$\text{or} \quad E/P = \frac{B_0}{\log\left(A_0 P^2 \Lambda^2/\gamma\right)} \qquad \ldots(4.9)$$

In case where there are many oscillations per collision, Brown (1959) has deduced an expression for the breakdown voltage taking the diffusion loss into consideration but in case when there are many collisions per oscillation as is the case investigated here the breakdown potential has been calculated by him in an indirect way; hence the above deduction which enables us to calculate theoretically the breakdown voltage from the knowledge of different known parameters has been adopted here. Kihara (1952) has treated the phenomena of electrical discharge by adopting a proper molecular model for collision processes. Assuming a suitable model for the crosssection of the molecule for elastic, exciting and ionizing collisions with Maxwellian distribution of velocities of electrons which is nearly valid in case of molecular gases as has been studied here, he has deduced expression for ν and D where

$$\nu = N \cdot \frac{3\sigma}{c_i} \cdot \frac{KT_e}{m} \cdot \exp\left(-\frac{m c_i^2}{2KT_e}\right) \quad \text{and} \quad D = \frac{KT_e}{mN\lambda}$$

and putting these values in equation (4.3) we get,

$$\frac{N \cdot \frac{3\sigma}{c_i} \cdot \frac{KT_e}{m} \cdot \exp\left(-\frac{m c_i^2}{2KT_e}\right)}{KT_e/mN\lambda} = 1/\Lambda^2 \qquad \ldots(4.10)$$

where σ is a molecular constant equivalent to collision crosssection and λ is another molecular constant introduced by Kihara having the dimension of Cm^3/sec.

N is the number density of gas atoms, K the Boltzman constant, C_i the molecular velocity and T_e is the electron temperature. Hence we get,

$$N^2 \cdot \frac{3\sigma}{c_i} \cdot \lambda \Lambda^2 = \exp\left(mc_i^2/2KT_e\right)$$

$$\text{or} \quad mc_i^2/2KT_e = \log\left[N^2 \cdot \frac{3.\sigma}{c_i} \cdot \lambda \cdot \Lambda^2\right] \qquad ...(4.11)$$

Further according to Kihara's theory the electron temperature T_e is given by

$$KT_e = \frac{e}{N} \cdot \frac{E_o}{\sqrt{2}} \cdot \frac{1}{(3\lambda\rho)^{1/2}} \cdot \left[1 + \frac{\omega^2}{N^2\lambda^2}\right]^{-1/2}$$

where ρ is another molecular model constant introduced by Kihara with the dimension of area divided by velocity and is related to the total crosssection by the relation $Q = \rho C$ which means that the total cross section is proportional to the speed of the colliding electron. Putting the value of KT_e we get,

$$\frac{N}{E} \cdot \frac{mc_i^2}{2e} \cdot (3\lambda\rho)^{1/2} \cdot \left[1 + \frac{\omega^2}{N^2\lambda^2}\right]^{1/2} = \log\left[\frac{3\sigma\lambda}{c_i}(N\Lambda)^2\right]$$

$$\text{then} \quad \frac{B_oP}{E}\left[1 + \left(\frac{C_1}{A_1P\bar{\lambda}}\right)^2\right]^{1/2} = 2\log\left(A_1 P \pi \Lambda\right) \qquad ...(4.12)$$

where A_1 and C_1 are the two derived constants introduced by Kihara and their values for different gases have been provided where

$$A_1 = \frac{N}{P\pi}\left(\frac{3\sigma\lambda}{C_i}\right)^{1/2} \quad \text{and} \quad C_1 = \left(\frac{\omega\bar{\lambda}}{\pi}\right)\left(\frac{3\sigma}{\lambda C_i}\right)^{1/2}$$

$\bar{\lambda}$ is the wavelength of the exciting r.f. field and $B_o = \frac{N}{P} \cdot \frac{mc_i^2}{2e} \cdot (3\lambda\rho)^{1/2}$ and B_o has been shown to be equal to the constant B introduced by Townsend in his theory of electrical discharge. From the values of the constants C_1 and A_1 as given by Kihara for different gases and $\bar{\lambda}$ the wavelength of the r.f. field the numerical value of the term $\left(\frac{C_1}{A_1P\bar{\lambda}}\right)^2$ becomes negligible compared to unity and the equation can be further simplified

$$\frac{B_o P}{E} = 2 \log (A_1 P \pi \Lambda)$$

or $$E/P = \frac{B_o}{2 \log (A_1 P \pi \Lambda)} \qquad \ldots(4.13)$$

Calculation of A_1

The value of the constant A_1 can be calculated according to Kihara from the constants A_o and B_o, the Townsend's constants, as follows. Kihara has shown that

$$A_o = \frac{N}{P} \cdot \frac{\sigma}{c_i} \cdot \left(\frac{3\lambda}{\rho}\right)^{1/2} \; ; \quad B_o = \frac{N}{P} \cdot \frac{m c_i^2}{2e} \cdot (3\lambda\rho)^{1/2}$$

and $$A_1 = \left(\frac{N}{P\pi}\right) \frac{3\sigma\lambda}{c_i}$$

then $$\frac{3\sigma\lambda}{c_i} = A_o B_o \frac{P^2}{N^2} \cdot \frac{2e}{m} \cdot \frac{1}{c_i^2}$$

and $$c_i = 0 \cdot 8 \left(\frac{2eV_i}{m}\right)^{1/2}$$

then $$A_1 = \frac{1}{\pi} \left\{ \frac{A_o B_o}{0 \cdot 64 \; V_i} \right\}^{1/2} \qquad \ldots(4.14)$$

where V_i denotes the ionization potential of the gas. The values of A_o and B_o have been given by Von Engel (1955) in case of air and hydrogen for the values of (E/P) used in this experiment; in case of CO_2 the values of A_o and B_o are provided for E/P varying from 500 to 1000 volts/cm. mm of Hg. which is much higher than (E/P) values used here and in case of oxygen no data has been provided. Consequently values of A_o and B_o have been calculated in case of oxygen and carbondioxide from the curves showing the variation of (α/P) against (E/P) (Brown 1959) for values of E/P lying between 50 to 100 volts/cm. mm. of Hg.

Gas	E_o Volts/cm.mm. of Hg.	A_o ion pairs / cm.mm. of Hg.	A_1 1 / cm. mm. Hg.	$\frac{1}{\Lambda}$
Hydrogen	130	5	2.5	10.61
Air	365	15	5.337	10.61
Oxygen	138	5.65	3.182	10.61
Carbondioxide	341	18.8	8.630	10.61

The values of E/p have been calculated both from the expression (4.9) and (4.13) for different values of $p\Lambda$ in case of all the gases and the results plotted side by side in figures 10, 11, 12 and 13 . The value of the constant γ in equation (4.9) has been taken from the experimental data provided by Dees and Emelius (1949) where the experimental variation of T_e with reduced field (E/p) for various molecular gases has been provided for large E/p values (0-300 v/cm. m.m. of Hg.). They are suitable because the variation of E/p values in our experiment also lies in this range. It is advisable to use the experimental values of γ because $\gamma = \frac{L}{\sqrt{R}}$ and no precise value of L is available in the literature.

Breakdown in electron attaching gases.

Kihara in his theory has provided the theoretical basis for calculating the breakdown potential in case of non attaching gases; Sen and Ghosh (1963) in calculating the breakdown potential in radiofrequency field in case of electron attaching gases adopted a simplified treatment. Though this simplified procedure has yielded better results, an alternative method based on more straight forward reasoning has been used here.

When attachment is also taken into consideration the breakdown condition is given by

$$\frac{\nu - \nu_a}{D} = 1/\Lambda^2 \qquad \ldots(4.15)$$

and if α_a is taken as the coefficient of attachment then

$$\alpha_a = \nu_a / \bar{K} E_a \qquad \ldots(4.16)$$

where $\bar{K}$ is the mobility coefficient and E_a is the breakdown voltage when attachment is taken into consideration. Putting the values of ν and D as before,

$$\frac{N.\frac{3.\sigma}{c_i}.\frac{KT_e}{m}.\exp\left(-\frac{mc_i^2}{2KT_e}\right) - \nu_a}{KT_e/mN\lambda} = 1/\Lambda^2$$

or $$N^2.\frac{3.\sigma}{c_i}.\lambda.\exp\left(-\frac{mc_i^2}{2KT_e}\right) = \left(1/\Lambda^2\right) + \frac{\nu_a mN\lambda}{KT_e} \qquad \ldots(4.17)$$

and $$\frac{\nu_a mN\lambda}{KT_e} = \frac{(\alpha_a/p)(E_a/p)\bar{K}p^2 mN\lambda}{eE_a/\{(3\lambda\rho)^{1/2}.N\}} \qquad \ldots(4.18)$$

and from Kihara's theory

$$\bar{K} = e/mN\lambda$$

then $$\frac{\nu_a}{KT_e/mN\lambda} = (\alpha_a/p).p^2.(3\lambda\rho)^{1/2}.\frac{N}{P} = 1/\Lambda_a^2$$

the breakdown voltage will now be given by

$$\frac{B_o P}{E_a}\left[1 + \left(\frac{C_1}{A_1 P\lambda}\right)^2\right]^{1/2} = 2\log(A_1 P\pi\Lambda_e) \qquad \ldots(4.19)$$

where

$$1/\Lambda_e^2 = 1/\Lambda^2 + 1/\Lambda_a^2 \qquad \ldots(4.20)$$

or as before neglecting $\left(\frac{C_1}{A_1 P\lambda}\right)^2$ in comparison to unity we get

$$E_a/P = \frac{B_0}{2\log(A_1 P \pi \Lambda_e)} \qquad \ldots(4.21)$$

Thus the effect of electron attachment consists in decreasing the value of effective diffusion length. The values (α_a/P) for oxygen and air have been obtained from Brown (1959) consequently $1/\Lambda_a$ and hence Λ_e can be calculated. As there is no available data for CO_2 attachment correction could not be carried out in this case. In his theory of high frequency breakdown in electron attaching gases Brown (1959) has also followed a similar treatment and as has been shown above and the effect of attachment consists in replacing the diffusion length Λ by Λ_e; so equation (4.9) can be modified and we get

$$E_a/P = \frac{B_0}{\log(A_0 P^2 \Lambda_e^2/\gamma)} \qquad \ldots(4.22)$$

Herlin and Brown (1948) by considering the effect of attachment has calculated the breakdown field as (Brown 1959)

$$\frac{\alpha}{P} = \frac{\beta}{P} + \frac{2}{3}\pi^2 \frac{V_{av}}{(E_a/P)(P\Lambda)^2} \qquad \ldots(4.23)$$

To calculate theoretically (E_a/P) for different values of $P\Lambda$ as has been done here the difficulty arises due to the fact that α/P, β/P and V_{av} are all functions of (E/P). Hence (E_a/P) can not be calculated independently of these quantities but from equation (4.22) (E_a/P) can be calculated for different values of $P\Lambda_e$ and such variation has been plotted in fig. 11, 12 and 13 in case of air, oxygen and carbondioxide.

