STUDIES
ON
BREAKDOWN PHENOMENA IN GASES
AND ALLIED PROBLEMS

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INTRODUCTION

The subject of electrical discharge phenomena has been studied for a very long time and may be said to have given birth to the atomic age. The subject, however, is far from being exhausted and several aspects of the phenomena have received intensive attention in recent years and significant progress has been made. However, much more investigation is necessary to understand completely the phenomena of dielectric breakdown of gases, specially by radiofrequency electric field, a phenomena which has drawn attention currently, as it serves as a link between discharge phenomena initiated by pure d.c. electric field and very high frequency electric field (microwave). The object of the present work is to study some of the salient features of discharge phenomena initiated by r.f. electric field and the study includes the following aspects.

(a) Dielectric breakdown by r.f. electric field of attaching and nonattaching gases at high pressure (a few mm. Hg.) and low pressure (micron Hg.) and the effect on breakdown property of external d.c. magnetic field when applied transverse to r.f. field.

(b) Effect of superimposed low and high external d.c. electric field on the r.f. breakdown property of gases when external d.c. and r.f. fields are parallel.

(c) Breakdown of gases at very low pressure ($1.5/\mu$ Hg.) by r.f. field and the effects of external d.c. magnetic field when applied transverse to r.f. electric field.

(d) Effect of d.c. magnetic field on the optical radiation property of a discharge column excited by r.f. electric field, when the magnetic field is applied perpendicular to the column.

CHAPTER - I

REVIEW OF PREVIOUS WORKS.

(A) RADIOFREQUENCY BREAKDOWN OF GASES.

(a) Without magnetic field (b) With magnetic field.

The mechanism of the breakdown of gases for an alternating voltage at 50 cycles/sec is substantially the same as that for d.c. voltage. However, under the influence of a high frequency alternating field, free electrons in a gas may acquire energies sufficient to excite and to ionise the neutral gas molecules. When the field is sufficiently large, the ionisation process is cumulative and the gas breaks down into a luminous glow discharge. The exciting field may be applied directly by electrodes connected to the source of high frequency potential. Alternatively the gas may be excited by a h.f. current flowing in a nearby conductor. The first type of discharge is called E- discharge and second type H- discharge. The mechanism of E and H discharges are fundamentally the same and division into two types is justified only when the wavelength of the exciting voltage is large compared with the linear dimension of the discharge tube. Comparatively little study has been made of H-discharge. The reason is probably to be found in the difficulties experienced in making precise measurements as the path of the discharge current is closed and there are no electrodes between which current and p.d. may be measured. The breakdown mechanism in E-discharge and the magnitude of the breakdown voltage V_s of a gaseous discharge in an a.c. field depend upon the nature and the pressure of the gas, the frequency of the applied field and the linear dimension of the discharge tube. The general characteristics of the breakdown curves have been studied by many workers and it has been reviewed by Darrow (1932, 1933). One of the earliest workers, Thomson (1930, 1934) enunciated two conditions for breakdown in a high frequency field. Assuming the electron under the influence of an a.c. field, the first criterion was that in time "t" the electron must acquire sufficient energy from the field so that the energy is either equal or greater than the ionisation energy of the gas; consequently the first condition states that

$$\frac{1}{2} m \left[\frac{E}{\omega} \frac{e}{m} \sin \omega t \right]^2 \geq e V_i$$

where V_i = ionisation potential of the gas. The second condition was that the distance traversed by the electron in time "t" must be either equal to or smaller than the mean free path

of the electron in the gas.

Hence

$$\frac{E}{\omega^2}\frac{e}{m}\cdot(1-\cos\omega t) \geq \lambda e$$

Combining these two conditions he obtained an equation for the breakdown voltage which is a function of pressure and frequency and shows that at a certain pressure the breakdown voltage becomes a minimum. Thomson (1937) next studied the sterting potential for hydrogen within the pressure range (0.25 mm to 9.5 mm) and for frequency 1.8 Mc/s to 99 Mc/s. In case of lower frequency (below 2.83 Mc/s) he obtained double minima and above this frequency single minimum . Double minima was also observed by Guttons (1928) who concluded that these were due to resonance phenomena in the gas; Gill and Donaldson (1931) found that the double minima disappeared if the discharges were away from the walls of the tube. To explain this, Thomson (1937) attempted to modify his theory. In order that a typical electron may acquire the maximum energy at a time, it is assumed that the electron begins to move at a time $t=0$ when the electric field is E $\cos(-\phi)$. Then the ionising velocity will be most quickly attained if it is acquired in a time t_1 such that the electric field at time t_1 is E $\cos(+\phi)$, for under this condition

$$\int_0^{t_1} \cos(2\pi f t - \phi).dt$$

is a maximum.

Gill and Donaldson (1931) showed that when the excitation was by a field at right angles to the long axis of the tube, double minima appear and when the field was along the axis one minimum (that at higher pressure) disappeared.

The explanation is seen by considering a cloud of electrons oscillating in the gas under the influence of the field. At a fixed pressure, as the field is increased the rate of ionisation increases and when this is just greater than the rate of loss, due mainly to diffusion, the glow appears. Now if the pressure is reduced the electrons acquire more energy from the field owing to their increased free path and the critical force required for breakdown is less. However as the

pressure is reduced the amplitude of oscillation of the electron also increases and when this becomes of the same order as the distance apart of the walls, rate of loss of electrons increases rapidly and the breakdown voltage is increased. The calculations of Gill and Donaldson relating to their conditions of experiments are in agreement with their views.

Breakdown in hydrogen for frequencies 5 to 11 Mc/s for pxd = 0.2 to 30 mm. cm. of Hg. was studied by Githens (1940) who attempted to correlate the appearance of the minima of (V_s , pxd) curves with the position of the walls of the discharge tube relative to the electrodes. He concluded that the breakdown of the h.f. discharge occured through three different process which he denoted by modes, a,b,c, each of which gave rise to a minimum in (V_s , pxd) curve. Similar results were observed by Pim (1948, 1949) using small gaps in air at pressures from 59 mm to 764 mm for frequencies ranging from 100 Mc/s to 300 Mc/s .

Hale (1948) tried to explain his measurements in argon and xenon over the range of frequencies 5 Mc/s to 50 Mc/s and at gas pressure 20-50 microns by assuming that the breakdown potential for h.f. field is determined by those electrons in the gas which succeed in acquiring ionising energy in one mean free path; there is considerable divergence of the theoretically calculated breakdown voltage with experimental results in case of lower frequencies. The value of the mean free path of the electron used was that given by Kinetic theory which can hardly be correct. As is known, the mean free path of the electron varies with the energy of the electron and as the energy of the electron varies between zero and ionising energy what is needed is an effective mean free path. Also the assumption that the probability of ionisation becomes a maximum when the electron acquires the ionising energy is not supported by experimental results because it has been shown by Smith (1930) that efficiency of ionisation increases quite rapidly with increasing electron energies slightly above the ionising energy.

The extent of the influence of the discharge in the walls and electrodes upon breakdown mechanism depends upon the relative magnitudes of p,f and d where p is the pressure f is the frequency and d is the electrode separation. Llewellyn Jones and Morgan (1951) showed that when "f" and "p" are sufficiently high the amplitude of motion of the electron cloud is small, and it can be much less than the linear dimensions of the discharge tube; V_s is independent of the nature of electrode surface and secondary electron production at the electrode surfaces does not appear to play important part. However at very low pressure, experiments of Gill and Von Engel (1948, 1949) and also those of Chenot (1948) show that a discharge can be started, provided the frequency is greater than a critical value, at quite a low potential which is independent of the pressure of the gas. In this case Gill and Von Engel have assumed that a single electron strikes the opposite glass surface and releases the secondary electrons which move in phase with the applied electric field and releases further electrons from the walls.

Applicability of similarity principle in h.f. discharge has been studied by Llewellyn Jones (1951, 1953) and his co-workers. Townsend and Williams (1958) studied the breakdown condition in air and hydrogen using a pair of geometrically similar electrode system and measurements were made for values of $p \times d$ = 15 mm. cm. of Hg. and frequency 5Mc/sec. to 70 Mc/sec. For f = 10 Mc/s or more, double minima appeared. The first minimum was not very sensitive to change of frequency but the second minimum moved to higher values of V_s and "P" as the frequency is decreased. The similarity theorem was found to be obeyed within the frequency range investigated. They have concluded that the multiple minima in (V_s , p.d) curves at high frequency can be interpreted on the basis of a single breakdown mechanism involving electron generation by collision with gas molecule and loss by diffusion and drift to the electrodes and to the walls of the discharge tube.

The first published results for breakdown in ultra high frequency region, appear to be those of Cooper (1947) who made measurements of the breakdown in air in

co-axial lines and wave guides for gaps between 0.1 and 0.3 cm. at gas pressure 20-760 mm. At the two wavelengths (10.7 cm. and 3.1 cm) and the breakdown gradient was found to be 70% of the d.c. breakdown value. Similar measurements were made by Posin (1943) who found that for 3 cm. wave, breakdown voltage for a 0.043 cm. gap in air under atmospheric condition is substantially independent of pulse duration provided that duration exceeds 4 secs. The nature of spark mechanism in a cavity resonator at these wavelengths has been studied by Prowse and Cooper (1948) and by Prowse and Jasinski (1949) using photographic and spectroscopic methods.

Series of investigations on microwave breakdown in gases in cylindrical cavities and between co-axial cylinders at a wavelength of 9.6 cm. have been made by S.C.Brown and his colleagues (1948, 1949, 1954, 1956). The gaps studied range from 0.06 to 7.6 cm. in air at pressures from 0.1 to 100 mm. Hg. The results are discussed in terms of a new theory for ultra high frequency breakdown, which is based on the criterion that at the point of breakdown ionisation rate equals the rate of loss due to diffusion. Other processes of removal of electrons, such as attachment and recombination, are considered to be negligible for the type of the discharges studied; when the gap length is small compared with the wavelength, the electron mean free path and the amplitude of oscillation, the breakdown condition is obtained from consideration of the continuity equations for electrons as

$$\frac{\partial n}{\partial t} = \nu n - \nabla \Gamma \qquad \ldots(1.1)$$

when "n" is the electron density, ν is the net production rate of electrons per electron and denotes the difference between the ionisation rate and the attachment rate. Γ represents the electron current density lost to the walls by diffusion. The threshold for breakdown is considered to occur when $\frac{\partial n}{\partial t}$ goes through zero. The breakdown is then the characteristic value of the electric field obtained from the solution of the equation

$$\nu n - \nabla \Gamma = 0 \qquad \ldots(1.2)$$

with the boundary condition that the electron density vanishes at the cavity surface. A high frequency ionisation coefficient can be defined as

$$f = \nu / DE^2 \qquad \ldots(1.3)$$

where D = diffusion coefficient.

Values of f have been calculated by Brown and others from their breakdown measurements under parallel plate condition in cylindrical cavity and are expressed as function of E/P and $P\lambda$ where λ is the wavelength. The data are then used to calculate breakdown voltage in air between co-axial cylinders and results are found to be in close agreement with the experimentally determined values. If the applied frequency is greater than the frequency of inelastic collision and less than the frequency of elastic collision, Holstein (1946) showed that the energy distribution of electrons in a h.f. field is closely the same as that of electrons in a static field equal in magnitude to the r.m.s. value of h.f. field. Holstein deduced the breakdown condition that the rate of production of electron by ionisation must exceed the rate of loss due to diffusion for non attaching gases. In case of a uniform field between parallel plates the calculated relation between the breakdown gradient E, the gap length " d " and the gas pressure " p " is

$$(pd)^2 = \frac{\pi^2 KTe}{e(E/p)\alpha/p} \qquad \ldots(1.4)$$

α is the Townsend's first ionisation coefficient.

In a series of theoretical papers on h.f. discharge, Margenau and Hartman (1948) have discussed methods for determining the electron energy distribution and have shown how such functions can be used in the calculation of the breakdown fields on the assumption that the only mechanism for electron removal is recombination with positive ions. The calculated values are appreciably lower than the measured values and the discrepancy is explained by the consideration that electron must also be removed by other mechanism.

Kihara (1952) assuming a proper model for collission processes in the molecular kinetic theory of electrical discharge and modifying the Boltzman's transport equation obtained expressions for the fundamental parameters involved in the discharge phenomena of gases. Dividing the whole problem into different parts Kihara obtained absolute expression for mobility coefficient, diffusion coefficient and electron temperature in terms of some molecular constants and some measurable parameters. The process by which these molecular constants for different gases and vapours are to be calculated have also been provided. Starting from Boltzman distribution of charged particles in a gas with uniform temperature and pressure and nonuniform density and applied external electric field, Kihara (1952) also obtained the well known relation $\left[\text{diffusion coefficient} = \frac{KT_e}{e} \cdot \text{mobility}\right]$ where T_e = electron temperature and K the Boltzman constant.

Assuming that the coefficient of elastic scattering between gas molecules and electron or ion as inversely proportional to the relative speed between the colliding particles an expression for the difference of gas temperature and electron temperature in terms of applied field and frequency has been obtained by Kihara. Extending this idea, the mobility coefficient of electron in gases is given by

$$\bar{K} = e/m N \lambda \qquad \ldots(1.5)$$

where

N = number of molecules per c.c. and λ is a molecular constant introduced by Kihara in this theory (dimension cm^3/sec). Kihara accounted for the excitation by electron with the help of model giving cross-section of excitation as $Q(C_0, C) = \beta C^3/C_0^2$ i.e. which involves a process such that the speeds of electrons decrease from C_0 to values below C because of inelastic collisions. Here β is a molecular model constant with the dimension of area divided by velocity. According to this model the total cross-section $Q(C_0, C_0) = \beta C_0$ is proportional to the speed of colliding electrons.

For high frequency field, the electron temperature is obtained as

$$KTe = \left(1 + \frac{\omega^2}{N^2\lambda^2}\right)^{-1/2} \cdot \frac{1}{(3\lambda P)^{1/2}} \cdot \frac{e E_0}{N\sqrt{2}}$$

and the dielectric constant

$$\epsilon = 1 - \omega_0^2/(\omega^2 - j\omega N\lambda)$$

The process of ionisation by collision with electron was explained assuming a model cross-section

$$Q = \begin{cases} \sigma (c^2 - c_i^2)^{3/2}/c_i c^2 & (c > c_i) \\ 0 & (c < c_i) \end{cases}$$

where σ is a molecular constant with the dimension of area and c_i corresponds to electron velocity at first ionisation potential. Since a few electrons with exceptionally large energies usually take the main part of ionisation, Kihara considered that the velocity distribution of electrons is not disturbed by the ionisation process so that it can be taken as Maxwellian. From this reasoning he obtained the expression for the first Townsend coefficient α as

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

where $A_0 = \frac{N}{P} \cdot \frac{\sigma}{c_i} \cdot \left(\frac{3\lambda}{P}\right)^{1/2}$ and $B_0 = \frac{N}{P} \cdot \frac{m c_i^2}{2e} \cdot (3\lambda P)^{1/2}$

When the gas is excited by microwaves and the pressure is high the loss of electrons is generally attributed to diffusion but in case of excitations by radiofrequencies the loss is due both to mobility and diffusion and the continuity equation in one dimensional treatment is given by

$$\frac{\partial n}{\partial t} = \nu n + D \cdot \frac{\partial^2 n}{\partial z^2} - \left[\bar{K} E_0 \cos \omega t\right] \frac{\partial n}{\partial z}$$

where $\bar{K}$ is the mobility coefficient of electron. The breakdown condition for r.f. discharge is

$$\frac{1}{\pi^2}\left(L - 2\bar{K} E_0/\omega\right)\frac{\nu}{D} = 1$$

which in explicit form can be written, on the assumption that electron's velocity distribution is Maxwellian, as

$$\exp(B_0P/2E) = A_1PL\left(1 - \frac{E/B_0P}{C_2L/\Lambda}\right) \quad \ldots(1.6)$$

where A_1 and C_2 are two derived molecular constants introduced by Kihara. Λ is the wavelength of the applied r.f. field. This theoretical expression is in agreement with the experimental observations upto a certain limited range. Taillet and Brunet (1965) in their conference paper investigated the Physical mechanism of high frequency discharges maintained by resonance. It was concluded that when a radiofrequency discharge is excited with a frequency $\omega/2\pi$ higher than the collision frequency ν, a resonance due to the dispersive properties of the plasma can control the steady state of the discharge and determine the value of the electron density for a given geometry and frequency.