Effect of Magnetic field.

Brown (1956) has shown that in presence of a magnetic field the diffusion coefficient can be represented in terms of the mean square displacement and if D_{xx}, D_{yy} and D_{zz} are the diffusion coefficients then

$$D_{xx} = D_{yy} = \frac{v^2 \nu_c}{3(\omega_b^2 + \nu_c^2)} \quad \text{and} \quad D_{zz} = \frac{v^2}{3\nu_c}$$

where $\omega_b = \frac{eH}{m}$, the cyclotron frequency. When the breakdown field is studied in a flat cylindrical cavity whose length is very short compared to its diameter and the magnetic field is placed transverse to the axis of the tube, most of the diffusion takes place perpendicular to the magnetic field and the breakdown field will show reduction in value. The mean square of displacement travelled by an electron is proportional to diffusion coefficient D and Brown has shown that the effective diffusion length Λ_P appropriate to infinite parallel plate will be given by

$$(\Lambda_P)^2 = \frac{\omega_b^2 + \nu_c^2}{\nu_c^2} \cdot \Lambda^2$$

$$= \left[1 + \left(\frac{eH\lambda_e}{m v_r}\right)^2\right] \cdot \Lambda^2$$

$$= \left[1 + \left(\frac{eL}{m v_r}\right)^2 H^2/p^2\right] \cdot \Lambda^2$$

denoting the constant $(eL/m v_r)^2 = C$ it reduces

$$\Lambda_P = \left[1 + C\, H^2/p^2\right]^{1/2} \cdot \Lambda \qquad \ldots(4.24)$$

Hence under the action of the transverse magnetic field the effective diffusion length increases and the breakdown field in case of a crossed electric and magnetic field is given by from equation (4.9)

$$E_H/p = \frac{B_0}{\log\left(A_0\, p^2 \Lambda_P^2/\gamma\right)} \qquad \ldots(4.25)$$

and from equation (4.13)

$$E_H/p = \frac{B_0}{2\log(A_1 p \pi \Lambda_p)} \quad \cdots (4.26)$$

The values of Λ_e and Λ_p can be calculated from equations (4.20) and (4.24) and hence the theoretical expression for E_H/p can be calculated. The values of C for Hydrogen was calculated by Blevin and Haydon (1958) and was also obtained independently by microwave measurements. C for Hydrogen was taken as 2.42×10^{-5}. The values of v_r, the random velocity have been obtained from radiofrequency conductivity measurements (Gupta and Mandal 1967), and the values of L were obtained from the values of A_0 (Townsend 1947). The values of C thus calculated are as follows.

Hydrogen	2.42×10^{-5}
Air	5.5×10^{-7}
Oxygen	2.159×10^{-7}
Carbondioxide	1.5×10^{-6}

The theoretical results calculated from the derived equations (4.25) and (4.26) have been plotted side by side in each case in the figures 10 to 13.

Hydrogen :- In fig. 10-1 it is observed that the agreement is quite satisfactory between the experimental results and theoretically calculated values of (E/p) both from Brown and Kihara's expressions throughout the range of pressure investigated. When the magnetic field is present the theoretical results indicate that the breakdown voltage becomes smaller in accordance with the experimental results obtained. The loss of electrons due to diffusion becomes smaller in presence of magnetic field and smaller voltages are necessary for breakdown. For 300 gauss and 600 gauss (figs. 10-2 , 10-3) the agreement is good for higher values of ($p\Lambda$) i.e. for higher pressure but for 900 gauss the experimental results are higher than those calculated both from the equations of Brown and Kihara for all the values of $p\Lambda$ investigated here.

Air :- Fig. 11-1 indicates that in absence of magnetic field the theoretical values calculated from Brown's expression are in better agreement with experimental results than those calculated from Kihara's expression. As in the case of hydrogen the breakdown voltages are smaller when the magnetic field is present. The values of (E/P), calculated from Brown's expression are however in better agreement with experimental results than those calculated from Kihara's theory specially for high pressure and small values of magnetic field; the disagreement becomes more and more when the pressure is low and the magnetic field is increased.

Oxygen :- Fig. 12-1 indicates good agreement between theory and experiment when no magnetic field is present. In presence of magnetic field (H = 300 gauss), (E/P) values calculatd from Brown's expression are in better agreement than those calculated from Kihara's but wide divergence is noted between the theoretical values calculated from both the equations and experimental results when the magnetid field is increased and the theory fails quantitatively to explain the results (fig. 12-3 , 12-4).

Carbondioxide :- Fig. 13-1 shows good agreement between theory and experiment when no magnetic field is present. In presence of magnetic field (H = 300 gauss and H = 600 gauss) (E/P) values calculated from Brown's expression are in better agreement with experimental results than those calculated from Kihara's theory specially for high values of pressure. Divergence is noted in case of low pressure and high values of magnetic field.

From comparison of experimental and theoretical results it can thus be concluded that in absence of magnetic field the theoretical and experimental results are consistent and diffusion is the main electron removal process. In general the results calculated from Brown's expression (equation 4.7) are in better agreement with experimental results than those calculated from

Kihara's theory. It is worth noting at this point that if in equation (4.7), the expression for electron temperature as deduced by Kihara be inserted then the expression for E/P becomes identical in both the cases. We get from equation (4.7) by putting

$$\frac{e}{KT_e} = \frac{N}{E} \cdot (3\lambda f)^{1/2}$$

$$A_o \; exp\,(-B_o P/E) \; . \; N \; P \, (3\lambda f)^{1/2} = 1/\Lambda^2$$

and according to Kihara $$A_o = \left(\frac{N}{P}\right)\left(\frac{\sigma}{c_i}\right)\left(\frac{3\lambda}{f}\right)^{1/2}$$

then $$N^2 . \frac{3\sigma\lambda}{c_i} . \Lambda^2 = exp\,(B_o P/E)$$

or $$\frac{N^2}{\pi^2} \cdot \frac{1}{P^2} \cdot \frac{3\sigma\lambda}{c_i} \cdot P^2 \pi^2 \Lambda^2 = exp\,(B_o P/E)$$

as $$A_1 = \frac{N}{\pi} \cdot \frac{1}{P} \sqrt{\frac{3\sigma\lambda}{c_i}}$$

$$A_1^2 \; P^2 \; \pi^2 . \Lambda^2 = exp\,(B_o P/E)$$

or $$E/P = \frac{B_o}{2 \log (A_1 P \pi \Lambda)} \qquad \ldots(4.27)$$

which is equivalent to equation (4.13)

Consequently the two equations become identical if a suitable expression can be deduced independently showing the variation of T_e with (E/P).

When the value of (H/P) is small and lies below 150 gauss/mm. of Hg. the theoretical values calculated are in agreement with the experimentally observed values in all the cases studied here and the agreement is better when calculated from Brown's equation but when (H/P) becomes greater than approximately 150 gauss/mm. Hg. the results are in wide divergence. To make this point clear the values of Λ_P/Λ have been calculated for each gas separately from the theoretically derived equation (4.24)

$$\Lambda_P = \Lambda \left[1 + C \; H^2/P^2\right]^{1/2}$$

for different values of (H/P) varying from 50 gauss/mm. of Hg. to 300 gauss/mm. of Hg. To examine whether the alternation in the effective value of Λ is in accordance with the theory developed, Λ_P/Λ has also been calculated from the experimental results as follows. We have from equation (4.13) and (4.26)

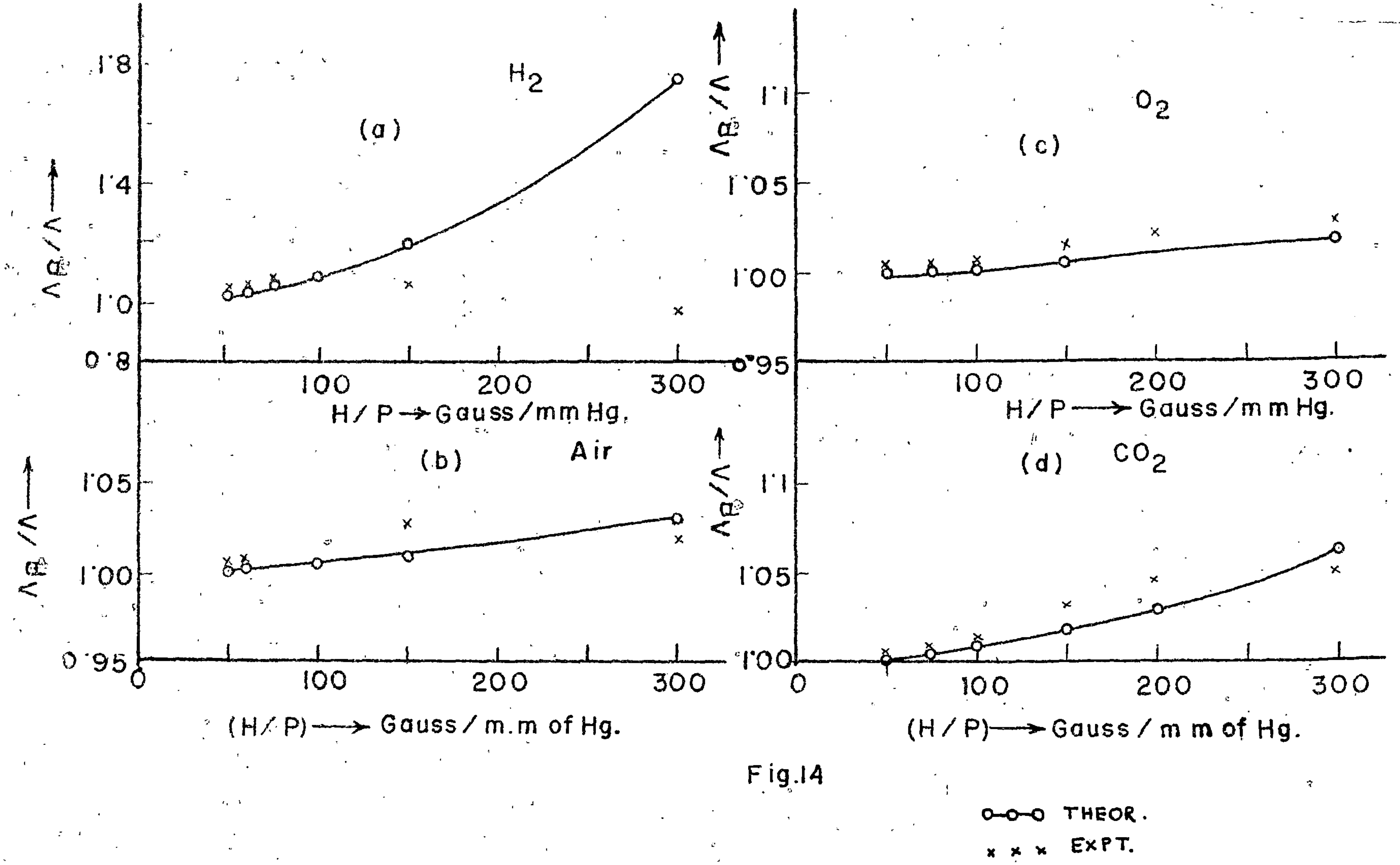
$$E/E_H = \frac{\log(A_1 P \pi \Lambda_p)}{\log(A_1 P \pi \Lambda)}$$

or

$$\Lambda_p/\Lambda = (A_1 P \pi \Lambda)^{(E/E_H - 1)} \quad ...(4.28)$$

The theoretical and experimental values of (Λ_p/Λ) for all the gases have been plotted side by side in fig. 14-a,b,c,d . It is observed that in each case the experimental values are quite close to theoretical values for (H/P) $<$ 150 gauss/m.m. of Hg. but for higher values there is wide divergence. This indicates that the concept of equivalent pressure upon which the deduction is based becomes invalid for (H/P) $>$ 150 gauss/m.m. of Hg. This fact has also been observed by Haydon (1961). In a previous paper Sen and Gupta (1964), it was also observed that the constant $C = (\frac{e}{m} \cdot \frac{L}{v_r})^2$ does not remain constant as the random velocity changes with magnetic field and hence the constant C becomes a function of the magnetic field. Further there is much uncertainty in the values of the molecular constants introduced by Kihara and this together with the uncertainty in the values of C can explain the divergence observed between the values of breakdown voltages observed in the present investigation and those calculated theoretically.

The theoretical deduction carried out above cannot be regarded as rigorous. Better agreement with experimental results can be expected if the magnetic field is introduced into Boltzman transport equation from which the energy distribution of electrons in presence of magnetic field and the rate of ionisation can be derived. However the above discussion clearly indicates that though results are better explained by Brown's theory, Kihara's molecular theory of radiofrequency breakdown can also explain satisfactorily the experimental results at least qualitatively specially for low values of magnetic field and the general



H2
(a)
1·8
1·4
1·0
0·8
Λβ/Λ
100
200
300
H / P → Gauss / mm Hg.
O2
(c)
1·1
1·05
1·00
0·95
100
200
300
H / P → Gauss / m m Hg.
Air
(b)
1·05
1·00
0·95
0
100
200
300
(H / P) → Gauss / m.m of Hg.
CO2
(d)
1·1
1·05
1·00
0
100
200
300
(H / P) → Gauss / m m of Hg.
o-o-o THEOR.
× × × EXPT.

Fig.14

equation can be conveniently modified to take into account of the phenomena of attachment and the effect of magnetic field.

REFERENCES.

Blevin H.A. and Brown S.C. (1958) Aust. J. Phys. **11** 18

Brown S.C. (1956) Hand buch der Physik Springer Verlag Berlin

Brown S.C. (1959) Basic data in Plasma Physics. Technology Press M.I.T. & John Wiley and Sons New York.

Deas H.D. and Emeleus K.G. (1949) Phil. Mag. **40** 460

Ferritti L. and Veronesi P. (1955) Nuovo Cimento **2** 639

Gupta R.N. and Mandal S.K. (1967) Ind. J. Phys. **41** 251

Herlin, M.A. and Brown, S.C. (1948) Phys. Rev. **74** 291.

Haydon S.C. (1961) Proc. Int. Cong. Ions. Phen. Gases. Munich **1** 7 763

Kihara T. (1952) Revs. Mod. Phys. **24** 43

Lax B., Allis W.P. and Brown S.C. (1950) J. App. Phys. **21** 1247

Sen S.N. and Ghosh A.K. (1963) Canad. J. Phys. **41** 1443

Sen S.N. and Gupta R.N. (1964) Ind. J. Phys. **38** 383

Sen S.N. and Bhattacharjee B. (1965) Canad. J. Phys. **43** 1543

Sen S.N. and Bhattacharjee B. (1967) Jour. Phys. Soc. (Japan) **22** 1477

Sen S.N. and Bhattacharjee B. (1966) Canad. J. Phys. **44** 3270

Townsend J.S. (1947) Electrons in Gases. Hutchinson London.

Townsend J.S. and Gill E.W.B. (1937) Phil. Mag. **26** 290

Von Engel E. (1955) Ionised Gases. Clarendon Press Oxford.

SECTION - B.

INTRODUCTION.

In continuation of the work done previously by Sen and Ghosh (1963) the breakdown of a gas excited by a radiofrequency field of frequency varying from 4 Mc/sec to 12 Mc/sec has been studied in a transverse magnetic field in case of helium, neon and argon. The breakdown of a gas in a high frequency field in presence of a magnetic field has been studied previously. Most of the previous work has been done in a resonant field, the frequency of the applied field and the magnitude of the magnetic field being such that the relation $f_{applied} = eH/2\pi mc$ was satisfied. It will be of interest to see the effect of a nonresonant magnetic field on the breakdown potential of a gas when the magnetic field is far removed from the resonance value, as regards both the value of the breakdown potential and the shift of pressure for minimum breakdown voltage. The condition for the breakdown of a gas excited by high frequency electromagnetic waves depends mainly upon factors such as the pressure of the gas, the dimension of the discharge tube and the frequency of excitation. It is well known that two dominent factors by which electrons are lost from the discharge are diffusion and mobility. It has been found that when the pressure of the gas is high and frequency of excitation is in the microwave region, the electrons are lost mainly by diffusion. The results of breakdown experiments of section A where the pressure of the gas has been maintained in the millimeter range, the dimension of the discharge tube is such that the electronic mean free path is much smaller than the length of the discharge tube and the discharge is excited by a radiofrequency voltage, show that under the circumstances diffusion is the only dominent factor for electron removal process.

This section however reports results when the pressure of the gas is of the order of a few microns and the length of the discharge tube is large compared to the mean free path of the electrons and the frequency of excitation lies in the radiofrequency region. The object of the present paper is to develop a consistant theory which can explain the observed results. Kihara (1952) starting from a molecular model has advanced a theory regarding the brakdown of a gas when it is excited by a radiofrequency field. In the r.f. field, the loss of electrons has been ascribed to diffusion and mobility of electrons. Sen and Ghosh (1963) modified Kihara's theory regarding radiofrequency discharge (1952) by the introduction of effects due to the magnetic field and deduced a new expression for the breakdown voltage and also the pressure at which the breakdown voltage becomes a minimum. To supplement the verification of the theory deduced by Sen and Ghosh (1963) previously and to extend it in case of other gases under identical conditions of breakdown in a nonresonant transverse magnetic field, the present work has been undertaken and the paper reports the results in case of helium, argon and neon when excited by a radiofrequency field of frequency varying from 4 to 12 Mc/sec and a transverse magnetic field varying from zero to 120 gauss.

EXPERIMENTAL ARRANGEMENT.

The breakdown potentials have been determined in the same way as has been done by Sen and Ghosh (1963), Gill and Von Engel (1948). The source of r.f. oscillation is a tuned plated tuned grid oscillator covering the frequency range 4 to 12 Mc/sec and the output can be varied continuously from 0 to 500 volts. The output r.m.s. voltage is measured by a vacuum tube voltmeter. The discharge tube with two outer electrodes is placed at the output of the detector and the pressure of the gas is measured by and Edward Penning Pirani vacuum gauge. The voltage from the radiofrequency source is increased gradually until a glow appears at the discharge tube and simultaneously there is an indication of a fall in voltage at the output voltmeter (internal impedance 50000 ohm/volt). This particular voltage is taken as the breakdown voltage. The pressure of the Pirani gauge is calibrated individually for each gas. The breakdown voltages have been measured in the case of pure and dry argon, neon and helium, which are spectroscopically pure samples and supplied by British Oxygen Co. Ltd. The magnetic field was provided by an electromagnet and observations were made for magnetic fields ranging from 30 to 120 gauss with the lines of force of the electromagnet at right angles both to the length of the discharge tube and to the direction of the electric field. Keeping the magnetic field constant at a particular value, the pressure of the gas has been varied and breakdown voltages determined for various values of the pressure of the gas. The same procedure has been repeated for different values of the magnetic field. The experiments have been repeated a large number of times with wide intervals and the results have been found to be consistent, the variation of "EL" was found to be within ± 2 volts, where E is the breakdown voltage per cm and L denotes the length of the tube.

RESULTS AND DISCUSSION.