Besides the two general type of loss of electrons in high frequency discharge namely mobility and diffusion, there may be a third type of loss mechanism which becomes very prominent in case of certain gases. This is the loss by formation of negative ion. Negative ions appear in gases under two circumstances, (a) they may be created in the gas largely through attachment of free electrons to atoms and molecules and rarely by dissociation of molecules in a polar phase by electron impact, (b) they may be introduced in the gas by interaction of fast particles of atomic mass with surfaces or by liberation from hot surfaces. Attachment of electrons causes loss of the former as ionising agents and leads to delayed and undesirable electronic ionising events in asymmetrical field breakdown. It may further act to increase the rate of loss of carriers by recombination.

This loss of electron by attachment is a very predominant factor in case of certain types of gas e.g. O_2, CO_2, So_2, halogens, some organic vapours etc. which have a strong affinity to attach the electrons to neutral atoms or molecules to form negative ion directly or by dissociation. The electron is bound to the molecule with an energy ε_a which is called the electron affinity. The phenomenon of electron attachment to neutral atom is a common occurance for gases whose outer electronic shells are nearly filled. The measure of the ease with which an electron

can attach to a neutral atom or molecule is given by the electron affinity energy which varies from about 4 volts for gases like F and O_2 to nearly zero for those gases which exhibit small atachment and is -Ve for those which do not. Atoms characterised by closed electronic shells are inert to extra atomic electrons. Molecules in a $\sum$ ground state are characterised by no resulting spin or angular momentum. Their electrons form closed groups and hence also show inertness to extra molecular electrons. Gases such as H_2 , N_2 and CO fall into this group and show no electron attachment.

The attachment of electrons in gases was not clearly perceived until about 1910 when the vacuum techniques and gaseous purification of gases led Franck and Pohl (1910) to study ion mobilities in inert gases and N_2 and they noted the presence of free electrons at higher pressures. The studies of Townsend (1914) and his co-workers Lattey, Tizzard (1912) etc. had led to the recognition of the existence of free electrons at lower pressures in gases. The experimental works leading to the ultimate discerning of electron attachment were studies of the variation of carrier mobilities in air as a function of pressure by A.F.Koverick (1910) with the Rutherford A.C. method of mobility measurements using photo electrons and those of E.M.Wellisch (1915, 1916, 1917) using the same method but producing ions by α-particles from Po in an auxiliary field below a gauge following the method of Franck.

Observation of Wellisch may be stated briefly in the following words. The seperation previously effected between the electrons and the negative ions in dry air at lower pressures has been further extended to Co_2 and H_2 as in these two gases the electrons are relatively more numerous than in air at the corresponding pressure. A trace of impurity is especially effective in reducing the number of free electrons when the gas is at relatively high pressure; at low pressure the effect of the impurity is less marked. In most cases a velocity greater than

that arising from thermal agitation at ordinary temperature appears to be necessary to enable the electron to effect a permanent union with an uncharged molecule of the gas or impurity. For the vapour of petrolium ether, whose molecules contain only atoms of carbon and hydrogen, the negative carriers appear to consist practically entirely of free electrons; a trace of impurity, however is sufficient to effect the production of a considerable number of negative ions. A brief investigation has been made of the motion of the free electrons through Co_2 ; the results do not indicate that the velocity of the electron is proportional to the applied field, but suggests that the electron may traverse a considerable distance with accelerated motion before its terminal velocity is acquired. In no instance was any evidence obtained of a change in the nature of either the positive or negative ion as the pressure of the gas was reduced. The present method was employed to determine the values of the ionic mobilities for a few vapours and the results have been compared with previous determinations.

Loeb (1921, 1923, 1924) in a series of work investigated the possible theories of formation of negative ion from electron and neutral molecules proposed by J.J. Thomson and by Wellisch. Mobilities of the carriers formed by photo electrons liberated from one plate of a parallel plate condenser by a beam of ultra violet light, focussed on it at a glancing angle from a quartz lens, were determined at different pressures for air using the Rutherford A.C. method. The results in general confirmed the results of previous observers, yielding a single class of carriers whose mobilities became abnormal below 150 mm. pressure. The values of these mobilities were also found to be a function of the frequency of commutation in agreement with earlier results. The manner of introduction of ultraviolet light into the chamber reduced the stray light effect and it was found that the asyaptotic feet of the curves observed below 200 mm pressure were a real and important feature of the phenomenon. The mathematical theory of J.J. Thomson was adapted to fit these measurements and on the basis of the equation so deduced the chance of ion formation " n " was determined from experiment. Within the limits of

accuracy of the method, "n" was found to be equal to about 2.5×10^5 for pure dry air. The current voltage curves computed on the basis of the Thomson theory were compared with the observed curves and marked general similarities were noticed below 200 mm pressures. The asymptotic feet of the computed and observed curves lie close together, which is significant in as much as it is these portions of the observed curves that yield the abnormal values of the mobility. Deviations of the observed curves from those computed at the higher and lower pressures are explained. Repetition of the Wellisch experiments shows that what he termed "free electrons" are the carriers of abnormally high mobilities observed by the earlier workers. It is shown that as the electrons do not attach to N_2 molecules, and that as the values of "n" obtained in pure O_2 and in N_2 with small quantities of O_2 in it agree with the values found for air on the basis of its oxygen content, one must conclude that it is to the O_2 molecules in air that the electrons attach. The value of "n" for O_2 molecules is then 5×10^4.

Most of the methods of measurements of "h", the attachment probability were handicapped due to different reasons. Because of the very low values of "h" in many gases, as well as the difficulty of achieving groups of electrons of narrow energy spread in gases of sufficient density for appreciable attachment, significant studies on the appearance potentials of ions and energy of ion formation with identification of ion species formed by mass spectrographs have not been successful, until when Hickam and Fox (1954) applied their retarding potential difference method to the study of attachment of electrons to SF_6 combined with mass spectrograph revealing a new technique of investigation.

An electron that makes ν_c impacts per sec and under the action of the field "E" moves μE centimeters per sec. takes $1/\mu E$ seconds to go one centimeter. Starting with "n" electrons, the number dn out of "n" that attach in going dx centimeters will depend on "n", $\nu_c/\mu E$ and on dx. If "h" is the proportionality constant, then $dn = - h.n.\nu_c.dx/\mu E$, "h" iscalled the probability of attachment and is the reciprocal of the average number of impacts an electron makes to attach and μ is the mobility coefficient. Another quantity "β"

may be defined as the probability of attachment per cm. travel in analogy to ionisation coefficient "α" and likewise β/p is a function of E/p. These two attachment coefficients are related by $h = \beta\mu E/\nu_c$. Hence another coefficient ν_a may be defined in analogy to ν_i, ionisation frequency, and may be called the attachment frequency and it is related to " h " by $h = \nu_a/\nu_c$. Taking into consideration this new mechanism, the continuity equation for number of electrons/ c.c. may be modified by putting $[(\nu_i - \nu_a)n]$ in place of ($\nu_i n$) as the frequency of production of electrons, when the breakdown condition in case of high frequency discharge with Maxwellian velocity distribution of electron can be given by $\frac{\alpha}{p} = \frac{\beta}{p} + \frac{2}{3}\frac{\pi^2 U_{ave}}{(E_e/p)(pd)^2}$ where E_e = effective field, U_{ave} = average electron energy in e.v. The quantities $\frac{\alpha}{p}$, $\frac{\beta}{p}$ and U_{ave} are all functions of E_e/p and depend on the energy distribution function. Different authors measured the variation of α/p and β/p with E/p. Considering different possibilities of energy dissipation of electron after attachment to the molecules and atoms and applying continuity equation Harrison and Geballe (1953) obtained the expression for D.C. current for applied d.c. voltage E as

$$i = i_0\left[\alpha/\alpha-\beta\right]\exp\left[(\alpha-\beta)d\right] - i_0\beta/\alpha-\beta \qquad \ldots(1.7)$$

where

d=distance between the electrodes. Variation of d.c. current with different electrode seperation for values of E/p = 60 to E/p = 25 volts/cm. mm. of Hg. were obtained. Variations of β/p with α/p were obtained for air, Freon, CF_3SF_3. Measurements of variation of "h" with E/p were made by Bradbury and Tatel (1934) for gases SO_2, N_2O, H_2S, NH_3, H_2O, HCl, Cl_2 and different mixtures of attaching gases. Burch and Geballe (1957) measured the variation of β/p with E/p of oxygen. Measurements of cross section of attachment of halogens Cl_2, Br_2, I_2 for different energy of the electron by Healey (1938) show a maximum near 2 volts of energy of electrons for all three gases. These are the some of the observations of variation of β/p variation with E/p.

These measurements of variation of β/p and α/p with E/p helps to compare

the breakdown voltage data observed in high frequency discharge of attaching gases taking the effective high frequency field as the applied D.C. field. Herlin and Brown (1948) measured the breakdown voltage in air at 3000 Mc/sec with the distance varying from 0.635 cm to 0.158 cm and the pressure varying from 70 mm Hg. to 2 mm Hg. Similar measurements were done by Pim (1949) at 2000 Mc/sec. with the gap length varying from 0.03 cm. to 0.06 cm. and the pressure varying from 760 mm. Hg. to 160 mm. Hg. The discrepancy between these observations and theoritical plot of breakdown curve, obtained by taking help of measurements of Healey and Reed (1941) for average electron energy as a function of E/p was of the order of 10% . However with increased purity of air - by taking every observation with fresh air after exhausting all air of the previous observation - the experimental curve shows much better agreement with the theoritical curve. The data of microwave breakdown measurements in oxygen at 3000 Mc/sec with gap length 0.635 cm. over a range of pressures from 70 to 2 mm. Hg. of them are in good agreement with the theoritical value calculated with the help of measurements of α/p and β/p for oxygen from the work of Harrison and Geballe (1953) and taking the value of $\nu_m = 3.5 \times 10^9 . p$ obtained from mobility measurements of Nielsen of Bradbury (1937) and the relation for the a.c. mobility, we get the value of E_e given by to

$$E_e^2 = \frac{E_p^2}{2} \cdot \frac{\nu_m^2}{\nu_m^2 + \omega^2} \qquad \ldots(1.8)$$

where

$E_p \exp(j\omega t)$ is the applied field (high frequency) and ν_m is the collison frequency.

Breakdown in presence of magnetic field.

Breakdown of a high frequency discharge in a gas in presence of magnetic field has been studied previously by some workers. Townsend and Gill (1937) calculated the effect of a magnetic field on the breakdown potential of a gas under r.f. excitation and showed that the mobility of the electrons in the direction of the electric field is reduced and is given by the equation

$$\bar{K}_H = \frac{\bar{K}}{1 + \omega_H^2 \tau^2} \qquad \ldots(1.9)$$

where $\omega_H = eH/mc$ the cyclotron frequency, and τ is the time between successive collisions. The diffusion coefficient D is reduced in a direction perpendicular to the magnetic field in the ratio

$$D_H = \frac{D}{1 + \omega_H^2 \tau^2} \qquad \ldots(1.10)$$

From these considerations, they observed that if the electric and magnetic fields are parallel, the diffusion perpendicular to the field is reduced and hence a smaller breakdown field is necessary. If the fields are perpendicular, not only the breakdown voltage is reduced but for certain values of the magnetic field and the applied frequency resonance will occur when

$$f_{applied} = eH/2\pi mc \qquad \ldots(1.11)$$

They carried out experiments in air for two frequencies namely 48 Mc/sec and 30 Mc/sec. and the range of pressure varying from a few μ Hg to 24 mm of Hg. A decrease of the starting potential was noted for values of pressure less than the minimum without field and increase of starting potential for values of pressure greater than that at which the breakdown voltage becomes minimum when the magnetic field is applied. The values of the magnetic field were so chosen that the resonance condition was satisfied. The work has further been extended by Brown (1940) to the case of hydrogen who obtained almost similar results.

Lax, Allis and Brown (1950) carried out experiments on the breakdown voltage of a gas excited by a microwave field in presence of a transverse magnetic field. The gas used was helium containing a small admixture of Hg vapour and they obtained breakdown curves for different values of pressure. The breakdown voltage becomes a minimum for a magnetic field (1125 gauss) for all values of the pressure, the effect of resonance being most marked at low values of pressure.

Ferritti and Verhonesi (1955) performed experiments in air for frequencies ranging from 10 Mc/sec 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 magnetic field.

Most of the work in this line were done in resonance magnetic field such that the frequency of the applied field and the magnitude of the magnetic field are of such a value that $f_{applied} = \frac{eH}{2\pi mc}$ was satisfied. So far practically little work has been done in which the magnetic field is far removed from the resonance value. Sen and Ghosh (1963) studied the breakdown in air and nitrogen in crossed nonresonant magnetic field applying the radiofrequency voltage of frequency 6.1 Mc/sec. and 7.15 Mc/sec. respectively in the pressure range of a few microns Hg. to 500 micron Hg. They obtained a family of curves for different steady magnetic fields whose value lies within 100 gauss. It was observed that each curve for a steady crossed magnetic field has got a minimum breakdown voltage at a certain pressure which shifts to higher pressure as the magnetic field is increased. An increase of breakdown voltage was also observed on the application of transverse magnetic field within the range of pressure for which the measurements were taken. Following the theory of Kihara (1952) for breakdown of gases by radiofrequency field and equivalent pressure concept introduced by Blevin and Haydon (1958) with the variation of mobility and diffusion coefficient in a magnetic field, and expression for the breakdown voltage of gases by r.f. field was developed to explain their experimental results. It was observed that the theoretical results are in fairly good agreement with experimental results. The discrepancy was attributed to uncertainities in the values of molecular constants introduced by Kihara in his theory. They also considered the effect of attachment loss to the breakdown condition and obtained the modification in their breakdown voltage expression as

$$E_o = \left(E_o^a\right) . b + \frac{L\omega(1-b)}{2\bar{K}} \qquad \ldots(1.12)$$

where

$$b = \left[\frac{\nu_i - \nu_a}{\nu_i}\right]^{1/2} = \left[\frac{\alpha/p - \beta/p}{\alpha/p}\right]^{1/2}$$ and $\overline{K}$ = mobility coefficient;

L = length of the gap; ω = applied frequency.

E_o = breakdown voltage without consideration of attachment.

E_o^a = breakdown voltage with consideration of attachment.

This new modification with the consideration of attachment loss showed a better agreement between theoretical and experimental breakdown voltage.

Begnall and Haydon (1965) studied the pre-breakdown ionisation in molecular nitrogen to establish whether the influence of a transverse magnetic field is equivalent to an increase in the gas pressure from " p " to $p_e = p\left(1 + \frac{\omega^2}{\nu^2}\right)^{1/2}$ where " ω" is electron cyclotron frequency, and ν, a constant, which is the effective electron molecule collision frequency. When the value of E/p_e lies within the range $150 < E/p_e < 250$ V cm^{-1} torr^{-1}, ν has a constant value equal to $8.3 \times 10^9 p$ sec^{-1} but when $E/p_e < 150$, ν/p must decrease with decreasing E/p_e for satisfactory agreement to be maintained. The possibility of extending the concept to account for the changes in secondary ionisation and the breakdown potential in nitrogen are also discussed. Considering the different complex situations of pre-breakdown ionisation at different range of E/p_e, they observed that the complex situation is not restricted to nitrogen so that an approach to the problem of breakdown in terms of an equivalent increase in gas pressure is by no means simple and at least for nitrogen the equivalent pressure concept is valid within a limited range of E/p_e value.

(B) RADIOFREQUENCY BREAKDOWN IN A SUPERIMPOSED D. C. FIELD

The first report of this type of work was made by F.Kirchner (1925, 1947) who measured the r.f. potentials necessary for the initiation and maintainance of a discharge in presence of a d.c. field in different gases. He found that the application of a d.c. potential of 60 volts to a r.f. discharge, maintained by an a.c. potential of 60 volts, caused the discharge to disappear completely.