The values of the breakdown potential have been plotted for various values of the pressure and for various values of the magnetic field in case of argon, neon and helium in figures 15, 16 and 17 respectively. Also the curve of breakdown voltage against pressure has been plotted in the absence of a magnetic field in the three figures for comparison. Experiments have been performed for values of H = 0, 30, 60, 90, 120 gauss. It is observed that the breakdown

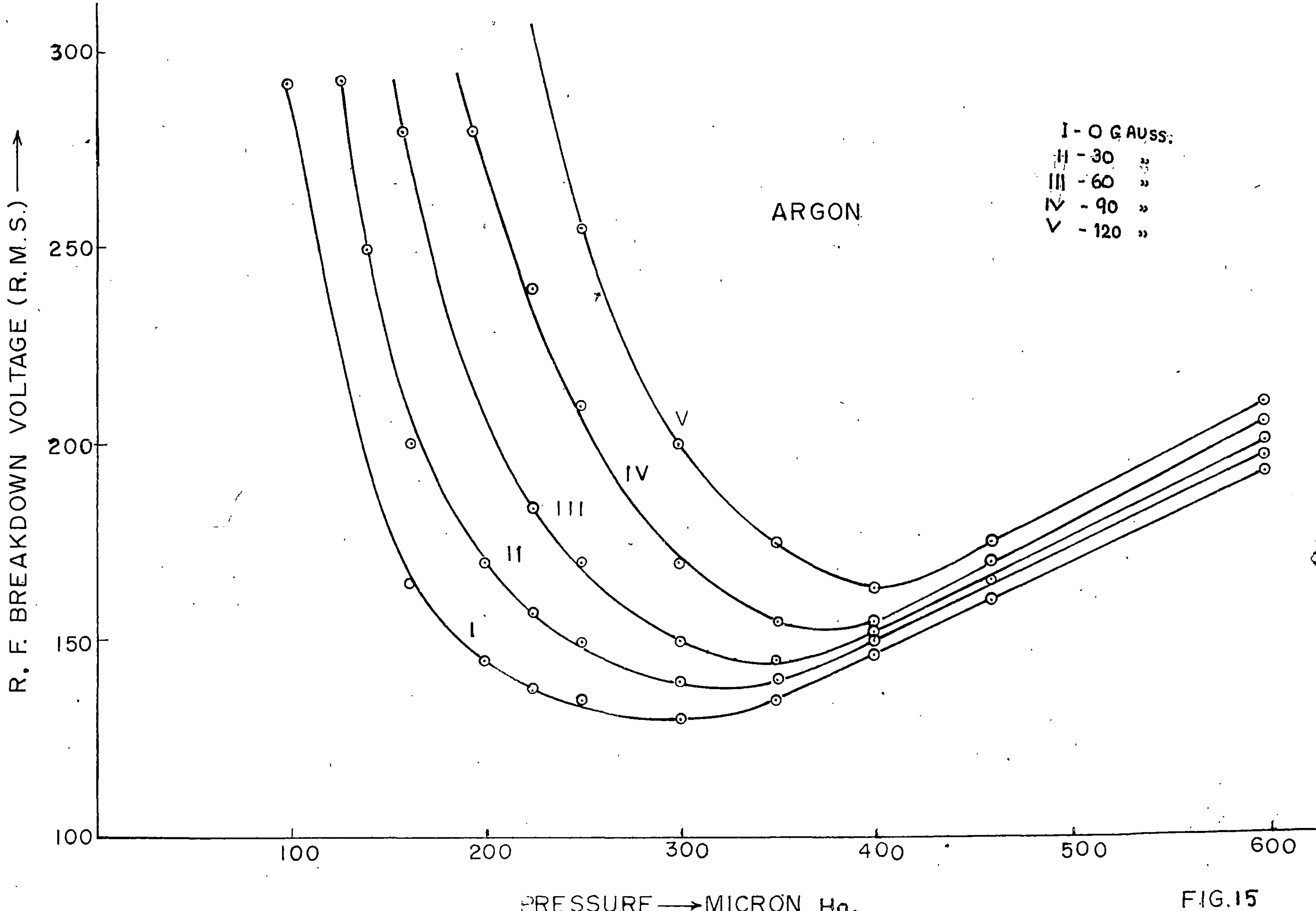
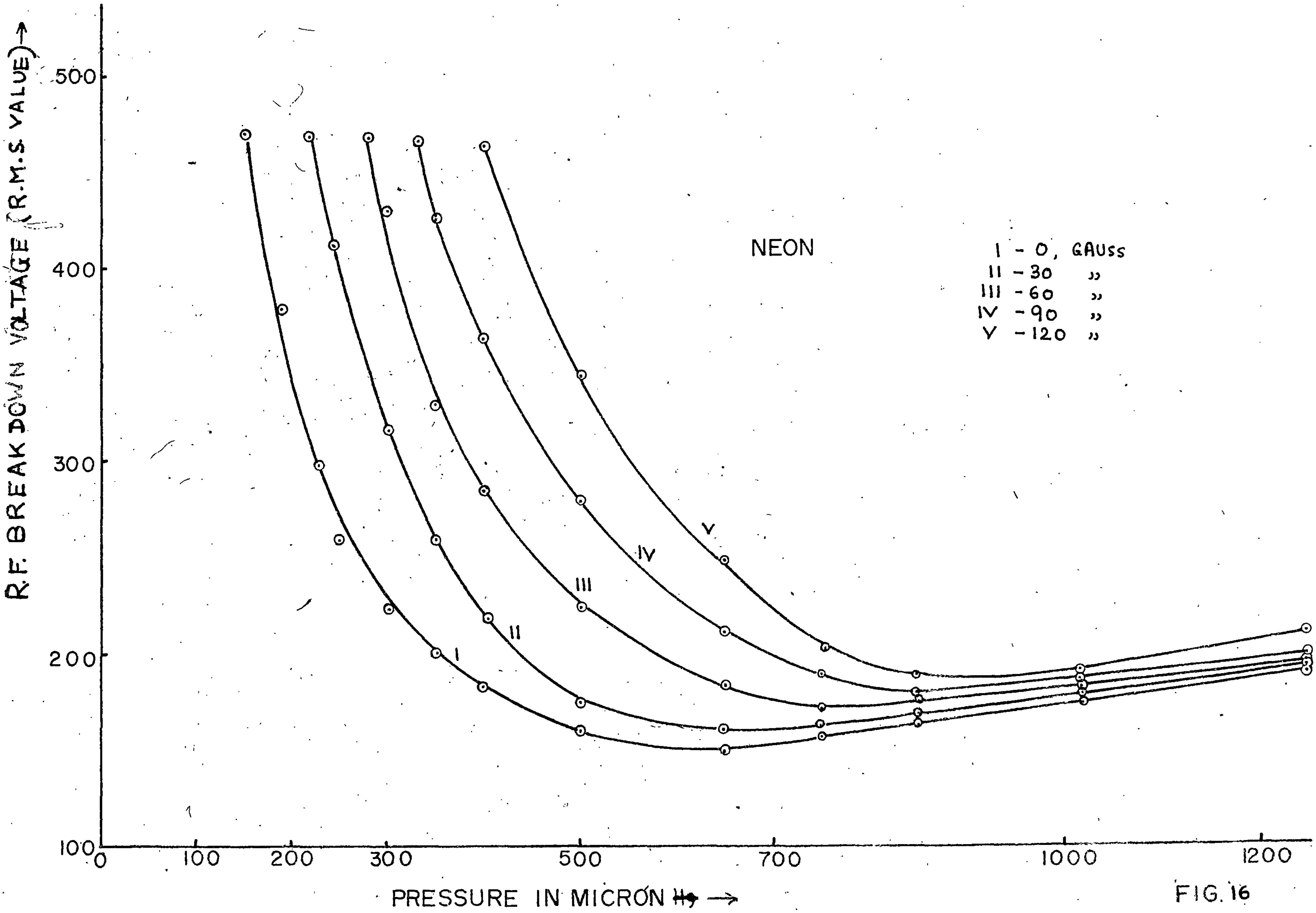

R. F. BREAKDOWN VOLTAGE (R.M.S.)
300
250
200
150
100
100
200
300
400
500
600
PRESSURE → MICRON Hg.
ARGON
I - O GAUSS.
II - 30 "
III - 60 "
IV - 90 "
V - 120 "
I
II
III
IV
V

FIG. 15



NEON
I - 0, GAUSS
II - 30 "
III - 60 "
IV - 90 "
V - 120 "
I
II
III
IV
V
R.F. BREAK DOWN VOLTAGE (R.M.S VALUE) →
500
400
300
200
100
0
100
200
300
500
700
1000
1200
PRESSURE IN MICRON Hg →

FIG. 16

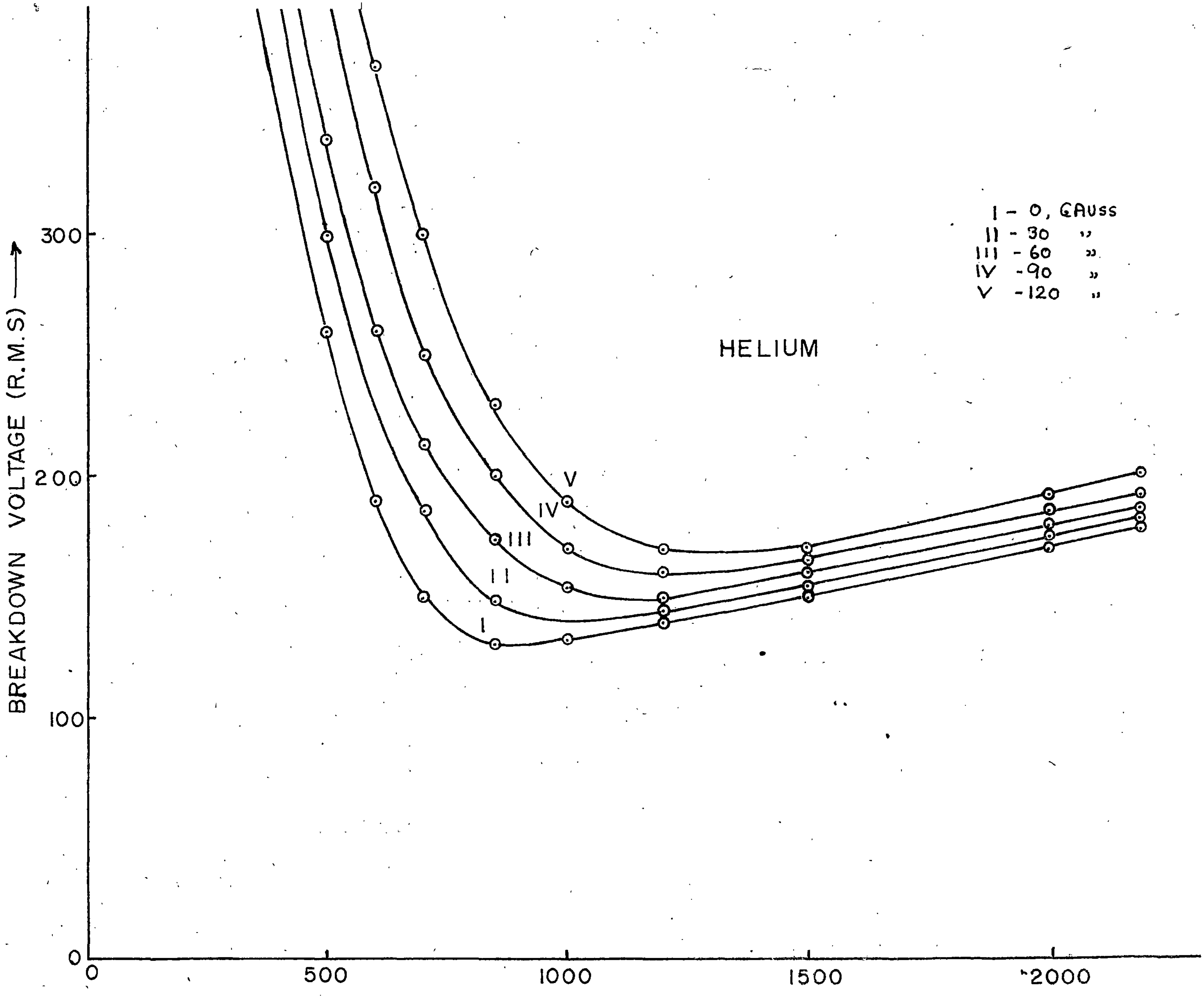

I - 0, GAUSS
II - 30 "
III - 60 "
IV - 90 "
V - 120 "
HELIUM
BREAKDOWN VOLTAGE (R.M.S) →
0
100
200
300
0
500
1000
1500
2000
PRESSURE MICRON Hg →
I
II
III
IV
V