He explained that the effect is due to the fact that when a.c. field is alone present displacement of the electrons during one period of the oscillation is of the same order of magnitude as, or is smaller than the distance between the electrodes, and that therefore these electrons can oscillate between the electrodes and give rise to a cumulative generation of ions . When a d.c. voltage of the same magnitude is superimposed on the a.c. voltage, during one half of the complete cycle the voltage becomes nearly equal to zero and the continous oscillation of electrons for production of ions and electrons ceases due to this effective nullification of accelerating voltage and hence the discharge disappears.

A.A.Varela (1947) superimposed a d.c. field, less then that required to initiate the discharge on a r.f. potential (120 Mc/s) in a discharge tube with the idea of hastening the discharge and obtaining a short deionisation time. It was also hoped that the intensity of the discharge should be increased by the direct current; but contrary to this it was observed that the application of a d.c. potential greatly impeded the formation of discharge and higher radio frequency potential was required for initiation of the discharge and also the admittance of the discharge was found to be lower when the bias was applied. Recovery was somewhat more rapid as had been expected. It was observed that ionisation occurs through a small angle at the voltage peak of the radiofrequency cycle when the voltage is above the ionisation threshold, the remaining period being utilised for removal of the ions; so when a d.c. bias of about the same value as the r.m.s. of the alternating potential was applied the field exceeded the ionisation threshold for only one period in each cycle and the ratio of ionisation time to deionisation time will be considerably reduced. The increase in ionisation rate due to higher potential during the ionisation period is not sufficient to offset the increase in deionisation time and so higher r.f. voltage is required to initiate the discharge; the same effects are present during the discharge and d.c. bias produces a reduction in intensity. The experiments were conducted at a

frequency of 120 Mc/s with 5 microsec. pulses at a rate of 60 persec. The discharge tubes had Al. electrodes in an atmosphere of about 5 cm of hydrogen with 20% Argon. No quantitative theory was formulated to explain these effects. Varnerin and Brown (1950) obtained the equality in expressions for electron energy distribution function and ionisation coefficients for both a.c. and d.c. discharge on the assumption that the collision frequency is constant at constant pressure which is specially true in case of hydrogen and helium. Taking the total electric field $E = E_{D.C.} + \sqrt{2} E_{A.C.} e^{j\omega t}$ where $E_{D.C.}$ represents the d.c. field, $E_{A.C.}$ the r.m.s. value of the a.c. field and 'ω' the radian frequency, and with the help of Boltzman transport equation the expressions for all the parameters in both the cases were obtained. An effective field was defined by $E_e^2 = E_{D.C.}^2 + \frac{\nu_c^2}{\nu_c^2 + \omega^2} E_{A.C.}^2$ when both d.c. and a.c. fields are present. The different parameters so obtained are found to be identical in both the cases and the effective nature of the d.c. and a.c. fields are same in the process of ionisation. This similarity makes it possible to modify the a.c. distribution function theory for breakdown to take account of the superposition of a d.c. field and to predict the behaviour of breakdown with both fields acting simultaneously.

The gas in a cavity will breakdown when losses of electrons to the walls of the cavity are replaced by ionisation in the body of the gas. When the a.c. field alone is applied, electrons are lost by diffusion. When a small d.c. sweeping field is applied, electrons are lost both by diffusion and mobility. The breakdown condition can be formulated mathematically by consideration of these processes. The equation

$$\nabla^2 n + \frac{E_{D.C.}}{D/\bar{K}} \cdot \frac{\partial n}{\partial Z} + \nu n = 0 \qquad \ldots(1.13)$$

represents the balancing condition expressed above when d.c. field is directed along the Z- axis (n = number of electrons/c.c. D= diffusion coefficient, $\bar{K}$ = mobility coefficient, ν = ionisation frequency). The solution of this equation for the case of a cylinder of axial height L and axial co-ordinate Z,

radius R and radial co-ordinate "r" will yield the breakdown condition. Regorous boundary conditions require the concentration to be small at a boundary and extrapolates to zero out side the boundary at a distance of the order of a mean free path. In the range of pressures to be considered, the mean free path is very small compared to the cavity dimensions and the condition of zero concentration on the cylinder walls is imposed. The solution is

$$n = \left[\text{constant} \cdot J_0(R_1 r)\right]\left[\sin(\pi/L)Z\right] \exp\left(-\bar{K} E_{D.C.} Z/2D\right)$$

where $R_1 = 2.404/R$ and Jo is the zero order Bessel function. This solution is subject to the condition $\nu/D = 1/\Lambda^2_{D.C.}$

where $\Lambda_{D.C.}$ defines a modified diffusion length given by the relation

$$1/\Lambda^2_{D.C.} = 1/\Lambda^2 + \left[E_{D.C.}/\frac{2D}{\bar{K}}\right]^2$$

where $1/\Lambda^2 = (\pi/L)^2 + (2.404/R)^2$ where Λ = Characteristic diffusion length.

The only difference between the breakdown condition in the a.c. - d.c. case and pure a.c. case is the substitution of a modified diffusion length for Λ. It will be noted that the modified diffusion length of a cavity is smaller than the characteristic diffusion length. A cavity whose electron loses are increased by a d.c. sweeping field is equivalent to a smaller cavity without a sweeping field. Using the proper distribution function theory to calculate breakdown and the modified diffusion length presented here, a theoretical breakdown curve for an $(E/p)_{D.C.}$ of 12 volts/cm has been obtained. The relative increase of a.c. breakdown field with superimposed d.c. field for air at a pressure of 38 mm. Hg. has been obtained upto $E_{D.C.}$=200 volts/cm. Yamamoto and Okuda (1955) made some study of high frequency discharge with a d.c. voltage applied perpendicular to high frequency field. The discharge tubes were filld with air and fitted with internal electrodes made of several materials. A high frequency voltage of 77 Mc/sec. was applied to two parallel electrodes from out side the tube; perpendicular to the high frequency field, a strong d.c. field is applied to a set of parallel electrodes placed inside the tube. The d.c. source has the maximum voltage of 20 KV and maximum current of 20 mA. During the experiment, the pressure was varied from 10 mm Hg. to 10^{-4} mm. Hg. Keeping the high frequency field constant, the d.c. voltage-current

characteristic curves were obtained. The main interesting observation was that in this system three types of discharge can exist, classified from the stand point of d.c. conduction. The first is like d.c. glow discharge type where the properties of the d.c. discharge is prominent with additional ionisation by h.f. field. The second is space charge limited type, the same as the conduction in the floating double probe in a plasma produced by high frequency field. And the third type is an intermediate stage between the first and second types which may be referred to as transition type between the above two types. According to the authors' analysis of the transition type at low pressure, the value of γ, the Townsend's second coefficient, in high electric field can be deduced from the measurement.

Rasquin (1965) studied the breakdown behaviour of air under the influence of a direct inhomogenous electric field with a superimposed alternating field. With an electrode configuration which produces an inhomogenous field, breakdown in air can occur even if the applied d.c. electric field is much smaller than the d.c. breakdown voltage, if a high frequency alternating field is superimposed whose peak value, however, is still small compared with the d.c. reference field. For this breakdown to occur, the d.c. field must be applied so that the electrode of greater curvature is more positive than the other. A possible explanation is that negative space charge near the inner cylinder prevents breakdown from developing. In this connection it should be noted that the density of the negative space charge takes a definite value dependent on the applied voltage. Under stationery conditions, the negative space charge is rather greater than that is necessary for the establishment of an arc. If the voltage on the electrode is changed, the space charge can not follow the voltage for an arbitrarily high rate of change. Thus for part of the time the space charge is less than the equilibrium value and during this time breakdown can occur.

(c) LOW PRESSURE DIELECTRIC BREAKDOWN OF GASES BY HIGH FREQUENCY UNIFORM FIELD (a) WITHOUT MAGNETIC FIELD (b) WITH d.c. TRANSVERSE MAGNETIC FIELD.

When the pressure is low enough so that loss mechanism is not governed by diffusion and mobility, the phenomenon of breakdown can be explained by secondary electron resonance. In the high pressure region the discharge is controlled by diffusion and mobility, but at pressure of the order of 10^{-3} mm. Hg. and less, the mechanism is different. Here the initiation of discharge by high frequency field is much easier than that by d.c. field. Many workers have studied the case with ~~high~~ high frequency field and have shown that the secondary emission of electrons by direct bombardment of the walls can cause a breakdown to occur. The different observations show that the breakdown phenomenon in this case depends not only on the magnitude of the electric field applied, but also on the phase of the electron motion with respect to the field. Under optimum conditions the electron motion must be in phase with the applied field. For the expected mechanism to occur, the general assumptions made by Danielsson (1943), Gill and Von Engel (1948), Hatch and William (1953, 1954, 1958) and other workers, for the simple theory of resonance breakdown, can be stated briefly as below. The fundamental hypothesis for this theory is the existance of the secondary electron resonance mechanism. In order that this mechanism can be operative it is necessary to assume that the electron mean free path and the wavelength of the applied high frequency field are both large compared to the electrode seperation. The mean free path of electron in H_2 at 0.C. and 1 μ Hg. pressure is of the order of 80 cm and for N_2 it is 40 cm. For mathematical simplicity it is convenient to assume that all electrons have half cycle transit times. It is assumed that the ratio of the electron arrival to emission velocity is a constant and the electron emmission velocities are normal to the electrode surfaces, though this assumption is not an accurate representation of secondary emission characteristics but is very useful in getting a simple formulation of the problem. It is further assumed that the electric field between the

electrodes is uniform in space, that space charge effects are negligible, that electron arrival energies exceed the ionisation potential of the gas, and that a few electrons are produced randomly between the electrodes by natural processes. The extent to which many of these assumptions compensate in an undetermined manner for the other processes in this breakdown mechanism is not clear.

An electron starting across the gap between the walls should collide with the opposite walls of the vessel and release secondary electrons just as the electric field passes through zero. The reversed electric field accelerates the secondary electrons back across the gap. The secondary electrons so formed by the initial electron become primary electrons for the next half cycle to form another group of secondary electrons, with the optimum conditions again requiring that the secondaries be formed just as the field reverses its direction. However, as was observed and is also obvious that a breakdown does not require the optimum conditions to occur, and there is a fairly broad region of fields and frequencies over which such a phenomenon may be observed. It is clear from the mechanism of this type of breakdown that the type of gas has got nothing to do with the electron multiplication so that breakdown field is independent of the nature of the gas, but depends much on the surface constitution of the wall of the vessel which is the only source of secondary electrons.

Almost all the workers relied for their explanation of the observation on a simple theory. The theory explains the general trend of the observations with the help of some empirically determined constants. The exact values of these parameters are very difficult to obtain theoretically as the actual mechanism is not known. As the parameters have got very flexible difinition, so suitable values could be placed for them and results followed. Different observers assumed different values of the parameters.

For the quantitative description, the motion of electron acted on by a sinusoidally varying electric field of peak value E_p and radian frequency "ω" is described by the equation

$$m \frac{dv}{dt} = e E_p \sin(\omega t + \phi) \qquad \ldots(1.14)$$

where ϕ is the phase angle of the secondary emission electrons. Neglecting collision of electrons with gas atoms and assuming the ratio of emerging velocity to impinging velocity a constant for all secondary emission i.e. $v/v_0 = K$ = constant, the expression of E_p for a tube length L cm is

$$E_p = \omega^2 L \, \Phi^{-1} \, m/e \qquad \ldots(1.15)$$

where $$\Phi = \frac{K+1}{K-1} \pi \cos\phi + 2 \sin\phi$$

writing the velocity in terms of the electron arrival energy u given by $e u = \frac{1}{2} m v^2$, the frequency " f " is given by

$$f = \frac{(K-1)\ \Phi}{K \pi L \cos\phi} \left(e u / 8m\right)^{1/2} \qquad \ldots(1.16)$$

Denoting a critical value of Φ by Φ_u i.e. maximising Φ, the critical values of " f " and E_p are obtained which are termed as values at cut off i.e. beyond this point the breakdown voltage rises sharply to infinity so that beyond the critical value of frequency, the tube will appear to any amount of high voltage as an insulator. The governing expressions at this point are $f_{c.o.} = A/L$ and $V_{c.o.} = B u$

where both the constants A and B are quantities which may be determined empirically. The voltage at cut-off is independent of electrode separation and applied frequency. The observations so far reported shows that $A \approx 79$ is the value which fits some of the observed data.

A good number of workers reported observations which have a fair amount of self consistency. Early investigations of breakdown field strengths in gases at low pressures and highfrequencies from 1 to 100 Mc/s were carried out by the Guttons (1924, 1928, 1930) and Kirschner (1925, 1930) using external and internal electrodes respectively. Their principal observation was that the breakdown field strength decreased with decreasing frequency to values as low as 10 v /cm until a cut-off frequency was reached below which breakdown could be obtained only with high field strength or not at all. A latter investigation by Beckmark and Bengston (1941) led to a theoretical analysis by Danielsson (1943). Assuming the zero electron emission energy Hamsberg, Orthuber and Steudel (1936) calculated the value of ϕ to be lying between 0° and 32.5°. Danielsson (1943) assumed $K = \alpha$ i.e. $v_0 = 0$ and ϕ varying between 0° and 90° and obtained the electron arrival energy to fit his observation as $u = 80$ e.v. for aluminium electrodes at various seperations at frequency 65 Mc/s. Gill and Von Engel (1948) however tried to verify the different possibilities of source of occurance of the secondary electrons and their dependence on various factors. With the help of observations made by Mueller (1945), Salow (1940) and Kalkhoff (1933) for the emission of secondary electrons from the surface of glass, they were able to explain successfully their observations for electrons of 40 e.v. and above impact energy; but no result is available for slower primaries. They observed that the starting field strength for high frequency uniform field (uniformity is observed by keeping $2r = 3.d$, d=length between electrodes, r=radius of electrodes. the dimension of the tube) at micron Hg. pressure for gases like He, Hg, H_2 and air is independent of the gas and only slightly depends on its pressure. By increasing the wavelength ($> 4m$) the starting field varies first inversely with the wavelength, then becomes constant and at a critical value rises discontinously probably to infinity. The cut-off wavelength is proportional to the diameter of the sphere and length of the cylindrical vessel respectively. The dependence of the production of

electrons on the secondary emission was verified by coating the inner glass wall with a poor secondary emitter, the starting field is increased while the cut-off wavelength decreases, the reverse is observed when clear pyrex glass is exchanged for soda glass, which agrees with the larger value of the coefficient of the secondary emission of the later.

Hatch and Williams(1954) measured the field strength in air and hydrogen at pressures of the order of 1 micron Hg and frequencies from 25 to 90 Mc/sec between flat metal electrodes at seperations from 1 to 4 cm. By suddenly applying a high voltage and then lowering it slowly an upper breakdown curve has been observed. This new curve was combined with the lower breakdown curve obtained by Cutton, Gill and Von Engel to form the boundaries of a breakdown region in the frequency-field strength domain. Measurements of breakdown field strength vs. frequency for 7.5 cm diameter mechined alclad electrodes at a seperation of 3 cm were made in dry oxygen. Existance of very low breakdown field strengths and a cut-off frequency was shown. It was found impossible in this case to get a breakdown below 34 Mc/s. The measurements distinctly showed two branches of breakdown curve joining at cut-off frequency and almost otherwise parallel within the points of observation which was restricted to 50 Mc/s for upper curve due to r.f. voltage limitation of the experimental arrangement. The lower breakdown curve upto 100 Mc/s was also obtained. Attempts were made to find experimentally the smoothness of the curve at the vicinity of cut-off. Experiments with silver copper electrodes in hydrogen showed that in the immediate vicinity of cut-off, breakdown was evidenced only by the appearance of a faint glow, there was no usual drop of r.f. voltage which appears to indicate the existance of a definite observable closure of the two breakdown curves. Dependence of breakdown on the secondary emission characteristics of the electrode surface was also observed with an appropriately modified apparatus using alclad electrodes at a seperation of 3.5 cm and a frequency of

50 Mc/s. From the same author (1953) additional confirmation of the existence of the secondary resonance mechanism has been obtained in the measurement of electron arrival energies and the observation suggests that a short of electron bunching occurs. Another observation has been that of electron resonance without any visible discharge or attenuation of applied voltage at pressures of the order of 0.05 μHg. For a fixed frequency and electrode seperation, electron resonance has been observed continously within a field strength range approximately the same as that within which visible breakdown occurs at high pressures.