FIG. 17

voltage always increases in presence of a magnetic field for all values of pressure and the pressure at which the breakdown voltage becomes minimum ~~always shifts~~ to higher pressure when the magnetic field is applied and this value increases with increase in the magnetic field. The experimental results are entered in Table I and II and III where E_{min} and P_{min} are minimum breakdown voltage and the corresponding pressure and $(E_H)_{min}$ and $(P_H)_{min}$ are corresponding quantities in magnetic field.

TABLE - I

Gas	Minimum breakdown voltage volts (r.m.s.)	Magnetic field in gauss	$(P_H)_{min}$ Experimental in m.m.	P_{min} & $(P_H)_{min}$ calculated from equ. (4·43) in m.m.	$(P_H)_{min}$ calc. from equn. (4·44) m.m.
	130	0	.285	.226	
	140	30	.325	.251	.252
Argon	145	60	.350	.261	.263
	155	90	.375	.292	.286
	165	120	.400	.306	.312

TABLE - II.

Gas	Minimum breakdown voltage volts (r.m.s.)	Magnetic field in gauss	$(P_H)_{min}$ Experimental in m.m.	P_{min} & $(P_H)_{min}$ calculated from equ. (4·43) in m.m.	$(P_H)_{min}$ calc. from equ. (4·44) m.m.
	150	0	.625	.595	
	160	30	.675	.651	.654
Neon	170	60	.750	.704	.710
	180	90	.850	.735	.762
	190	120	.925	.768	.812

TABLE - III.

Helium

Minimum breakdown voltage volts (r.m.s.)	Magnetic field in Gauss.	$(P_H)_{min}$ Expt. in m.m.	From the 1st set of values of the consts. given by Kihara.		From the 2nd set of values of the const. given by Kihara	
			$(P_H)_{min}$ calculated from Equn. (4·43) in m.m.	$(P_H)_{min}$ calculated from Equn. (4·44) in m.m.	$(P_H)_{min}$ calculated from Equn. (4·43) in m.m.	$(P_H)_{min}$ calculated from Equn. (4·44) in m.m.
130	0	.85	.70		.876	
140	30	1.00	.76	.763	1.08	1.17
150	60	1.10	.82	.84	1.19	1.42
160	90	1.20	.87	.91	1.30	1.69
170	120	1.35	.91	.98	1.42	1.98

To ascertain the dominent causes for electron removal process under the present experimental setup the following points can be noted.

(a) Assuming that the mean free path of the electron in the gas is given by $L' = 1/A_0$ where A_0 is the constant introduced by Townsend in his theory of electrical discharge and L' is the electronic mean free path at a pressure of 1 m.m, the values of L' can be calculated from the values of the constant A_0 given by Brown (1959).

TABLE - IV.

GAS	A_0 ionpairs cm. mm. of Hg.	L' in cm.
Argon	14	.0714
Helium	3	.3333
Neon	4	.2500

The actual values of mean free path are however much smaller as has been shown by Townsend (1947). The general range of pressure under which the present experiments have been carried out vary from a few microns to 1.5 mm. of Hg. Taking an average value of pressure as 250 μ the mean free path λ_e of the electron becomes 0.2856 cm, 1.32 cm and 1.00 cm. in case of argon, helium and neon respectively. Hence under the pressure considered the mean free path becomes much smaller than the length of the discharge tube (10 cm.).

(b) The collision frequency $\nu_c = c_i/\lambda_e$ where c_i is the random velocity and assuming an average velocity of 10^8 cm/sec. the collision frequency is nearly 10^9 cycles/sec whereas the frequency of the exciting radiofrequency field is 6.4 Mc/sec and hence the collision frequency is much larger than the applied frequency.

(c) The amplitude of oscillation of the electron is given by Brown (1956) as

$$x = \frac{e E_p}{m\omega(\nu_c^2 + \omega^2)^{1/2}} \qquad ..(4.29)$$

where E_p is the field intensity, ν_c the collision frequency and since $\nu_c \gg \omega$ the amplitude of oscillation is given by

$$x = e E_p / m \omega \nu_c \qquad ...(4.30)$$

Putting the values of E_p = 13 volts/cm, ω = 6.28 x 6.4 x 10^6 and $\nu_m = 10^9$ $x \simeq 0.52$ cm which is much smaller than the length of the discharge tube. Hence though all the electrons cannot sweep over completely across the tube and collide with the walls on every half cycle, those electrons which are very near the walls will be swept over to the walls and be lost.

Under the above conditions, the electrons make many collisions for each oscillation of the field and drift as a cloud in the field. Their motion can be described by a mobility term and as the pressure is comparatively low and exciting frequency is small in comparison with collision frequency, the above calculation shows that the amplitude of oscillation is finite and some electrons are lost due to mobility. Consequently the loss of electrons can mainly be attributed both to mobility and diffusion.

When the diffusion is the only electron removal process, the theory of breakdown has been worked out by Herlin and Brown (1948). If for the sake of argument we neglect the loss due to mobility and assume that the diffusion is the only electron removal process then according to Kihara (1952) the breakdown voltage E is given by

$$\frac{B_0 P}{E}\left[1 + \left(C_1/A_1 P \lambda_0\right)^2\right]^{1/2} = 2 \log\left(A_1 P \pi \Lambda\right) \qquad \ldots(4.31)$$

where B_0 is the constant introduced by Townsend in his theory of electrical discharge, C_1, A_1 and λ are the molecular constants introduced by Kihara and λ_0 is the wavelength of the exciting radiofrequency field. Putting the values of C_1, A_1 as given by Kihara and λ_0 and assuming $P = 200\,\mu$ the numerical value of the term $(C_1/A_1 P \lambda_0)^2$ becomes negligible in comparison to unity and the pressure at which the breakdown voltage becomes minimum can be calculated to be

$$P_{min.} = 2\, E_{min}/B_0 \qquad \ldots(4.32)$$

The values of P_{min} can be thus be calculated for the three gases and results are entered in table V where the values of B_0 have been taken from Brown (1959).

TABLE- V.

Gas	P_{min} (calc.) in m.m.	P_{min} (Expt.) in m.m.
Argon	.144	.285
Helium	.765	.85
Neon	.30	.625

Thus it is observed that there is wide divergence between theoretical and experimental values of P_{min} and it can be concluded that diffusion cannot alone account for all the losses.

Consequently in our present work Kihara's theory has been used to explain the result, because he has taken both mobility and diffusion as electron removal processes. It is noted as Kihara suggests that his theory loses its validity when $\omega/N\lambda_{0} \gg 1$ where ω is the frequency of the applied field, λ is a molecular constant introduced by Kihara the numerical values of λ for various gases has been given by Kihara and N is the number of molecules per unit volume. As the frequency employed in the experiments is of the order of 6.4 Mc/sec, the theory is not expected to hold for pressure less than 15 μ because when the values of ω, N and λ are inserted, the left hand side of the equation be comes greater than unity when P is smaller than 15 μ. Further it has been shown by Kihara that the breakdown voltage E is given by

$$\exp\left(B_0P/2E\right) = A_1PL\left[1 - \frac{E/B_0P}{C_2L/\lambda_0}\right] \qquad \ldots(4.33)$$

where B_0 is Townsend's constant and

$$A_1 = \left(N/P\pi\right)\left(3.\sigma.\lambda/c_i\right)^2$$

C_2 is another molecular constant and C_i is the random velocity of electrons, σ is equivalent to the collision cross section, and λ_0 is the wavelength of the r.f. voltage; from equation (4.33) $(P)_{min}$, the pressure at which the breakdown voltage becomes a minimum is given by

$$P_{min} = \left(2E_{min}/B_0\right)\log\left(2A_1LE/B_0\right) \qquad \ldots(4.34)$$

The values of $(P)_{min}$ have been calculated in the case of argon, neon and helium. The values of A_1 have been provided by Kihara (1952) in his paper and the results are entered into the fifth column of table I and II for argon and neon respectively and in the fourth column of table III incase of helium; the results are some what in agreement with the experimental values in case of argon and neon and the discripency can be attributed to the uncertainties in the values of the constant involved in Kihara's theory. The discrepancy is more in case of helium . It is however observed that Kihara in his paper has given two values of the constants in case of helium. If we chose the second set of values of the constants in case of helium then the results are in quite good agreement with the experimental values. The theory given by Kihara is only valid for one dimensional treatment that is when the area of the electrodes is large enough in comparison to its length. In our experimental setup the length of the discharge tube is 10 cm and radius of the electrodes is 5 cm so that the area of the electrodes becomes 78.5 sq. cm. This does not essentially justify one dimensional treatment and consequently an attempt has been made to calculate the breakdown voltage by considering both the mobility and diffusion loss in three dimensions. When a superimposed d.c. field is present in addition to exciting radiofrequency field the continuity equation is given by Vernarin and Brown (1950) as

$$\frac{dn}{dt} = \nu . n + D . \nabla^2 n - \mathrm{div} (n \bar{K} E_{DC}) \qquad ...(4.35)$$

and the breakdown condition is given by

$$\nu / D = 1/\Lambda^2 + \left(\bar{K} E_{DC} / 2D \right)^2 \qquad ...(4.36)$$

where Λ is the diffusion length of $\bar{K}$ is the mobility and D, the diffusion coefficient; the effect of the d.c. field is to increase mobility which is the same effect produced by the radiofrequency field in addition to loss due to diffusion. The effective radiofrequency field which will produce the same effect as the d.c. field is $E . \left(\nu_c^2 / \nu_c^2 + \omega^2 \right)$ and as $\nu_c >> \omega$ the effective field becomes E and the equivalent diffusion length becomes

$$\nu / D = 1/\Lambda_{eff}^2 = 1/\Lambda^2 + \left(\bar{K} E / 2D \right)^2 = 1/\Lambda^2 + \left(E / 2KT_e \right)^2 \qquad ...(4.37)$$

where T_e is the electron temperature. Putting the value of T_e as deduced by Kihara

$$KT_e = \left\{ 1/(3\lambda.\rho)^{1/2} \right\} (eE/N)$$

and

$$\nu/D = (3\sigma N^2 \lambda / c_i) \exp(-B_0 P/E)$$

we get

$$(A_1^2 P^2 \pi^2) \exp(-B_0 P/E) = (1/\Lambda^2) + (\tfrac{3}{4})(\tfrac{N}{P})^2 (\lambda.\rho.P^2) \quad \ldots (4.38)$$

and the pressure at which the breakdown voltage becomes a minimum is given by

$$(A_1^2 \pi^2/\alpha) \left[1 - B_0 P/2E \right] = \exp(B_0 P/E) \quad \ldots (4.39)$$

where α is a constant for a particular gas and is given by $\alpha = (\tfrac{3}{4})(\tfrac{N}{P})^2 \lambda.\rho$. For the values of pressure at which the breakdown voltage becomes minimum, for the three gases studied here, the left hand side becomes negative whereas the right hand side is always positive and hence the equation cannot hold and a three dimensional treatment gives negative results. Consequently though the experimental setup indicates that the three dimensional treatment is necessary the experimental results indicate that a major portion of mobility and diffusion losses take place along the axis in which the field is applied.

When the magnetic field H is applied, Sen & Ghosh (1963) modified Kihara's theory by introduction of effects due to magnetic field as regards the change of mobility and diffusion and deduced the expression for the breakdown voltage in the presence of a magnetic field as

$$\exp\left[\frac{B_0 P}{2E_H} (1 + CH^2/P^2)^{1/2} \right] = A_1 PL (1 + CH^2/P^2)^{1/2} \left[1 - \frac{E_H/B_0 P}{(C_2 L/\Lambda)(1 + CH^2/P^2)} \right] \quad \ldots (4.40)$$

and

$$\exp\left[\frac{B_0 P}{2E_H} (1 + CH^2/P^2)^{1/4} \right] = A_1 PL (1 + CH^2/P^2)^{1/4} \left[1 - \frac{E_H/B_0 P}{(C_2 L/\Lambda)(1 + CH^2/P^2)^{1/2}} \right] \quad \ldots (4.41)$$

Equation (4.40) was deduced on the expression for equivalent pressure in presence of magnetic field as given by Townsen and Gill (1937)

$$\bar{\lambda}_H / \bar{\lambda} = \frac{1}{(1 + C\,H^2/P^2)}$$

where $$C = \left(\frac{e}{m} \cdot \frac{L'}{c_i}\right)^2$$

where L' is the mean free path of the electron in the gas at a pressure of 1 m.m. whereas equation (4.41) was deduced on the expression for equivalent pressure given by Blevin & Haydon (1958)

$$\bar{\lambda}_H / \bar{\lambda} = \frac{1}{(1 + C\,H^2/P^2)^{1/2}}$$

To calculate $C = \left(\frac{e}{m} \cdot \frac{L'}{c_i}\right)^2$, L' was obtained from table IV whereas c_i was obtained from results obtained previously (Sen and Gupta 1967). The values of C have been entered in the table VI

TABLE - VI.

Gas	L'	$c_i \times 10^{-8}$ cm/sec	C
Argon	.0714	12.65	$.97 \times 10^{-6}$
Neon	.2500	13.2	1.1×10^{-5}
Helium	.3333	12.40	2.17×10^{-5}

The solution of these two equations for E, one without the magnetic field and the other with the field, cannot be performed in the usual way and hence transcendental solutions of the two equations have been obtained. Curves have been obtained for $\exp(B_0P/2E)$ against E and also for $A_1PL\left[1 - \frac{B_0P/2E}{C_2L/\Lambda}\right]$ against E, the intersection of the curves giving the values of E at the particular pressure. The results are entered in Table VII and the graphical results for this pressure are shown in fig. 18-a,b,c and 19-a,b,c.

VARIATION OF

I: $\exp(B_0P/2E)$

II: $A_1PL\left[1-\dfrac{B_0P/2E}{C_2L/\lambda}\right]$ AGAINST E

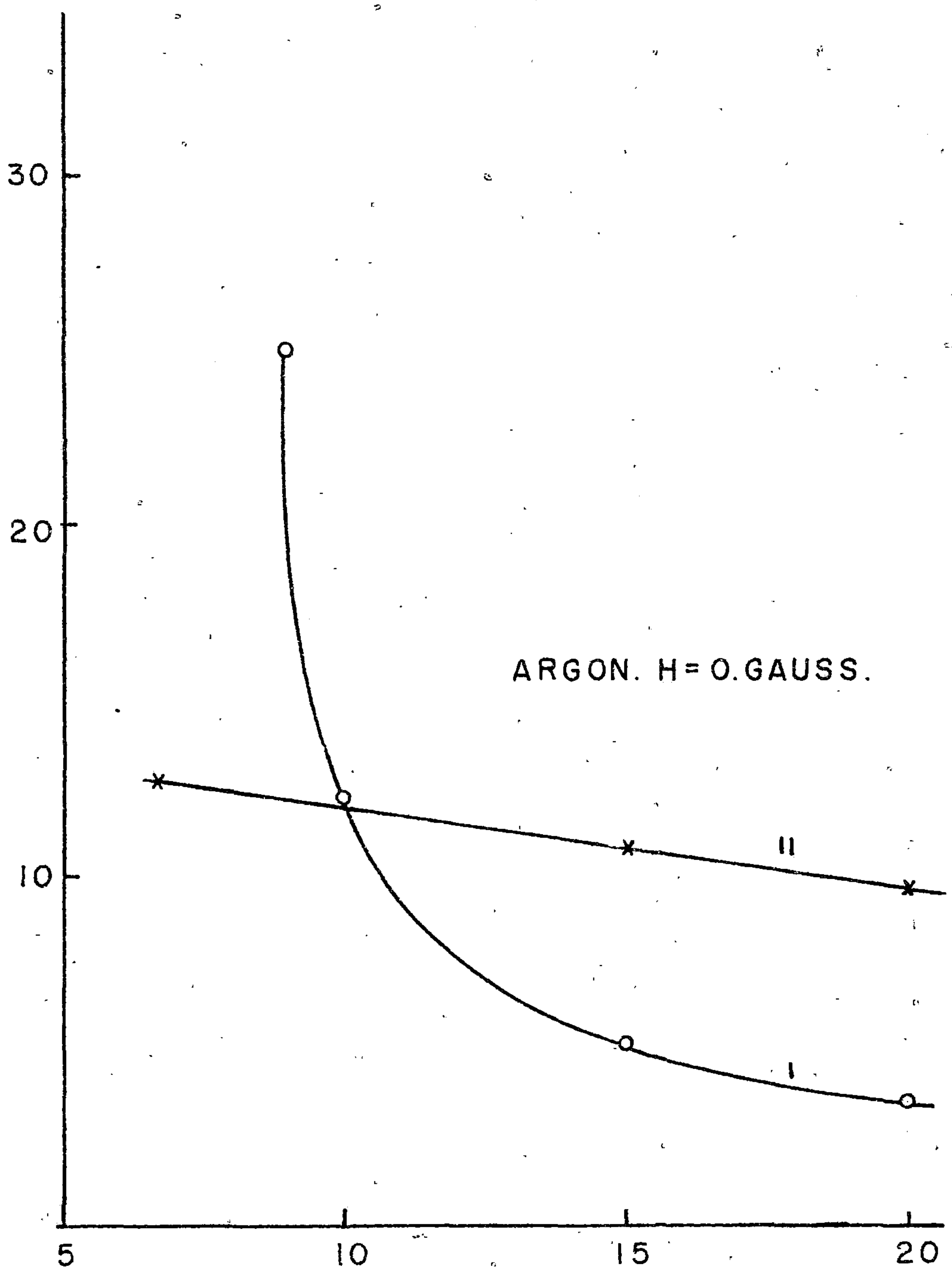
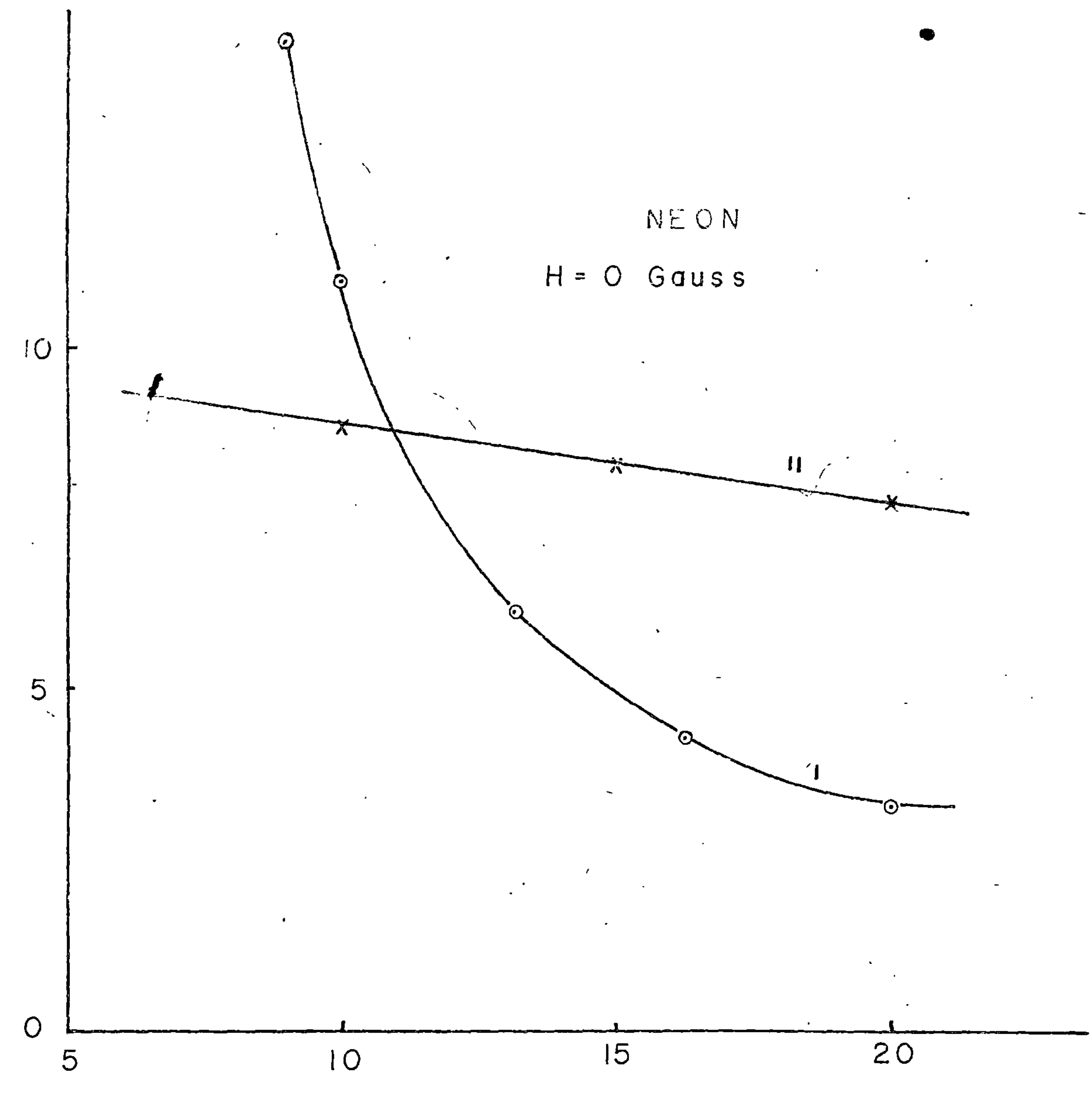