Hatch and Williams (1958) extended their work with internal electrodes from conventional half cycle mode to higher order modes. A semitheoretical plot of breakdown voltage versus the product of frequency times electrode seperation using representative fitting parameters is given for the half through 9/2 cycle modes. In addition to the customary half cycle cut-off, the theory predicts a modified cut-off in each of the mode transition regions. The basic equation of undamped electron with r.f. voltage of frequency "f" gives the first arrival velocity of electron at the opposite electrode as

$$v_f = \frac{K}{K-1}\left(2eE/m\right)\cos\phi \qquad \ldots(1.17)$$

where ϕ is the time phase angle at which secondary electrons are emitted and corresponding breakdown voltage by

$$V = \frac{4\pi^2 (fd)^2}{(e/m)\ \Phi_n} \qquad \text{where} \qquad \ldots(1.18)$$

$$\Phi_n = (2n-1)\frac{K+1}{K-1}\cos\phi + 2\sin\phi$$

For maximum value of Φ_n the limiting phase angle is given by

$$\phi_l = \tan^{-1}\left[\frac{K-1}{K+1}\ \frac{2}{(2n-1)\pi}\right] \qquad \ldots(1.19)$$

Finally combining the expression for electron arrival energy at an electrode the relation

$f.d = \frac{(K-1)\,\Phi_n}{K\cos\phi}\left(eu/8m\right)^{1/2}$ is evaluated at cut-off portion to evaluate u. These equations are fitted to observations and different constants including u are calculated within reasonable values. Attempts were made for fitting the observations assuming that different cut-off points are observed depending upon the modes which are initiating the mechanism. Each mode represents a close curve with a cut-off point and assuming all the modes are operative, the cut-off points of all the modes are fitted on the observation curve to explain the mechanism as dependent on multiplication by different modes. An attempt was made to justify the theory by fitting the observations of Cuttons, Gill and Von Engel, and Hoover and Smither etc. The Hoover and Smither's (1955) data represent multipacting in a heavy particle r.f. linear accelerator rather than in a system designed expecially for basic breakdown studies. Multipacting breakdown was observed in a 50 Mc/sec. re-entrant cylindrical copper lined cavity. Breakdown occurred at 70 volts in a 2.54 cm gap. Different aspects of this mechanism also were studied by different authors from time to time. Francis and Von Engel (1953) did extensive work on the growth of the currents in this type of discharge. Levin and Rubin (1961), Miller and Williams (1962), Fouret and Guillemard (1960), Hatch (1961) and Paschke (1961) etc are some of the authors who investigated in various characteristic phenomena associated with this type of discharge mainly initiated by highfrequency field.

Recently Chandrakar and Von Engel (1965) studied the ring discharge at very low and moderately high pressure respectively. A theory based on the secondary electron resonance breakdown mechanism to explain the different features of ring discharge at very low pressure has been put forward. The effects of side walls on the breakdown mechanism of very low pressure discharge have been treated in some detail.

Miller and Williams (1962) made recent observations of multipacting discharges subject to axial magnetic fields of a few hundred gauss which indicated that very large periodic pulsation in the electron current may occur in an apparently steady state discharge. Such pulsations occur with frequencies of the order of a few hundred Kc/sec and have been shown to be simultaneous with the pulsations in the light intensity. The experimental discharge chamber was of 9 cm internal diameter pyrex cylinder sealed to brass end plates. The electrode seperation was adjustable from 0 to 6.5 cm. A pair of Helmholtz coil supplies the magnetic field. Pumping is done with oil diffusion and liquid N_2 or solid ice-trap. R.F. power was supplied at 40 Mc/s from 600 w transmitter and at 55 Mc/s from 60 w transmitter. Electron currents were sampled through 0.025 cm.-dia. hole in the centre of one of the electrodes and observed by Tektronix-type 585 oscilloscope. Electron current pulsations were observed with r.f. excitation at both 40 and 55 Mc/s but the frequency of pulsation was not noticeably sensitive to the excitation frequency. On the other hand, the pulsation frequency was found to be approximately inversely proportional to the axial magnetic field strength in the range of 200-600 gauss and nearly proportional to the inverse square of the peak applied r.f. voltage. Pressure variations between 5×10^{-4} and 1×10^{-3} torr. strongly effected the frequency of the current pulsations, but no useful data were obtained in this connection. In general the frequency appears to increase with increasing gas pressure. Several types of gases were fed into the discharge chamber by a continuous bleeding process, but again the pulsation rate did not seem to change noticeably for different kinds of gases. Argon, hydrogen, helium (all industrial grade) and air were used. Extensive alterations were made in the external circuitary and arrangement in order to detect any external influence causing pulsation. Pulsation did not stop and so it was concluded that it lies in the discharge. Pulsation could be stopped by at least two ways. First if the r.f. power was increased above some critical value, a transition into the high frequency

plasmoid mode occured and the pulsations ceased. Second, a d.c. bias of 20 to 50 v placed between the two electrodes also stopped the pulsations without an appreciable change in the visual appearance of the discharge even with r.f. voltage upto 1 K.V. (peak) applied between the electrodes. Paschke (1961) in a note on the mechanism of the multipactor effect based his analysis on the following premises (a) the fields and currents are one dimensional (b) effects of space charge are ignored except for one particular case (c) the applied field is sinusoidal (d) at the onset of the breakdown, it is only one particular velocity class which is in resonance and thus responsible for breakdown.

Integration of force equation $\frac{dv}{dt} = \eta E \sin \omega t$ gives velocity

$$v = v_s - (\eta E/\omega)(\cos \omega t - \cos \omega t_0)$$

and position

$$x = -(\eta E/\omega^2)(\sin \omega t - \sin \omega t_0) + (\eta E/\omega^2)\omega(t-t_0)\cos \omega t_0 + \omega(t-t_0)v_s/\omega$$

where η is charge to mass ratio of an electron which is emitted from $x=0$ at a time "t_0" with a velocity $v_s = (2\eta V_s)^{1/2}$. If the particle impinges on an electrode at x = d at a time given by $\omega(t-t_0) = \pi$, the secondary electrons of velocity class v_s released from the electrode will see the same field along their path as did the primary electron. With sufficient secondary yield the charges will avalanche until breakdown occurs. From above the resonance condition is derived as

$$\left[(\omega v_s)/\eta E\right]\left[(\omega d/v_s) - \pi\right] = 2\sin(\omega t_0) + \pi \cos \omega t_0 \qquad \ldots(1.20)$$

which relates the starting phase ωt_0 with the breakdown field strength and the impinging velocity at resonance $v_d (2\eta V_d)^{1/2} = (2\eta E/\omega)\cos \omega t_0 + v_s$

The minimum electric field for breakdown to occur is

$$E_{min.} = (\omega v_s)\left|(\omega d)/v_s - \pi\right| / \eta(4+\pi^2)^{1/2} \qquad \ldots(1.21)$$

with starting phase $\omega t_0 = 32.5°$. $E > E_{min.}$ is a necessary but not sufficient condition for the breakdown to occur. The secondary yield has to have a certain

minimum value to get the avalanche process started. The continuity equation $I = I_o \left(dt_o/dt \right)$ relates the current I_o emitted at $x = 0$ in a time interval dt_o to the current I arriving at a position x over a time interval dt. If $\left| dt_o/dt \right|_{\omega(t-t_o)=\pi} > 1$ electrons are emitted in an interval dt_o around the proper starting phase ωt_o. If $\left| dt_o/dt \right|_{\omega(t-t_o)=\pi} < 1$ the emitted electrons will move to non resonant state. The theoretical curve enclosing the breakdown region agrees remarkably well with the experiments of Hatch and Williams. The conclusion to be drawn are (1) The emission velocity distribution of the secondaries is important for low frequencies (2) The upper limit of the breakdown field is caused by space charge enhanced recombination of particles with the emitting surfaces (3) The cut-off frequency is determined by the secondary yield at the field strength where recombination starts.

Hatch (1961) described the salient features of the multipacting bunching and are illustrated by plots of electron trajectories for transit times of ½, 3/2 and 5/2 cycle. The way in which the secondary emission characteristics of the electrodes influence multipacting bunching is also discussed briefly. Electron bunching in the multipacting mechanism of low pressure high frequency discharge, also known as the secondary electron resonance mechanism is analysed by an extension of simple multipacting theory. The bunching range is assumed to be that range in the electrical phase angle ϕ within which secondary electrons emitted from one electrode can successfully traverse the interelectrode gap in half cycle and arrive at the opposite electrode with energy equal to or greater than emission energy. At the lower voltage limit, the range is narrowed to $-90^\circ \leq \phi \leq -40^\circ$. Typical examples of multipacting bunching, including higher order modes, are illustrated with graphical trajectories. The effects of secondary emission characteristics on bunching are also discussed. Francis and Von Engel (1953) treated growth of the discharge in detail,

the calculations being based on known atomic data only. When secondary electrons leave an end wall a positive wall charge is left behind, which retards the electrons. This is important only near the cut-off wavelength. These wall charges cause the phase at one wall to become increasingly negative until finally the electrons would fail to escape, and the multiplication would cease, which is contrary to experience. However the growth can be explained by considering the velocity distribution of the secondary electrons. Then a distribution in phase ensues, which must be repeated in successive half cycles for an avalanche to develop. During this first stage the current is therefore essentially controlled by secondary emission and grows exponentially with time. At these low pressures electrons rarely collide with gas molecules. Thus the electron must make many transits across the vessel to form a large number of positive ions. The ions remain almost stationary in the gas, they are nearly uniformly distributed although slightly concentrated at the centre of the vessel. A second stage in the growth of the discharge begins when the ion space charge first appreciably affects the motion of the electrons. Although electrons are still produced mainly at the end walls, the rate steadily decreases as the ion space charge grows. The rate of production of ions and electrons in the gas also decreases and losses of both ions and electrons due to self repulsion become important. The current thus rises more slowly than it would if space charges did not develop until it reaches a constant value. It is shown that at very low pressures, this second stage may not be reached, because self repulsion of the electrons stops the development earlier. The final equilibrium state for large pressures is not included in this treatment. This theory predicts the dependence of the growth on the material of the walls, on the nature of the gas and its pressure, and the effect of the field greater than the starting field. A new experimental technique has been employed to measure the current actually flowing across the external electrodes by a bridge method, the bridge becoming unbalanced when a current flows through the gas.

Karras (1966) studied radiofrequency breakdown in Penning geometries with nonlinear fields. R.F. breakdown in air within the pressure range of 10^{-3} to 10^{-6} torr. is studied analytically and experimentally for two electrode configurations which lead to nonlinear Mathieu like differential equations for the confined electron motion. Experimental data are identified with two energy gain mechanisms which are described as the collisional and resonance modes. Breakdown voltages are predicted from stability plots which show several resonance minima where the observed radiofrequency breakdown voltages are very low. Resonance minima predicted by a linear analysis are shifted by nonlinear effects, from which it is shown that the collisional mode is apparently triggered by excitation of the 7.7 ev. level of the nitrogen molecule with subsequent electron emission from the cathode surface. The resonance mode is found to be largely surface independent.

Though a substantial amount of work on the secondary resonance has been done, yet very little is reported about the influence of external fields on this type of breakdown. The works of Kossel and Krebs (1954) and Huber, Ozaki and Kleider (Ninth gaseous electronics Conference, Pittsburgh) are worth mentioning in this respect. It has been found that superimposing a d.c. electric field parallel to the high frequency field, starting can be made more difficult. A small static magnetic field perpendicular to the high frequency electric field, causes a general increase in breakdown field and a lowering of the cut-off frequency, but leaves the general shape of the electric field vs. wavelength curve unaltered. In large magnetic fields, the starting potential is almost independent of frequency. A discharge at very low pressure, say at 10^{-5} mm Hg, once started, can be put out by either increasing the electric field or decreasing the magnetic field. Little light was thrown on the mechanism of the processes under the changed experimental setup.

Deb and Goswami (1964) investigated theoretically the problem of secondary electron resonance breakdown in the presence of a steady transverse magnetic field following the method of Von Engel for similar discharge without such field. Curves

giving the breakdown field as a function of wavelength with " α " the ratio of the cyclotron frequency to the frequency of the applied field, have been drawn. It was shown that with increase of " α " the breakdown field tends to increase and the main region of the curve is displaced towards longer wavelengths. The increase in breakdown field with a given change in " α " is found to be more pronounced with the higher order modes of discharge. The effect of angle of arrival at the end walls of the charged carriers on the breakdown mechanism has also been considered. Results indicate that the effect should counteract appreciably the aforsaid tendency of the breakdown field to increase in the presence of a magnetic field. The so called cut-off value increases with increase in " α " and in contrast to the situation in the absence of a magnetic field, might define either a long or short wavelength limit of discharge depending upon the value of " α ".

(D) RADIATION FROM GLOW DISCHARGES.

The radiation emitted by gas molecules after excitation by collision has been the paramount source of existing knowledge about the internal structure of the gas molecules, about the environment in which the gas molecules exist, and about the stimulating collisions themselves. Radiation from gas discharges has supplied means of measuring atomic abundances, identities and chemical reaction rates. An understanding of the radiation from gas discharges rests on the elucidation of two seperate stages in the process (1) the release of energy as radiation by the gas molecules and (2) the delivery of energy to the gas molecules. Each atomic or molecular species radiates a characteristic set of frequencies which are governed by the Planck relation

$$h\nu_{ji} = E_j - E_i \qquad \ldots(1.22)$$

The probability per unit time that such a transition will occur spontaneously in an atom excited to the jth state is given by

$$A_{ji} = \frac{64\pi^4 e^2 \nu_{ji}}{3hc^3} |x_{ji}|^2 \qquad \ldots(1.23)$$

where

$$x_{ji} \quad (= x_{ij})$$

is the matrix element of the dipole moment for the transition from E_j to E_i. Most commonly occuring radiations are dipole radiations, but transitions which are forbidden in dipole radiation by the identical vanishing of χ_{ji} can sometimes be observed weakly in quadrupole or magnetic dipole radiation with a probability which is roughly in the ratio of $(a_j/\lambda)^2$ to that of an allowed transition. Here a_j is the orbital radius of the upper state. Extraneous fields can permit forbidden transitions also.

If the probability per unit time of spontaneous emission of frequency ν by a single radiator is known, it is in principle possible to compute the intensity of radiation. Low pressure gas discharges, despite the real complexity of their energy transfer processes, are simple to analyse when compared with the vastly more complex situation in terrestrial high pressure discharges or in stellar atmospheres whether at high or low pressure, these last being complicated by their vast extension over space. A working criterion for a low pressure gas discharge, from the optical point of view, can be that it should not appreciably reabsorb its radiations or in other words that spontaneous emission is its sole radiation process.

For those transitions which pass unhindered through the gas, the analysis of radiated intensity is straight forward. If N_j refers to the population of the jth excited state of the radiator, then the essential changes in this population will be brought about by radiative transition to lower states, radiative transitions from upper states, absorption of blockaded ground state radiations, and collision interactions with other particles. Then a system of equations governs the energy level populations.

$$\frac{\partial N_j}{\partial t} = \left\{ D_j \nabla^2 N_j + B_{0j} \int N_0 - \sum_{i=0}^{j-1} A_{ji} N_j \right\} + \left\{ \sum_{K=j+1}^{\infty} A_{Kj} N_K \right\} + P_j \quad \ldots(1.24)$$

where D_j is the diffusion coefficient for state j radiators. When j is one of those states which radiate to the ground state, then assuming that the diffusion treatment of blockaded radiation is adequate, a second set of equation is needed.

$$\frac{\partial f}{\partial t} = D_\nu \nabla^2 f + h\nu_{j0} \left[A_{j0} N_j - B_{0j} f N_0 \right] \quad \ldots(1.25)$$

where D_ν is a photon diffusion coefficient defined as $c/3R$ where "c" is the velocity of light and R is photon absorption coefficient. Eliminating the absorption term between the last two equations and assuming that the gas density is large enough that the photons spend much less time in the free state than in the radiators

$$N_j > P/h\nu$$

where $f(\nu_{ji})$ = monochromatic radiant energy density.
P = production function.

one set of equations can be obtained as

$$\frac{\partial N_j}{\partial t} = D_j \nabla^2 N_j - \sum_{i=1}^{j-1} A_{ji} N_j + \sum_{K=j+1}^{\infty} A_{Kj} N_K + P_j \qquad \ldots(1.26)$$

Elatation is the primordial source of all radiation from gas discharges. Radiators in any state may absorb the kinetic energy of impinging particles and go over into higher energy states with a minimum of restriction by selection between states for which the reverse radiative transition is allowed.