FIG-18a

VARIATION OF

I: $\exp(B_0P/2E)$

II: $A_1PL\left[1 - \frac{B_0P/2E}{C_2L/\Lambda}\right]$ AGAINST E



E Volts / Cm. ⟶

Fig. 18b

VARIATION OF

I: $\exp(B_o P/2E)$

II: $A_1 P L\left[1 - \frac{B_o P/2E}{C_2 L/\Lambda}\right]$

AGAINST E

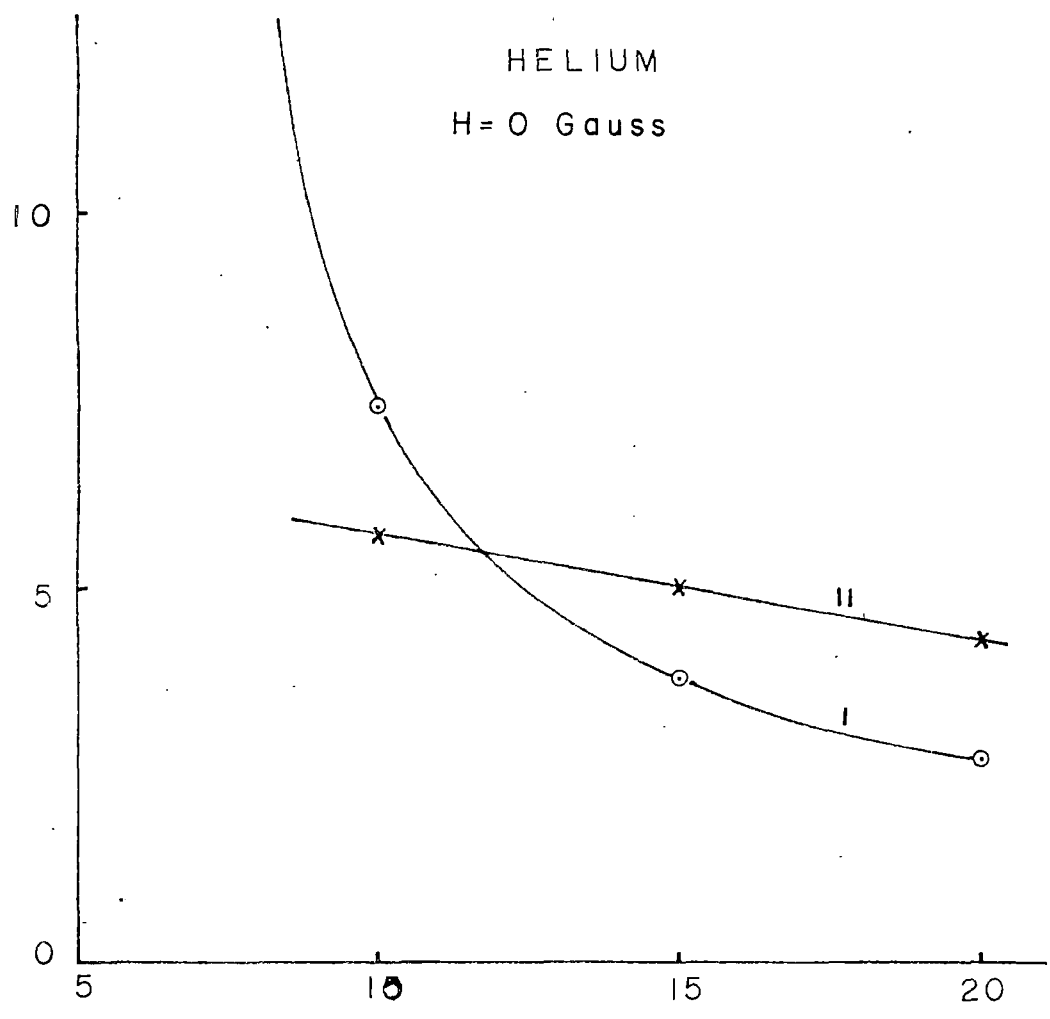


Fig.18c

VARIATION OF

I: $\exp\left[\frac{B_0 P}{2E_H}\left(1 + CH^2/P^2\right)^{1/2}\right]$

II: $A_1 PL\left(1 + CH^2/P^2\right)^{1/2}\left[1 - \frac{E_H/B_0 P}{(C_2 L/\Lambda)\left(1 + CH^2/P^2\right)}\right]$

AGAINST E

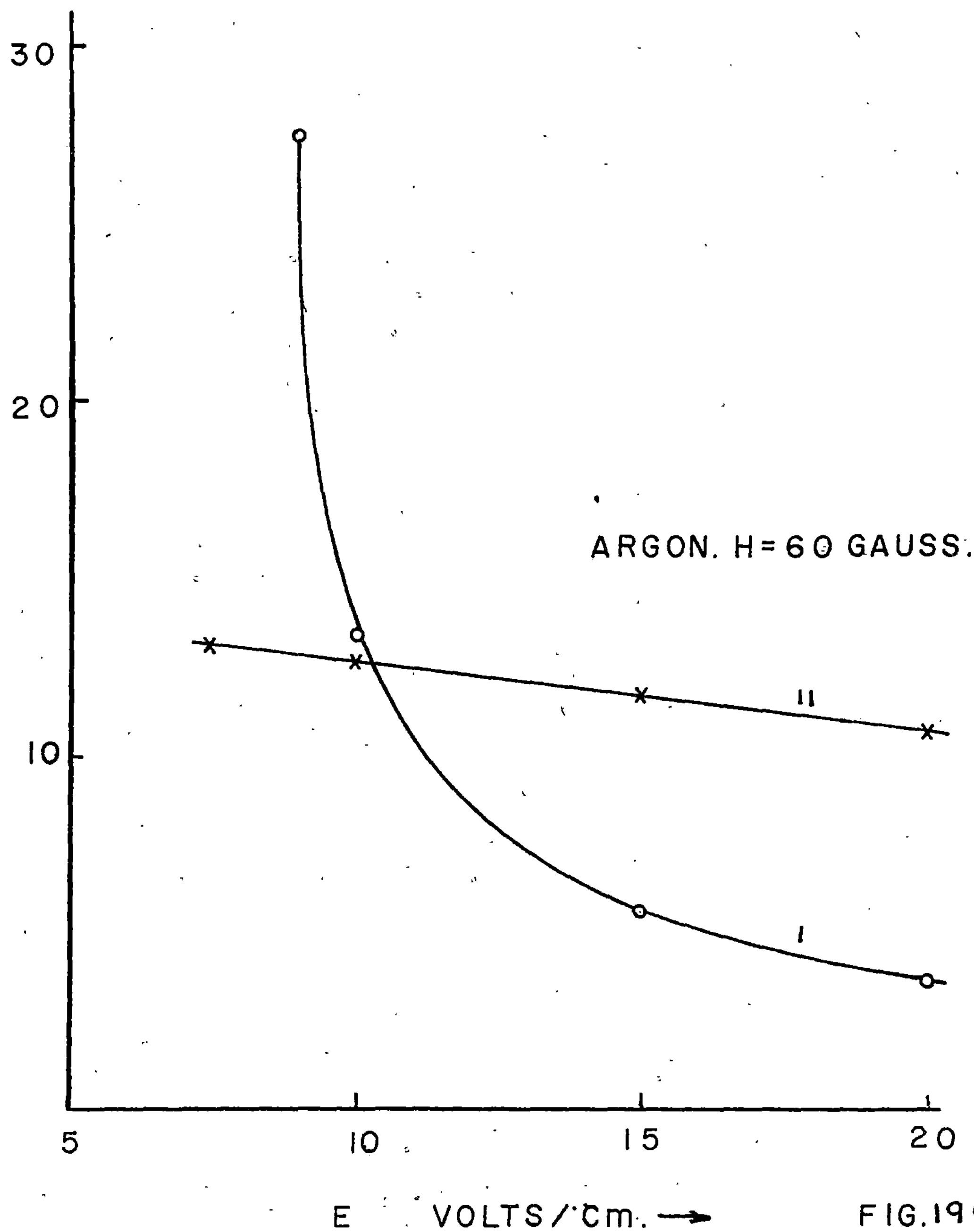


FIG.19α

VARIATION OF

$$I : \exp\left[\frac{B_0 P}{2E_H}\left(1 + C H^2/P^2\right)^{1/2}\right]$$

$$II : A_1 P L \left(1 + C H^2/P^2\right)^{1/2}\left[1 - \frac{E_H/B_0 P}{\left(C_2 L/\Lambda\right)\left(1 + C H^2/P^2\right)}\right]$$

AGAINST E

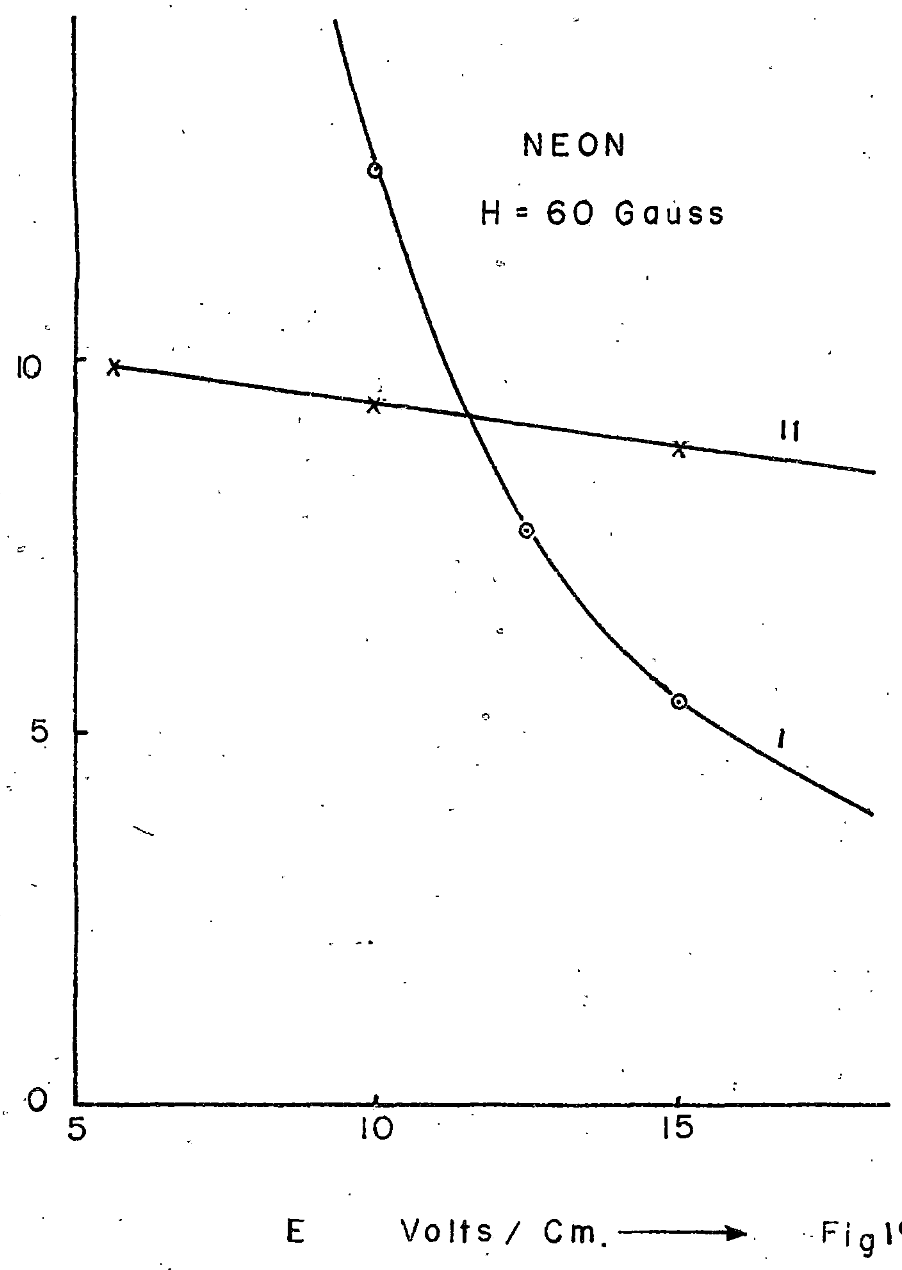


Fig 19b

TABLE - VII.

Mag. field. Gauss	NEON		HELIUM		ARGON	
	E volts/cm Theoretical	E volts/cm Experimental	E volts/cm Theoretical	E volts/cm Experimental	E volts/cm Theoretical	E volts/cm Experimental
0	10.9	13.6	11.6	11.8	10.05	11.81
30	11.2	14.5	11.8	12.7	10.25	12.7
60	11.5	15.4	12.15	13.6	10.4	13.1
90	11.9	16.3	12.6	14.5	10.75	14.0
120	12.4	17.2	13.2	15.4	11.2	15.0

The same procedure has been adopted for the case when there is a magnetic field and curves obtained from equation (4.40). It is noted that agreement is quite satisfactory, and shows that the breakdown voltage is always higher when the magnetic field is present than that without a field. Similar calculations have also been carried out for other values of pressure and it is found that the breakdown voltage is always higher than when no magnetic field is present. The agreement is satisfactory not only from the qualitative point of view but it is also quite good quantitatively, considering the approximations involved. The same result was observed earlier in case of other gases by Sen & Ghosh (1963), Townsend & Gill (1937). The value of the pressure at which the breakdown voltage becomes minimum is obtained from equation (4.40) by the condition

$$\partial E_H / \partial P = 0$$

$$\therefore \exp\left[\frac{B_0 (P_H)_{min}}{2(E_H)_{min}}\left\{1 + CH^2/p^2\right\}^{1/2}\right]\frac{B_0}{2(E_H)_{min}} = A_1 L - \frac{A_1 (E_H)_{min} \Lambda}{C_2 B_0 P^3} \cdot \frac{CH^2}{(1+CH^2/p^2)}$$

.... (4.42)

The second term on the r.h.s. of the expression has been computed and its numerical value has been found to be negligibly small in comparison with other terms. Hence

$$(P_H)^2_{min} = \frac{4(E_H)^2_{min}}{B_0}\left[\log \frac{2(E_H)_{min} A_1 L}{B_0}\right]^2 - CH^2$$

...(4.43)

and in the same way we can obtained from equation (4.41) the pressure at which the breakdown voltage becomes minimum i.e. $(P_H)_{min}$ which is given by

$$(P_H)^4_{min} + CH^2 (P_H)^2_{min} - \left[\frac{2(E_H)_{min}}{B_0} \log \frac{2(E_H)_{min} A_1 L}{B_0}\right]^4 = 0$$

...(4.44)

The values of $(P_H)_{min}$ have been calculated from both equation (4.43) & (4.44) and the results entered into Table I, II & III for different values of the magnetic field. From a comparison of these results with the observed experimental values it is noted that both the equations predict a shift of pressure towards higher values than that in the absence of a magnetic field though the quantitative agreement is not very satisfactory; further in case of argon and neon for higher values of magnetic field equation (4.44) gives better values then equation (4.43) in comparison with experimental results. In case of helium we get two sets of values corresponding to two sets of constants given by Kihara and the results corresponding to the second set are more satisfactory than the results obtained from the 1st set of constants in comparison with the experimental results. In the second set we find equation (4.43) gives better values than equation (4.44) for higher values of magnetic field.

It is further observed that in case of all the three gases the disagreement with the experimental results is more in case of magnetic field greater than 90 gauss. This is to be expected because as has been shown earlier (Sen and Ghosh 1960 , Gupta and Mandal 1967) that the equivalent pressure concept is valid for a limited range of pressure and magnetic field and specially for magnetic field less than 100 gauss. Besides, the theoretical deductions of Townsend and Gill that

$$D_H = \frac{D}{1 + \omega_H^2 \tau^2} \quad \text{and} \quad \bar{K}_H = \frac{\bar{K}}{1 + \omega_H^2 \tau^2}$$

where $\bar{K}_H$ is the mobility coefficient and D_H the diffusion coefficient in presence of magnetic field are also valid for a limited ranges of pressure and magnetic field. The question as to whether D_H varies inversely as ω_H^2 or ω_H has not yet been settled beyond doubt (Hok 1962). As has been pointed out earlier the discrepancy between the theoretical and experimental results is to be partly attributed to the inaccuracy of the molecular constants introduced by Kihara in his theory. Particular reference should be made to the values of the constants for helium in which case two sets of values have been given by Kihara and as has been shown above, if calculation is made with one set of values much better agreement is obtained with experimental results than that calculated from the other set. In fact it is one of the main draw-backs from which the theory suffers. The value of the constant C has been calculated in an indirect way and there is no alternative method to test its accuracy. Further it has been shown by Sen and Gupta (1964) that the value cannot be regarded as constant but varies with the magnetic field and it becomes a function of (H / P). This variation of C with (H / P) may also account to a certain extent the discrepancy between the theoretical and experimental results for higher values of magnetic field.

Thus it can be concluded that within certain limitations, Kihara's theory of radiofrequency discharge can explain quite satisfactorily the observed experimental results. When magnetic field is applied, the theory put forward by Sen & Ghosh (1963) by modifying Kihara's theory can explain not only the increase of breakdown voltage quantitatively but predicts quite well the shift of pressure for minimum breakdown voltage and this paper shows that the theoretical results are quite general as the experimental results are explained satisfactorily not only in the case of molecular gases but in the case of inert gases also.

REFERENCES.

1. Brown, S.C. (1956), Hand buch der. Physik. Springer, Verlag Berlin.
2. Brown, S.C. (1959), Basic data in Plasma Physics (Technology Press, M.I.T. and John Wiley and Sons)
3. Blevin, H.A. and Haydon, S.C. (1958) Aust. J. Phys. 11 18
4. Gill, E.W.B. and Von Engel, A. (1948), Proc. Roy. Soc. (London) A 192, 446
5. Gupta, R.N. and Mandal, S.K. (1967) Ind. J. Phys. 41, 251
6. Moh, F.C. (1962) Revs. Mod. Phys. 34, 267.
7. Herlin, M.A. and Brown, S.C. (1948), Phys. Rev. 74, 291
8. Kihara, T. (1952), Revs. Mod. Phys. 24, 43
9. Sen, S.N. and Ghosh, A.K. (1963), Canad. J. Phys. 41, 1443
10. Sen, S.N. and Gupta, R.N. (1967), Ind. J. Phys. (in press)
11. Sen, S.N. and Ghosh, A.K. (1962), Ind. J. Phys. 35, 101
12. Sen, S.N. and Gupta, R.N. (1964) Ind. J. Phys. 38, 383
13. Townsend, J.S. (1947), Electrons in gases, Hutchinson London.
14. Townsend, J.S. and Gill, E.W.B. (1937), Phil Mag. 26, 290.
15. Vernerin, L.J. and Brown, S.C. (1950), Phys. Rev. 79, 946.