Experimental measurements of the cross sections which gas molecules offer to electrons for various exciting transitions have been carried out along two general lines. First, electrical measurements have been made of the fraction of electrons which have lost discrete amounts of energy. Second, optical measurements have been made of the number of photons of a given species emerging from a gas through which a known charge has passed. Both methods are difficult and the results have proved quantitatively discordant with each other and with theory whenever quantitative measurements have been possible.

There are different processes of excitation where the higher energy levels are populated. The electron impacts of the first kind in where electrons collide with other particles to give its excitation energy and the process is governed by the relation

$$\frac{dN}{dt} = \sigma N_1 N_2 \bar{u} \qquad \ldots(1.27)$$

where N_1 and N_2 are concentrations of colliding particles of both species,

$\bar{u}$ their mean relative velocity and $\frac{dN}{dt}$ is the rate of production of the altered molecular state. Excitation by massive particle impacts have got radiation effeciencies extremely low compared to that of electron and it is easy to set up subsidiary processes involving impacts of free electrons which will mask the desired effects.

In the process of excitation by absorption of photons it is found as in the emission of radiation, the selection rules appear to govern its absorption rigorously. Apparant deviations have always resulted in the discovery of subsidiary process involving other systems. The role of volume recombination into excited states proved as having very minor effect both electrically and and in the production of radiation at low pressures. Volume recombination of an electron, +ve ion and photon system and positive ion negative ion system may be looked upon as potentially leading to radiation. Volume recombination in any of its forms, while inconspicuous in active discharges, is the prominent and unique source of radiation from low pressure after glows. In complete generality, the problem of the flux of population of any one state must be dealt with by finding the fluxes for all states. In restricted cases however, it is possible to define a cascading coefficient which makes the general solution unnecessary. The restriction is fulfilled by (1) electron excitation from the ground state (2) recombination process (3) collisions of the second kind between foreign radiators and ground state particles, where the necessity that the original population of each state be derived from a source which is independent of the individual excited state populations is fulfilled. The process of cascading is important to spontaneous transition from the upper states of a radiator to the lower states which furnishes a significant portion, although not a major portion of population of each state.

The chief process of depopulating levels is almost invariably spontaneous emission. Collisions of the second kind are also a depopulating process as well as a populating process. Sometimes the result of the collision is an exchange of

states in which both populating and depopulating processes figure. Rössler and Schönherr (1938) studied the radiation of Hg ($6^3P_1 - 6^1S_0$) as a function of pressure and current and identified both pressure and current dependent losses which they attributed to collisions of the second kind with neutrals and electrons respectively. At large densities many workers have observed that a marked decrease sets in the intensity of radiations from discharges. This is specially true of the inert gases. In helium this decrease sets in at approximately 2.5 mm. Hg. Meyerott (1944) opened the way to an understanding of this process by the suggestion that the population of He_2 and He_2^+ and presumably other molecular ions might be larger than previously estimated. Bates (1950) suggested that the large microwave recombination coefficients could be understood as dissociative recombination with He^+. Phelps and Brown (1952) isolated large quantities of He^+ from helium discharges at 5 mm. Hg. pressure but found little at 1 mm. Hg. Hornbeck and Molnar (1951) suggested that the appearance potentials of molecular ions in noble gases could only be explained by the existence of a collision process of the second kind in which excited helium atoms formed molecular ions upon collision with neutral atoms. Fowler and Duffendack (1949) had proposed an unidetified process of the second kind as one possible cause of the intensity decrease but discounted the possibility because of the supposition that it would require degradation of the entire excitation energy in the kinetic form, in defiance of the Franck-Condon principle. The dependence of the intensity of the spectral lines upon the tube current was investigated at both high and low gas densities holding tube potential constant. The relationship was found to be linear within the experimental error between the extremes of 1.4×10^{14} and 2.5×10^{16} atoms/c.c. This relationship was observed for all types of transitions and over a current range from one to one hundred mA. This has been further extended by the work of Lees who reports a linear dependence existing as low as 0.2 mA for all transitions. Special

intensities as a function of gas density of particles per unit volume were investigated over a wide range of density extending from 2×10^{13} to 1×10^{18} molecules /c.c. holding tube current and potential constant. All the density vs. intensity curves have essentially the same form, rate of decay and location of the maximum. One outstanding exception is found in the $2^3P - 3^3D$ transition which had a broader maximum and slower rate of decay than the others. The maximum was located at about 15 mm. Hg. pressure about five times the value found for other transitions. Since this transition corresponds to 5875 Å, the anomaly leads to a pronounced color change in the discharge between high and low pressures, the high pressure discharge being yellow, while the low pressure discharge is bluish green. Measurements have been made of the intensity of radiation from the low voltage arc in helium as a function of gas density, tube current and tube potential. The experimental results indicate that the radiation is the result of a primary electron process. This process has been generally assumed to be direct excitation. Such an explanation is not fully in accord with the phenomena observed and so possibility of an unrecognised process has been suggested.

Little or nothing has been reported about the radiation from Townsend discharge. Cragge and Joffe (1947) indirectly showed the presence of high energy photons in this type of discharge. If β_j is the number of excitation to state j per unit length of electron path defined as

$$\beta_j = \frac{N_0 \int_0^\infty \sigma_j u^3 \phi(u)\, du}{U \int_0^\infty u^2 \phi(u)\, du} \qquad \ldots(1.28)$$

where U is the drift velocity for electrons in the electric field present, and $\phi(u)$ is the electron distribution compatible with the field, then the energy of radiation in a transition ν_{ji} is given by

$$h\nu_{ji} A_{ji} \frac{\beta_j}{\alpha} \left(e^{\alpha x} - 1\right)$$

per avalanche of length x . From this basic expression the power radiated can be calculated in the various eventualities which may arise.

The radiation property of the monoenergetic electron discharge was studied and utilised for different purpose of measurements. Maxwell (1928, 1930, 1931, 1932) found that it was possible to detect the life times of ionic excited states by sidewise shift of their radiations in the applied electric cross field. Intensity variation of the spark lines due to the motion of the positive ions was the main problem of observation . Spark lines due to singly and doubly charged ions show a variation of intensity along their length in such a manner that it is possible to distinguish tem from the arc lines. It is also possible to differentiate between the lines of the first and second spark spectrum. Electrons in mercury vapour with velocities greater than the ionisation potential were confined into a beam by a magnetic field. The light produced was projected on the slit of a spectroscope with the direction of the beam at right angle to the slit. Perpendicular to the beam an electric field withdrew positive ions before they recombined. The intensity of the arc lines was found to be independent of the electric field which indicates that recombination contributes very little to the formation of these lines. Two sets of exposures of different spectral lines with and without cross field were taken and compared. It is noticed that the arc lines and the lines of the first spark spectrum are uneffected by the field while the lines due to the doubly charged ions show a change in their intensity distribution.

Duffendeck and Koppius (1939) examining the radiation from negative glow found that intensities of the family of transitions ending with 6^3P states increased according to an exponential saturation curve with mercury concentration and increased linearly with tube current. Assuming in steady state of discharge, the intensity of a spectral line due to the transition from state j to state K of the atom will be proportional to the concentration N_j , of atoms in the state j, the probability of transition A_{jk} and the magnitude of the light quantum $h\nu$ i.e.

$$I_{\nu_j} \propto N_j A_{jK} h\nu$$

and in terms of the current i, passing through the discharge, it was

written

$$I_{\nu_j} = A \cdot i \left(1 - e^{p \cdot d/\lambda_{IE}}\right) P_j \quad \ldots(1.29)$$

where "A" is a multiplicative constant, " p " is the pressure in mm. Hg, "d" is distance between electrodes and λ_{IE} = average mean free path for the excitation of the mercury atom at unit pressure i.e.

$$\frac{1}{\lambda_E} = \frac{p}{\lambda_{IE}} \quad \ldots(1.30)$$

(0°C and 1 mm. Hg.) and when mercury and other foreign atom is present the formula was modified to

$$I_{\nu_j} = A \cdot i \cdot \frac{1/\lambda_E}{1/\lambda_E + 1/\lambda_A} \left(1 - e^{p \cdot d/\lambda_m}\right) P_j \quad \ldots(1.31)$$

where λ_A is the average mean free path of an electron for excitation of a foreign atom. λ_m is the average mean free path of an electron for excitation of either a mercury or a foreign atom. At the densities studied no reversal whatsoever was observed. In admixtures of argon, in addition to the same saturation behavior, excitation was found to be apportioned between mercury and argon in the proportions of their relative abundances. Everything observed was in complete accord with the hypothesis that monoenergetic primary electrons in a fixed finite numbers were expended in single collisions to the extent to which the abundance of obstructing molecules permitted. Assuming monoenergetic stream of electrons having a particle current density, i/e, the number of losses from a unit area of the beam in a distance dx is

$$\frac{di}{e} = -\sigma \cdot \frac{i}{e} \cdot N_0 \cdot dx \quad \ldots(1.32)$$

and is equal to the change of particle current density. Integrating

$$i = i_0 \, e^{-\sigma N_0 x} \quad \ldots(1.33)$$

is the equation of decrement of the primary electron stream. The cross section σ is the cross section for all significant energy losses, ionisation plus excitation of all kinds. The power radiated per unit volume in any transition excited by the electron stream is now given by

$$\beta_{ji} \cdot h \cdot \nu_{ji} \cdot \sigma_j \cdot \frac{i_o}{e} \cdot N_o \cdot e^{-\sigma N_o x}$$

Integrated over the whole stream from cathode to anode the power radiated is

$$\beta_{ji} \cdot h \nu_{ji} \cdot \frac{\sigma_j}{\sigma} \cdot \frac{I_o}{e} \left(1 - e^{-\sigma N_o x}\right)$$

where "β" measures transition probabilities.

While the theoritical dependence conforms well with the experimental result, the total elatation cross section σ required by Duffendack and Koppius[u] to fit their curves is surprisingly large. In the radiations stimulated by monoenergetic electrons, general opinion favors direct electron excitation as the chief mechanism of population rather than recombination.

The thermal electron discharges are positive columns of glows, arcs and sparks, high frequency discharges and anode glows. Analysis of the radiation from thermal discharges must be made on a basis of electron concentration and its velocity distribution. Discharges are never and can never be in true thermal equilibrium. Experiment shows and theory suggests that it is reasonably accurate to consider the electron temperature[te], which governs the velocity distribution, constant over large regions of the discharge. This is because the electron temperature is almost directly proportional to the electrostatic field in the gas and the electrostatic field is tangentially constant at least from its conservative properties. Further more, in the absence of space charges which are usually small in regions where thermal elatation predominates, there can be no change in the normal component either thus establishing the conditions for constancy of electron temperature[t]. A fairly general theory of this type can be based on an assumption of separability of space and velocity dependences of the electron distribution to give the number of primary electrons

dN_- at x, y, Z having velocity u_x, u_y, u_z

as

$$dN_- = N_-(x, y, Z)\, dx \cdot dy \cdot dZ \cdot \Phi(u_x \cdot u_y \cdot u_z) \cdot du_x \cdot du_y \cdot du_z.$$

The production function can now be written for elatations of a type governed by

the cross-section $\sigma_j(u)$ per unit volume per unit time

$$P_j = 4\pi N_- \int_{u_{min}}^{\infty} u^3 \sigma_j \phi . du .$$ where

$$u = \left(u_x^2 + u_y^2 + u_z^2\right)^{1/2}$$

and electron velocity is assumed much larger than molecular velocity. Since the major portion of discharge current density is given by the expression $i = eN_- U$ for the electron current density at least in gases which do not attach electrons, the production is directly proportional to current density, and if radiation is the chief energy loss mechanism, the radiation must be proportional to the current.

Much qualitative and some truly quantitative knowledge exist concerning the radiation from the glow discharge. A large part of this applies to the positive column which is by far the most spectracular region of the discharge. Angstroom found that the radiation reaching a bolometer from the positive column was only a few percent of the energy supplied to the column electrically probably because the tube walls failed to transmit the bulk of the radiation of the discharge. Penning (1938) has made an analysis of the energy losses by the thermal electrons swarm. He finds that when an electron current moves through a gas, the energy received from the electric field is partly lost in collisions with the gas molecules. An infinitely small electron current " i " flows in a homogenous electric field E which case occure in the starting of a glow discharge between large parallel plates at not too high pressures. From the observations it is clear that only for very low values of $E/_p$ the energy transfer in elastic collisions is important which may be treated to a certain extent with the classical laws for mechanical collisions. At higher values of $E/_p$ however the conduction of electricity through the gas is governed wholly by the laws of quantised energy transfer between electrons, molecules and excited molecules.

Hodges and Michels (1928) examined the pressure dependence of radiations from positive column of helium discharge. The absolute and relative intensities

of thirteen lines of the helium spectrum extending through the visible regions have been measured by a modification of the method developed by Ornstein (1925) and Dorgelo (1925). The method consisted in comparing each line directly with the known emission from a tungsten filament, operated under constant conditions. The results for a discharge in a capillary tube, with pressures from 1.92 to 34.3 mm. Hg show that the absolute intensities increase rapidly to a maximum for pressures in the neighbourhood of 2 to 4 mm, below which they tend toward zero. The relative intensities of the singlet system are favoured by lowered pressures, and the higher members of the triplet system are likewise favoured over the lower members, while the relative intensities within the singlet series show little effect of pressure. Following observation of Dymond (1925) that the efficiency of excitation of a given initial state is greatest when the energy of the exciting electron is only slightly greater than that needed to excite that state, they obtained the probability relation from kinetic theory consideration as

$$e^{-V_1/gy} - e^{-V_2/gy}$$

where for a given state with energy V_1 will be excited in most cases by electrons which have, at the time of impact, an energy between that necessary for excitation of this state and that of the next higher state V_2. "g" is the potential gradient in the tube and "y" is the electron mean free path. This relation though dosnot agree quantitatively yet gives the general type of curve obtained. The indications are that the two processes (1) dissociative recombination of molecular helium ions and (2) collisions of excited states with neutrals are active here also. The enhancement of the upper triplet states is understandable if process (2) is active, since the energy deficiency between corresponding singlet and triplet levels is less for the higher levels.

Parkinson (1951) observed interesting behaviour in a 15 Kc alternating current glow discharge in air and noble gases, and especially in helium, where the molecular ion seems to play an important role. Observing the light in front of one electrode which is alternately a cathode and an anode, Parkinson found that the neutral molecular band spectrum was strong during the anode period

and absent during the cathode period. At the same time atomic radiations were observed which displayed the same after glow decay behaviour as the molecular bands during the anode cycle, but followed the discharge current wave form during the cathode cycle. Low level singlet transitions showed a perponderence of cathode cycle current governed response over anode cycle after glow, but high level triplets have completely the reverse behaviour. Parkinson found that all decays occured with the same time constant (35 μsec.) . He found also that the intensity of the molecular and atomic after glows decreased very rapidly with pressure, as would be expected if the the three body process of molecular ion formation were the contributory case. The light from the electrodes of an ac. glow discharge in helium is found to be particularly rich in the He_2 spectrum. This light occurs at an unusual phase of the voltage cycle. The process which forms excited molecules also gives rise to excited atoms. Further more the process is inhabited by the presence of an electric field. There are indications that the process is one of recombination between electrons and atomic positive ions. It is a well known phenomenon that the light from near the anode of a d.c. glow discharge extends only as far as the front face of the anode being free of any luminosity. In an a.c. discharge the regions areund the two electrodes appear the same to the eye. If investigated with a photomultiplier tube and oscilloscope it is found that the situation is really the same as in the d.c. case. The output of light is confined to the time during which the electrode is a cathode. There is no light output during the anode half cycle except from the positive column, which extends from a point a few m.m. in front of the front face of the electrode along the tube to the other electrode. Further more the light from the electrode during the cathode half cycle is directly proportional to the current which itself is directly proportional to and in phase with the voltage. Thus if the current is a sine wave, the wave from of the light output is like the output of a half wave rectifier. This applies upto about 100 Kc. The above considerations have been found to be applied to discharges in air, neon, argon and krypton at all pressures

and to helium below about 5 mm. The pressure dependence of molecular light and molecular component of atomic light show an increase with pressure in the lower pressure region upto 35 mm and 15 mm after which for higher pressure the intensity decreases. But the normal component of atomic light intensity shows gradual increase as the pressure is lowered. The intensity of molecular light is governed by two independent factors. One is the presence of an electric field. The other factor causes an approximately exponential decrease in molecular light with a time constant of 35 μ sec. This time constant is independent of pressure. It is evidently due to a decrease in the concentration of some participant in the process which forms molecules. It seems unlikely that this can represent the fall in the concentration of metastable atoms. The rate of decrease found here is reasonable for the concentration of positive atomic ions. The atomic spectrum of the negative glow during the anode half cycle is suggestive of a recombination spectrum. The different considerations point to a recombination process in which an excited molecule and an excited atom are formed.

Microwave and high frequency discharges have almost identical emission and temperature characteristics with steady glow discharges of the same power density. In a point to point comparison Beck (1935) found a steady glow discharge in mercury indistinguishable from 100 Mc/s discharge. Margenau and Hartmann (1948) have shown that the theory of microwave discharges leads to this same conclusion of similarity, barring the space charge effects which are possible in steady discharges. Corliss, Bozman and Westfall (1953) find that an electrodeless discharge at 300 Mc/s will excite the pure metal spectrum of involatile metals which have been introduced as pure halides. The atomic spectra of high melting point metals can be excited in electrodeless lamps if a volatile salt of the metal is introduced into the lamp together with a noble gas at a pressure of a few mm. Hg. The lamps are simply prepared from lengths of pyrex or vycor tubing, excited with microwaves and produce sharp spectral lines free from self reversal. Lamps have been prepared which emit atomic spectra of Be, Ti, Fe, Ni,

Cu, Mo and U . Relative intensities of copper line wavelength Å 5153.24, 5218.20, 5105.54, 5782.13 and 5700.24 from d.c. arcs and a $CuCl_2$ lamp are measured. Frisch and Schreiden (1949) proposed a similar discharge mechanism for quantitative spectrographic analysis of gas mixtures.

Rohlin (1939) observed the effect of a magnetic field on the radiation from a mercury vapour discharge where

$p \sim 10^{-3}$ m.m.Hg ; $i = 1.5$ to 4 Amp.

He used two solenoids spaced a few cm. apart, the magnetic fields could be coincident, giving an almost uniform field between them or opposite giving a distored field having strong radial components. The image of a diameter section was observed in a spectroscope and the intensities of the 1850 Å and 2537 Å resonance lines were measured by the brightness of a flourescent probe placed in the tube. With coincident fields the discharge is visibly costricted into a cord, at first rapidly and then more slowly with increasing H. At higher pressures or currents the effect is less marked and finally ceases to be noticeable. The cord follows the lines of magnetic force and can be moved about by displacing the solenoid coils or by the presence of a magnetic field. At the centre of the tube the variation of relative intensity of several lines like 5791 Å , 3906 Å shows first a maxima near H = 100 oersted and almost no change at higher magnetic field. The line 3704Å gradually decreases in relative intensity with magnetic field with almost no change for magnetic field of the order of 200 oersted. The fall in intensity is pronounced in lines from high excitation levels, indicating a decrease in number of fast electrons. The maximum is due to two opposing effects, the increased concentration of electrons at centre and the decrease in their energy. Rohlin comes to the general conclusion that the constriction of the discharge is due to the radial components of the magnetic field on the cathode side of the plasma: the longitudinal part of the field however, did not extend far enough for a proper assessment of its effect.

Experiments have been made on the effect of magnetic fields on the radiation from the column of a constricted discharge in a capillary tube in transverse magnetic field. Kulkarni (1944) studying discharges in He, Ne and N_2 found that the intensity of a spectrum line reaches a maximum and then decreases quickly with increasing magnetic field H. The value of H at the intensity maximum depends on the wavelength of the line and the presence of any foreign gas. For a given discharge voltage V there is a critical H above which the discharge goes out and just below which it throbs. In these conditions the rare gases show the molecular spectrum in regions near the electrodes. The applied potential for maintainance of discharge in ^{5} of the order of 10 KV to 15 KV and H of the order of 10 Kilo oersted without any specification of pressure. In the Zeeman effect experiment usually performed in the laboratory with a neon tube, it is observed that the magnetic field, besides producting the well known splitting of the lines, effects to a marked extent the intensity of the glow in the discharge tube. It was thought that a detailed spectroscopic investigation of the effect of the magnetic field on the variation in the intensity distribution amongst the spectral lines, would give useful information about the collision processes involved in the mechanism of discharge of electricity in rarefied gases. Preliminary experiments with helium, neon and hydrogen have revealed some interesting facts. The experiments were performed with the ordinary capillry discharge tubes placed between the poles of an electromagnet capable of giving a field upto 10,000 Gauss. The tubes were worked between 10 and 15 K volts. The results of observations may be summarised as follows :- (1) The intensity of lines increases with the magnetic field, reaches a maximum and then decreases, the decrease being more rapid than the increase. This is shown in spectrum of helium with magnetic fields 4, 6.2 and 7.8 K Gauss. (2) The field at which a line reaches its maximum intensity, the conditions of pressure and excitation remaining the same, depends on two factors (a) wavelength and (b) the presence of foreign gas. The dependence

on wavelength was best exhibited with the Balmer series of hydrogen. " H_δ " appeared as a weak line in zero field, reached a maximum intensity at 4000 Gauss, after which the intensity fell rapidly and the line was not excited at all at higher field. " H_γ " reached its maximum intensity at 600 gauss, whereas H_β and H_α showed a continous increase in intensity even upto 10000 Gauss, the maximum field obtainable in the experiment. The effect of foreign gas on the intensity of the lines is shown which gives the spectra of a mixture of helium and neon. The spectrum were obtained for magnetic fields of strength 4.9, 7 and 8.2 Kilo Gauss respectively. It is to be noted here that in contrast with the case of (1) the lines continuously increase in intensity without showing a maximum. The effect of the foreign neon gas seems to be to increase the field strength at which the helium lines will have their maximum intensity. (3), For a given applied potential at the terminals there is what may be called a "critical" field at which the discharge stops altogether and the tube becomes nonconducting. As this critical field is approached and just before what may be called the throbbing state of the tube, the intensity in the capillary portions which is kept in the magnetic field is considerably reduced and the intensity of the glow in the wider portions of the tube near the electrodes, is correspondingly increased. A spectrum of helium from this wider portions is shown under this condition without magnetic field and with 6.2K Gauss magnetic field. It is observed that without the field only weak atomic spectrum is produced, while with the field on, not only is the intensity of the atomic lines increased but the molecular spectrum of helium is fully brought out. The spectra from the wider portions of the tube for lower values of the field at the capillary, showed only the atomic lines. It is to be inferred that the excitation of the helium molecular bands is a sudden process occuring within a narrow range of the field strength near about the throbbing field. Most of the He molecular bands are identified with the triplet electronic states and they involve only

two lowest states

$$2\,p\pi^3\,{}^1\Pi_g \qquad \text{and} \qquad 2s\,\sigma^3\,{}^1\Sigma_u^+$$

Davies (1953) made measurements of the intensity distribution in the recombination spectrum, the relative densities of the electrons and their velocity distribution in the positive column of a caesium discharge as determined in the presence of a longitudinal magnetic field. The effect of a longitudinal magnetic field was investigated for both d.c. and r.f. discharges. In both cases, as the intensity of the magnetic field was increased, the glow surrounding each of the electrodes was compressed towards the electrode, but no visible effect was produced in the positive column. The spectrographic determination of the distribution of intensity in the recombination continuum showed that there was a Maxwellian distribution of electron speeds in all discharges investigated, within the experimental error. An initial survey was carried out over the available range of discharge pressure with the r.f. discharge current maintained at 0.98 A (r.m.s.). In this case the electron temperature T_1 was evaluated using equation

$$\log\left\{\nu \cdot J(\nu)\right\} = -\frac{h\nu}{KT_1} + \text{Constant} \qquad \ldots(1.34)$$

where $J(\nu)$ is the intensity of the 6P recombination radiation of frequency ν. An additional experiment with r.f. excitation was carried out with a mean current density of 5A cm^{-2} at a frequency of 6.65 Mc/s. At a pressure of 0.078 mm. Hg, the value of T_1 was increased by 175 ± 100.K by a magnetic field of intensity H = 1450 Gauss, from its initial value of 4000.K for H = 0. This increase was determined using equations

$$N_{1a}/N_{1b} = \left[J_a(\nu)/J_b(\nu)\right]^{1/2}\left(T_{1a}/T_{1b}\right)^{3/4} \exp\left[h\nu\left(T_{1a}^{-1} - T_{1b}^{-1}\right)/2K\right]$$

i.e.

$$\frac{d}{d\nu}\left[\log\left\{J_a(\nu)/J_b(\nu)\right\}\right] = -2{\cdot}084\times10^{-11}\left(T_{1a}^{-1} - T_{1b}^{-1}\right)$$

where N_{1a} and N_{1b} are the number of electrons /c.c. in state "a" and "b" respectively.

In all the experiments in which the discharge was excited by r.f. energy, the application of a longitudinal magnetic field produced no measurable change in the axial value of the electron density N_1 . It is estimated that a change in the value of N_1 of 5% or more would have been detected. Measurements were also made of the change produced in the value of the total potential drop across the discharge tube when it was subject to a longitudinal magnetic field. In all cases the change in potential difference across the tube was less than 3% for a value of the field H = 1500 Gauss. In general the potential difference was increased by a magnetic field of this value, but the increase was not always a monotonic function of H.

Hobbs, Mcwhirter, Griffin and Jones (1961) studied both experimentally and theoretically the temporal variation of the intensity of line radiation in the ultraviolet from impurities in the zeta discharge. The comparison between computed and observed intensities is discussed in terms of simple ionisation recombination and excitation processes and used to establish the adequacy of the ionisation coefficients employed. If the spectrum emitted by zeta discharge is examined it is found to contain lines of various impurity elements. Further examination shows that the line intensities vary in time during the period of the discharge in a grossly reproducible manner. The intensity variation of the impurity spectral lines from the impurities nitrogen, carbon, oxygen has been observed from the zeta discharge. The data was obtained using a grazing incidence vacuum monochromator with an effective wavelength range of 100 Å to 1500 Å. The line intensities were measured by a photomultiplier with a sodium salicylate phosphor and were recorded by photographing an oscilloscope trace.

Different authors utilised the absolute intensity of a line and relative intensity of a family of lines to measure the electron density, electron temperature etc. The absolute intensity I of a spectral line by a transition

from an upper state "S" to a lower state "t" is given by Pearce (1958)

$$I = \frac{g_s n e^{-E_s/KT} A_{st} h\nu_0}{U(T) \cdot 4\pi} \qquad \ldots(1.35)$$

where suffixes "S" and "t" indicate the upper and lower states respectively and

g_s = statistical weight of the upper state

n = total number of atoms/c.c. of the element concerned

E_s = energy of the upper state in ergs

K = Boltzman's constant.

T = absolute temperature °K ; A_{st} = Einstein's transition probability from upper to lower level

h = Planck's constant; ν_0 = central frequency of the line

U(T)= partition function of the atom.

John (1961) utilised several methods for determining the temperature of a plasma jet derived from argon containing 5% hydrogen based on the absolute intensity of H_α or H_β line, the relative intensity of H_α and H_β lines and the profile of H_β line. Intensity measurements were made photoelectrically.

Reeves and Parkinson (1961) also measured the peak brightness temperature and spectral energy distribution of flash discharges of Lyman, co-axial and capillary types for the wavelength range from 2580 Å to 4520 Å by measuring the intensity of lines and utilising the derived emission coefficient for low radiation density for the frequency independent region as

$$\epsilon_\nu = \frac{32\pi^2}{3\sqrt{3}} \cdot \frac{e^6}{c^2(2\pi m)^{3/2}} \cdot (\overline{Z+S})^2 \cdot \frac{N_e N_i}{(KT)^{1/2}} \qquad \ldots(1.36)$$

and for frequency dependent region

$$\epsilon_\nu = \frac{32\pi^2}{3\sqrt{3}} \cdot \frac{e^6}{c^3(2\pi m)^{3/2}} \cdot (Z+S)^2 \cdot \frac{N_e N_i}{(KT)^{1/2}} \cdot \frac{\varepsilon^{h\nu_g/KT}}{(\varepsilon^{h\nu/KT} - 1)} \qquad \ldots(1.37)$$

where Ne = electron concentration, e = electron charge, Ni = ion concentration, Z = atomic number and $\overline{Z+S}$ = effective atomic number in which

$$n^2 \cdot \frac{(E_i - E_n)}{E_{iH}} < \overline{Z+S} < Z^2$$

when Ei = ionisation energy n = principle quantum number, En = excitation energy E_{iH} = ionisation energy of hydrogen. Using Wien's law for the standard lamp and Planck's for the flash tube, the brightness temperature of the standard capillary discharge was obtained from the relationship

$$I_{SL}/I_{FL} = \epsilon^{-c_2/\lambda.S}\left(\epsilon^{c_2/\lambda.S_{FL}} - 1\right) \qquad ..(1.38)$$

when S = brightness temperature of the standard lamp, S_{FL} = brightness temperature of flash source, C_2 = 1.438 cm deg., I_{FL} = recorded signal for flash source, I_{SL} = recorded signal for standard lamp.

Golant, Krivosheev and Tachnev (1966) investigated the plasma parameters for a stationary ultrahigh frequency discharge in argon and their dependence on magnetic field intensity. The U.H.F. is 3150 Mc/s. It is observed that the charged particle densities and total light intensities are maximum near the second and third harmonics of the electron cyclotron frequency i.e.

$$\omega = 2\omega_H \ , \ 3\omega_H$$

No maxima are observed near the electron cyclotron resonance frequency. When the U.H.F. power input is approximately 10 watt / cm^3, the magnetic field 500 oerstede and pressure of argon approximately 1 x 10^{-2} mm. Hg. densities in excess of 10^{12} $cm.^{-3}$ are obtained.

Burlamacchi and Pratesi (1966) reported the enhanced emission of the 3889 Å ($3^3P - 2^3s$) and 5016 Å ($3^1P - 2^1s$) lines of He during the initial transient of a pulsed r.f. discharge with oscillator frequency at 24 Mc/s. Very strong overshoots have been observed in the 3889 Å and 5016 Å lines when viewed along the axis of the tube, both in pure He and He - He mixture. The overshoots of the 3889 Å and 5016 Å lines have been interpreted as due to the low 2S metastable densities and hence low absorption of these lines during the initial transient. A measurement of the absorption present

under pulsed condition has been attempted for the 3889 Å and 5016 Å lines. The pressure dependence of the 5016 Å output is shown for both He and He - Ne. The full signal intensity is plotted. The optimum values of pressure for steady state and overshot outputs results from a balance between the increasing atom density on one side and the increasing loss mechanisms and the falling electron temperature on the other side. No substantial difference has been found between the cases of pure gas and He - Ne mixture, though in the latter case the ratio between peak and steady state values is bigger and the emission vanishes at higher pressure.

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CHAPTER - II.

SCOPE AND OBJECT OF THE PRESENT WORK

SUMMARY OF THE PRESENT WORK

SCOPE AND OBJECT OF THE PRESENT WORK

Though the various aspects of the phenomena of electrical discharge have been explained by the exhisting theories there are certain problems which require more exhustive theoretical and experimental treatment and the present work undertakes to investigate some of these problems.

(a) BREAKDOWN OF GASES BY A RADIOFREQUENCY ELECTRIC FIELD.

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 dominent factors by which electrons are lost are diffusion and mobility and if the gas is an electron attaching one, then by electron attachment also. The electrons are assumed to be produced mainly by ionisation collision. Based on these assumptions Herlin & Brown (1947)[8] developed the theory of high frequency breakdown where the dominent cause for electron removal process is diffusion. Starting from a molecular model and assuming suitable crossections for ionization and excitation processes Kihara (1952) has developed a phenomenological theory of electrical discharge phenomena. In his theory he has assumed both diffusion and mobility as electron removal processes. In order to ascertain which process is dominent under certain conditions as the cause of electron removing process it is necessary to carry out experiments with discharge tubes of different dimensions and the pressure varying within wide limits. Consequently breakdown experiments have been performed with discharge tubes of different dimensions while the pressure is varied from a few microns of Hg. to a few millimeters of Hg. and with different frequencies of excitation. It will also be of interest to see whether the experimental results can be explained by Kihara's theory because no systematic experimental verification of the theory has so far been carried out. Electron attachment is also another process by which electrons are lost in electron attaching gases and this factor has to be incorporated in the general equation of breakdown. Attempt will be made to take into consideration the

effect of attachment and to see whether the experimental results support the modified theory.

The breakdown of a gas excited by a radiofrequency voltage in presence of a transverse magnetic field has been studied by previous workers and theoretical interpretation of the experimental results has been advanced. Both longitudinal and transverse magnetic fields have been used and the frequency of excitation and the value of the magnetic field have been adjusted in such a way that the relation $\omega = eH/mc$ is satisfied where ω is the frequency of the applied field and eH/mc is the cyclotron frequency. It will be of interest to see how the breakdown voltage as well as the pressure at which the breakdown voltage becomes a minimum change when the magnetic field is far removed from the resonance value. The procedure to adopt in such a case is to modify the breakdown equation taking into account the effect of magnetic field. It is proposed to carry out such calculation in case of both Brown's and Kihara's theory and verify the theoretical deductions with the experimental observations. This study is expected to give us information regarding the interaction of the magnetic field with ionised gases.

(b) GAS BREAKDOWN IN A RADIOFREQUENCY FIELD IN PRESENCE OF A SUPERIMPOSED D.C. FIELD.

It was observed by Verela (1947) and Kirchner (1947) that the breakdown potential of a gas excited by a radiofrequency field increased when a d.c. field is superimposed across the discharge tube. It was expected however that the presence of the d.c. field would hasten ionisation and a smaller breakdown voltage would be necessary, but the results were contrary to what was expected. Vernarin and Brown (1950) calculated theoretically the distribution function of electrons in an ionised gas in presence of both radiofrequency and d.c. fields and they suggested that when the radiofrequency field is only present, the

electrons are lost mainly by diffusion but when in addition a d.c. field is applied the electrons are lost by mobility also. This increase in loss can be compensated by the increase in generation of electrons and consequently the value of the radiofrequency breakdown voltage increases. The theory was verified by Varnerin and Brown (1950) in case of air at a pressure 38 mm. of Hg. where a d.c. field upto 200 volts/cm was applied. No systematic study of the breakdown of gases under the simultaneous action of the a.c. and d.c. fields have so far been made and it is expected that this study will throw more light in the mechanism of breakdown. As Kihara's theory (1952) is a general one it will be interesting to see how the theory can be further modified by taking into consideration the increased loss due to mobility and to corroborate it with the findings of the experimental results. Further Varnerin and Brown (1950) in deducing their theory only considered the effects of increased loss due to mobility and diffusion but did not take into account the contribution made by increased ionization due to d.c. field. This factor may be small when the applied d.c. field is small but it has to be taken into consideration when the d.c. field becomes comparable with the radiofrequency voltage applied. Consequently the general theory has to be modified by taking into consideration this increase in the electron generation process and it is expected that at a certain value of the d.c. field the breakdown voltage will show a maximum and with the further increase of the applied d.c.voltage, the radiofrequency breakdown voltage will show a decrease, because at higher d.c. voltages ionization by the d.c. field will be considerable. The object of this part of the work is thus to see whether the breakdown phenomena will follow this process and whether the experimental results agree with the theory developed. The study of the effect of attachment in this type of gas breakdown in some electron attaching gases will also be studied.

(c) SECONDARY ELECTRON RESONANCE BREAKDOWN MECHANISM

The theory of mechanism of breakdown of a gas at pressures less than a few microns and excited by a radiofrequency field has been provided by Gill and Von Engel (1948) and Hatch and Williams (1953, 1954). It has now been established that breakdown is caused by the increase of electron by the resonance of secondary electrons with the electric field. A few electrons present initially by natural causes were accelerated to one end electrode where they produced secondary electrons by impact. These secondaries where emitted in a reverse electric field which carried them to the opposite electrode in approximately half a cycle to produce another group of secondaries. If secondary emission yield is greater than unity, electrons are multiplied to a very large quantity in a very short duration and this results in a breakdown of the gas. Hatch and Williams extended the theory by assuming higher modes besides the conventional half cycle one. The theory of Gill and Von Engel predicts an cut off law relating cut off frequency and electrode separation. Though the above theory can explain most of the experimental observations, it is worth while to investigate some of the consequences of the theory with regard to variation of starting voltage and the cut off frequency with the length of the discharge tube.

The effect of super imposing an external field upon this type of discharge was investigated by Kossel and Krebs (1954) but no quantitative explanation of the observed results was provided. It has been found that superimposing a d.c. field parallel to high frequency field starting can be made more difficult. A small static magnetic field perpendicular to high frequency electric field causes a general increase in breakdown potential and a lowering of the cut off frequency without changing the nature of the ($E - \lambda$) curve where E is the starting field and λ is the wavelength of the radiofrequency field. Deb and Goswami (1964) made a theoretical approach to the problem when a steady magnetic field is placed perpendicular to the high frequency field.

No systematic observation of the phenomena of the secondary electron resonance under the action of an external magnetic field has so far been undertaken. The object of this part of investigation is to study the effect of a transverse magnetic field on the breakdown potential in discharges controlled by the phenomena of secondary electron resonance and also the effect it produces on the cut off frequency. It is evident that the theory of the previous workers has to be modified to take into consideration the effects produced by the magnetic field and it is presumed that these investigations may throw some light on the mechanism of such discharge.

(d) LIGHT INTENSITY OF GLOWDISCHARGES IN A STEADY MAGNETIC FIELD.

The radiation property of glow discharges excited by d.c. electric field has been studied previously and the different processes contributing to the intensity have been identified. Rossler and Schonherr (1938) identified both pressure and current dependent losses of the radiation of Hg. ($6^3P_1 - 6^1S_0$) and attributed them to the collisions of the second kind with neutrals and electrons respectively. Fowler and Duffendeck (1949) found the dependence of the intensity of spectral lines upon the tube current and observed that the variation is linear within the experimental error for all types of transitions and over a current range of half a milliamp. to one hundred milli ampers . The effect of an external magnetic field on the intensity of glow discharge was studied by Rokhlin (1939) who observed maxima of some of the resonance lines of mercury vapour by applying a longitudinal magnetic field. Kulkarni (1944) studied discharges in some gases, including some rare gases in a transverse magnetic field and found that the intensity of some of the lines shows a maximum at different magnetic field intensity and the magnetic field at which the maxima occurs depends upon the wavelength and the presence of the foreign gas. No mathematical theory was however presented to explain quantitatively the observed experimental results. Though the factors which contribute to the line intensity in a glow discharge have been identified, yet no

systematic theory has so far been developed to explain how the intensity will change when the pressure or the tube current changes or an external perturbing force is superimposed upon the glow discharge. The nature of the exciting field to produce the glow discharge has also not been investigated systematically. Beck (1935) however in the point to point comparison found steady glow discharge in mercury indistinguishable from a 100 Mc/sec discharge and the nature of the radiation property was also found to be identical.

In view of the above consideration it has been decided to study the intensity of lines in glow discharge in various gases when the exciting field is either a d.c. source or a Radiofrequency one. The influence of a transverse magnetic field on the intensity of the lines will be studied and an attempt will be made to develop a theory which can explain the experimental observation. The study is important not only to explain how external perturbing forces affect the factors contributing to intensity but will also help in better understanding of the processes involved in the emission and absorption of spectral lines.

In the present scheme of work, the above problems will be studied experimentally and attempt will be made to advance theories which can explain the observed experimental facts. The subject of Electrical discharge phenomena is receiving more attention now a days because of the availability of new experimental techniques with which it can be investigated and also because it provides basic datas for the science of Plasma Physics.

SUMMARY OF THE PRESENT WORK.

A. DIELECTRIC BREAKDOWN OF GASES BY RADIOFREQUENCY UNIFORM FIELD(ELECTRICAL) (a) WITHOUT SUPERIMPOSED MAGNETIC FIELD (b) WITH NON-RESONANT EXTERNAL d.c. MAGNETIC FIELD TRANVERSE TO ELECTRIC FIELD.

The work has been done in two parts at two different pressure ranges and with different gases as dielectric medium. In the first part measurements of breakdown voltages have been carried out in molecular in gases such as hydrogen, air, oxygen and carbondi-oxide at pressures varying from 1 m.m. to 6 m.m. of mercury, under the excitation of a radiofrequency voltage of frequency 17.6 Mc/sec. The length of the discharge tube is 0.4 cm. and radius 1.4 cm. Measurements have been taken in presence of a transverse magnetic field varying from zero to 1800 gauss. It has been observed that if (E/P) is plotted against " $P\Lambda$ " where "E" is the breakdown voltage per cm., " P " the pressure and " Λ " the diffusion length, then (E/P) gradually decreases with increasing values of " $P\Lambda$ " for all the gases studied. The experimental conditions indicate that electrons are lost by diffusion and the results have been sought to be explained by the theories of Herlin and Brown (1947[8]) and Kihara (1952) after modification due to the effects produced by electron attachment and magnetic field. The theoretical expressions thus deduced can explain the observed results quantitatively for low values of magnetic field and high pressure and the expressions deduced from Herlin and Brown's theory are in better agreement with experimental results than those deduced from Kihara's theory. At higher magnetic fields there is divergence between the theoretical and experimental results which has been attributted to the inadequcy of the equivalent pressure concept at high (H/P) values where H is the magnetic field and also to the uncertainity in the values of molecular constants introduced by Kihara in his theory.

In the second part of the work, the pressure range lies between a few microns to 1.5 mm. of mercury and some rare gases such as helium, neon and argon have been used. Steady d.c. magnetic field placed transverse to high frequency electric field (frequency lies between 4 Mc/sec to 12 Mc/sec) is varied from zero to 120 gauss. The discharge tube length is 10 cm. and the radius of the electrode is 5 cm. The breakdown voltage has been found to be greater than when no magnetic field is present for all values of pressure and the pressure at which the breakdown voltage becomes minimum increases with the increase of the magnetic field. The experimental results indicate that the major diffusion and mobility losses take place along the axis in which the electric field is applied. The theory of Kihara (1952) regarding the breakdown of a gas when it is excited by radiofrequency voltage, ascribed the loss of electrons to diffusion and mobility and Sen and Ghosh (1963) modified this theory by the introduction of the 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 minimum. This work has been undertaken to supplement the verification of this theory and extend it to the case of rare gases under identical conditions of breakdown in a nonresonant transverse magnetic field. In order to conform with the experimental set up, three dimensional treatment of the problem has been carried out but it is observed that one dimensional treatment shows better agreement with the experimental results. The discrepancy with the experimental results for higher values of magnetic field has been attributed to the identical causes as in the earlier experiment.

B. DIELECTRIC BREAKDOWN OF GASES BY RADIOFREQUENCY ELECTRIC FIELD IN THE PRESENCE OF PARALLEL SUPERIMPOSED d.c. FIELD.

Results of high frequency (10 Mc/sec.) breakdown voltage with superimposed d.c. electric field have been obtained for helium, neon argon and the molecular

gas oxygen, keeping the pressure of the gas constant at 10mms of mercury. The variation of applied d.c. voltage along the length of the tube is from zero volts/cm to 70 volts/cm . It is found in all the cases studied that the high frequency breakdown voltage is higher when both the fields are present than when the gases are excited by the radiofrequency field alone and the breakdown voltage gradually increases with the increase of the applied d.c. field. The variation of breakdown field with d.c. field is of the same nature in all of the gases studied. A theoretical expression for the breakdown voltage in presence of both r.f. and d.c. fields has been deduced from the theory of electrical discharge by Kihara (1952) together with the expression of equivalent length as deduced by Varnerin and Brown (1950). The theoretical expression could not explain satisfactorily the experimental results, and the rate of rise of breakdown voltage in the d.c. field as obtained from theory is smaller than that obtained from the experimental results. The discrepancy has been ascribed partly to the uncertainity in the values of the numerical constants introduced by Kihara (1952) and also to the increase of diffusion caused by the presence of positive ions-a factor which has not been taken into consideration in this treatment.

This work has been further extended by measuring the breakdown voltage in molecular gases like air, hydrogen, oxygen and carbondi-oxide at different pressures with the d.c. field now varying from zero to 240 volts/cm. Like the earlier part of this work, here also it is found that the breakdown voltage increases when d.c. field is small and when the field is further increased it shows a maximum and then gradually falls for all the gases studied, the maximum occuring at a d.c. voltage which is different for different gases and is also different for different pressures. It has been shown that, when the d.c. field is small, the dominant factor is the loss of electrons by diffusion as well as by mobility which causes the breakdown voltage to increase, but when the d.c. field is increased, contribution due to d.c.

ionisation has also to be taken into consideration. This d.c. ionisation contributes to total ionisation and causes a decrease in the radiofrequency voltage necessary for breakdown. A mathematical expression has been deduced which explains satisfactorily the observed experimental results. In the expression deduced the effect of secondary ionisation as well as that of electron attachment have been taken into consideration.

C. LOW PRESSURE BREAKDOWN IN GASES IN A UNIFORM HIGH FREQUENCY ELECTRIC FIELD (i) WITHOUT MAGNETIC FIELD (ii) WITH A STEADY TRANSVERSE MAGNETIC FIELD.

Dielectric breakdown of air under the action of a high frequency uniform electric field has been studied at a pressure of 1.5 μ of mercury in three cylindrical discharge tubes of length 5 cm, 7cm and 15 cm (diameter = 3.5 cm each tube) with external electrodes. Since at this low pressure range, the starting voltage should be independent of the nature of the gas, so starting voltages for air and hydrogen have been obtained in the same discharge tube (length = 15 cm) . The exciting frequency range is limited by the oscillator voltage output. The breakdown voltage against frequency of the applied field curve shows identical nature for both air and hydrogen. The breakdown voltages at different frequencies are obtained for other two discharge tubes and results obtained are compared with those of the previous workers. It is found that the breakdown voltage is higher in tubes of shorter length and the cut-off wavelength increases with the length of the discharge tube. A new value of the constant appearing in the cut-off law is obtained empirically which is found to satisfy the experimental results for cylindrical discharge tubes of length larger than 2 cm. The breakdown under the present experimental set up is due to secondary electron resonance and following the theory of Gill and Von Engel (1948), Hatch and Williams (1954, 1958) the phase angle ϕ and the kinetic energy of the oscillating electron at the opposite end have been calculated which are in agreement with results obtained previously.

Starting potentials are also measured in presence of a steady transverse magnetic field varying from 18 gauss to 45 gauss in the discharge tube of length 5 cm. only and in the frequency range permitted by output voltage limitation of the oscillator. It is observed that in presence of steady transverse magnetic field the breakdown voltage as well as the cut-off wavelength increase with the magnetic field. The theory of breakdown in presence of steady magnetic field has been developed following Deb and Goswami (1964) and the effect of the angle of arrival at the end wall on the breakdown mechanism has been considered. The observations with magnetic field and the subsequent fitting of these observations with the theory have yielded the values of the phase angle and the effective kinetic energy of the arrival of the electron with fair amount of accuracy specially for magnetic fields smaller than 30 gauss. The probability of electrons colliding with the side walls has been considered and it has been shown that under the present experimental setup majority of electrons with energy sufficient to cause breakdown are freely transmitted between the two ends of the discharge tube. The validity of the simplifying assumptions made in the theory has been discussed.

D. VARIATION OF LIGHT INTENSITY OF GLOW DISCHARGE IN TRANSVERSE STEADY MAGNETIC FIELD.

The intensity of light from the glow discharge columns of rare gases like neon, argon and helium excited by a uniform radiofrequency electric field has been studied when the columns are placed in a steady magnetic field, transverse to high frequency electric field. The pressure of the gas was fixed at 10 mms of mercury. The total intensity of the visible light, as measured by a photo voltaic surface placed arbitrarily at any position near the columns shows a steady increase with the increase of the magnetic field. The observations

were limited by the maximum value of magnetic field (2000 gauss) as the present setup could not supply higher magnetic field. Spectra have also been photographed for these three gases at different magnetic fields and the intensity profiles of the spectral lines have been obtained. The profiles clearly indicate that the overall increase of total intensity of radiation is always associated with it the increase of intensities of all the spectral lines. The lines show increase of intensity at different rate i.e. the intensity of some of the lines of the column are not seriously effected by the presence of transverse magnetic field. However in the present setup no detailed observation with line spectra is made and so no quantitative approach has been made for explaining the phenomenon. Assuming that the total intensity of radiation is proportional to the total production rate of excited levels of atoms, an expression for the intensity of radiation has been obtained. The effect of magnetic field on the intensity has been introduced through the equivalent pressure concept of Belavin and Haydon (1958) and the variation of different parameters in the above expression that are known to be effected in presence of transverse magnetic field are considered. An expression for I_H/I_o is obtained where I_H is the total intensity of radiation in presence of transverse magnetic field and I_o is that without magnetic field. The theoretical results agree quite satisfactorily with the experimentally obtained curve of I_H/I_o against the magnetic field for all the three gases studied. The deviation of the theoretical values from experimental results at very high magnetic field has been attributed to the failure of equivalent pressure concept at high values of (H/P) where P is the pressure of the gas. The uncertainities in the values of the different parameters contributed to a certain extent towards the limitation in the agreement between theoretical and experimental values. A broad field of future work has been pointed out.

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CHAPTER - III.

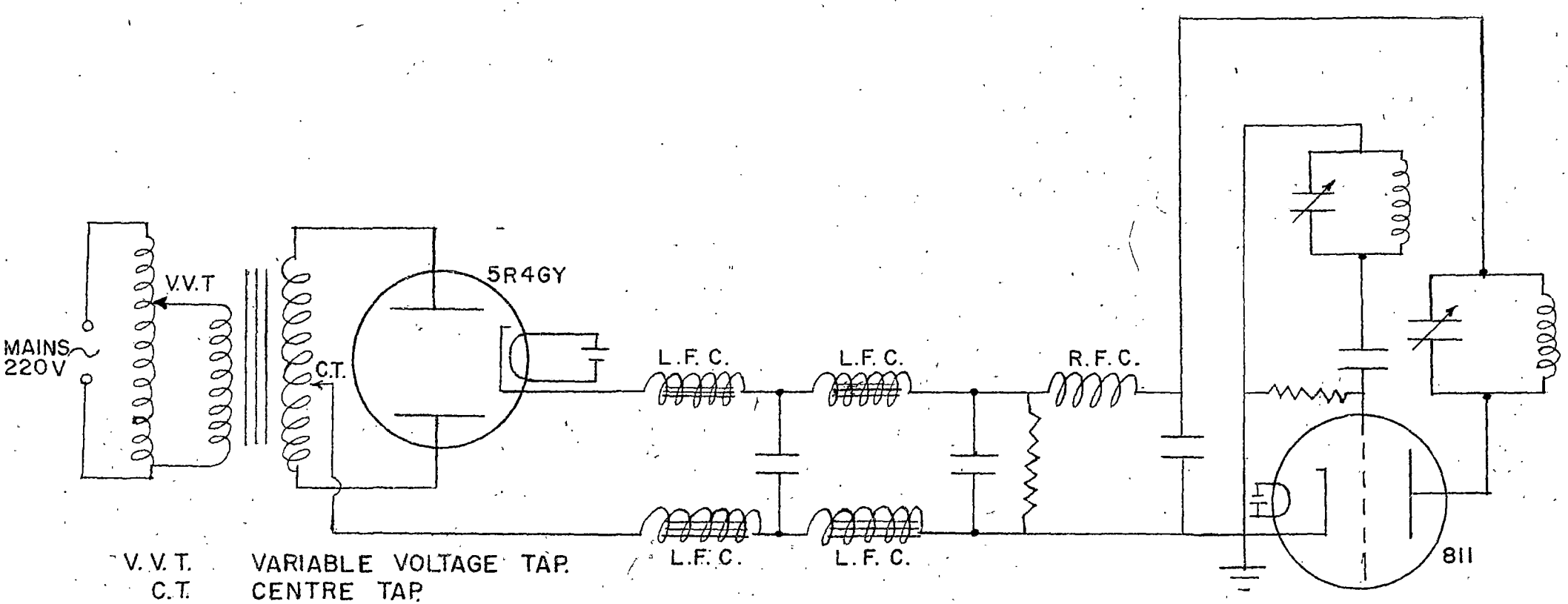
EXPERIMENTAL TECHNIQUE

A. Radiofrequency breakdown measurements (a) without magnetic field (b) with crossed steady magnetic field.

Apparatus :-

(1) R.F. Oscillator (2) Electromagnet (3) Pirani Penning Gauge (4) Mercury manometer (5) Gas generation and purification system (6) Exhaust Pump. Before the actual experiment is started, it is necessary to calibrate the R.F. Oscillator and the Electromagnet. The radiofrequency oscillator is a tuned plate tuned grid oscillator designed for generation of voltages in the output range of frequency 4 Mc/s to 40 Mc/s in three stages. The oscillator tube used was of the type 811. The plate voltage of the oscillator tube is supplied from a full wave rectifier circuit using tube of the type 5R4GY. The input of the rectifier circuit is made variable by means of a variac connected between the mains and input terminals of the transformer used in the rectifier circuit. By this arrangement the plate voltage of the R.F. oscillator can be varied from zero and hence the R.F. output. The composite circuit in its simplest form is given in fig. (1). To calibrate the oscillator for frequency, the absorption wavemeter as well as the communication receiver have been used. Preliminary measurements of frequency were made with the absorption wavemeter. Then using the receiver the final measurements were taken for frequency correct upto 0.1 Mc/s. The two dials of the condensers are given identical marks and is calibrated in terms of the frequency. A curve is plotted for dial reading against frequency fig. (2).

The electromagnet is calibrated using two different methods viz. (1) by using gauss meter and (2) by using a ballistic galvanometer. To calibrate it by using a ballistic galvanometer and search coil, the galvanometer constant is determined first using a standard solenoid fig. (3). When the secondary of the standard solenoid is connected to the galvanometer, the instantaneous



V. V. T.	VARIABLE VOLTAGE TAP.
C.T.	CENTRE TAP.
L.F.C.	LOW FREQUENCY CHOKE.
R.F.C.	RADIO FREQUENCY CHOKE.
5R 4 G.Y.	FULL WAVE RECTIFIER VALVE
8 1 1	HIGH POWER OSCILLATOR VALVE.

Fig. (1) RADIO FREQUENCY OSCILLATOR.

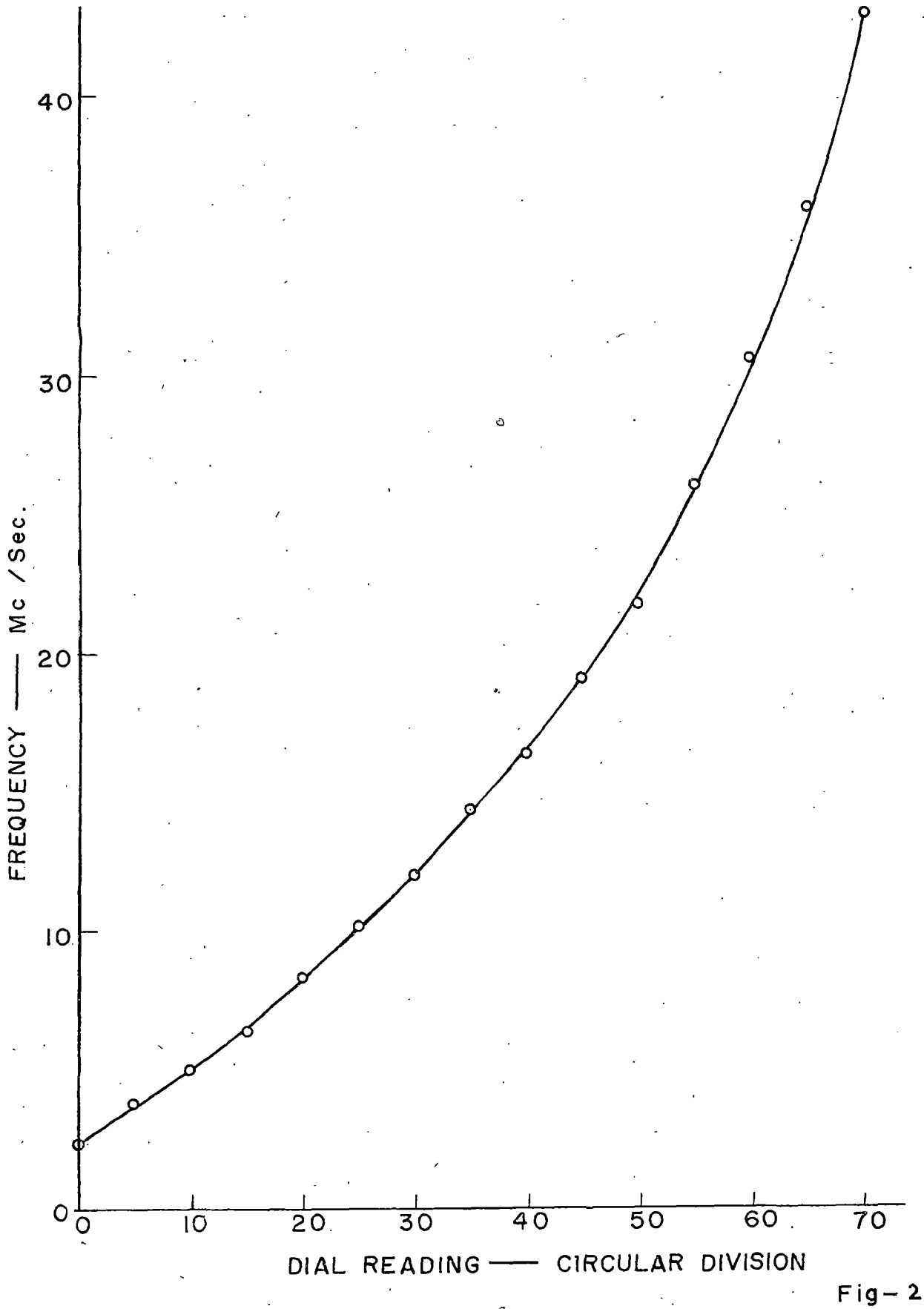
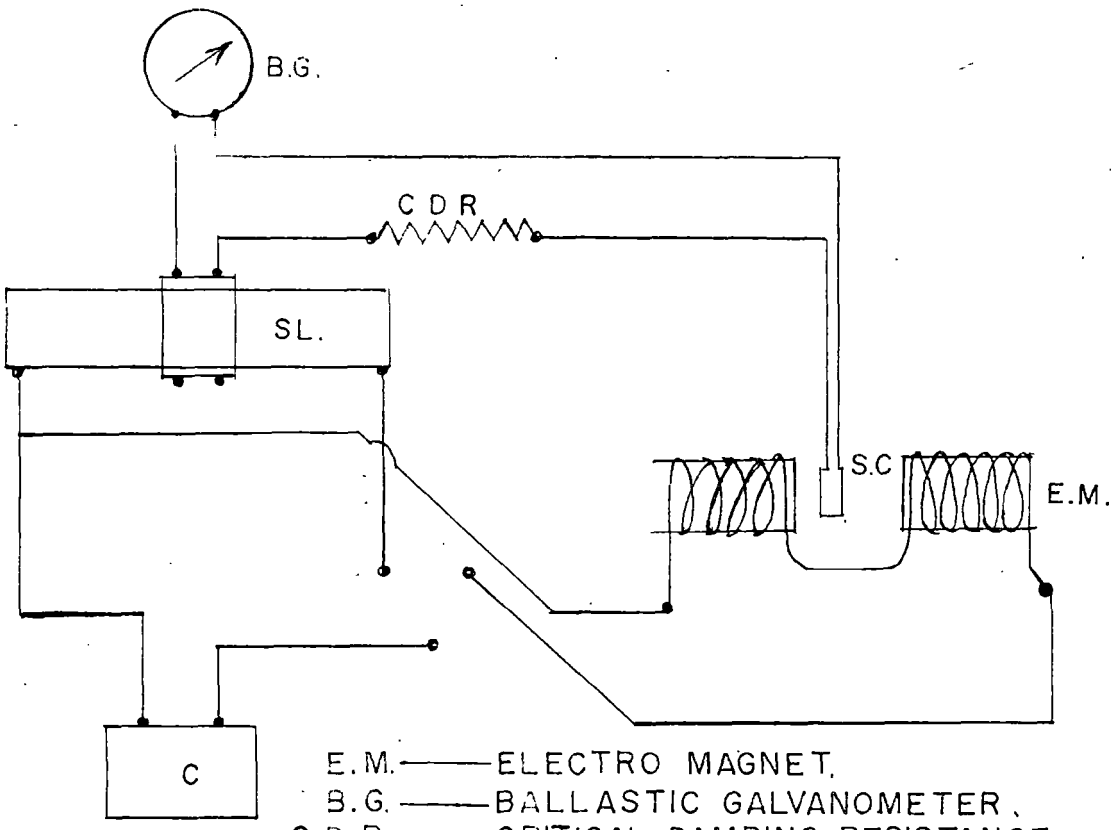

40
30
20
10
0
FREQUENCY —— Mc / Sec.
0
10
20
30
40
50
60
70
DIAL READING —— CIRCULAR DIVISION

Fig-2



E.M. —— ELECTRO MAGNET.
B.G. —— BALLASTIC GALVANOMETER.
C.D.R. —— CRITICAL DAMPING RESISTANCE.
S. L. —— SOLENOID.
S. C. —— SEARCH COIL.
C —— D.C. CURRENT SOURCE.

Fig.(3) CALIBRATION OF MAGNETIC FIELD.

current through the galvanometer when current i is established in primary, produces a deflection " d_1 " given by

$$\frac{4\pi^2 n_1 n_2 r_2^2 i}{(R+G).10} = K d_1 \qquad \ldots(3.1)$$

where K = a constant of galvanometer

n_1 = number of primary turns / cm

n_2 = total number of secondary turns

r_2 = radius of the secondary coil in cm.

i = current through the primary of the solenoid expressed in amp.

G = Galvanometer resistence in ohms.

R = resistance of the secondary circuit including the search coil.

The resistance of the search coil is a few ohms which is small compared to the total resistance of the secondary circuit which is few thousand ohms. If now a uniform magnetic field H is developed through this search coil, then flux linked with the search coil is $4\pi n_3 r_3^2$ and if this change of flux produces an observed throw " d_2 " in galvanometer, then

$$\frac{4\pi n_3 r_3^2}{(R+G)} = K.d_2$$

where n_3 = number of turns of serch coil

r_3 = mean radius of search coil turns

Hence $$H = \frac{2\pi n_1 n_2 i r_2^2}{5 n_3 r_3^2} \cdot \left(\frac{d_2}{d_1}\right) \qquad \ldots(3.2)$$

Two sets of observations were made with two search coils of different number of turns and it was assumed that the resistance of the secondary circuit remains uneffected due to the small change of the search coil turns.

Results : Length of primary coil = 50 cm.

Total number of primary coil turns = 250

Diameter of the primary coil = 7.2 cm. (average)

Length of the secondary coil = 9 cm.

Diameter of the secondary coil = 8.5 cm.

Total number of secondary coil turn = 1000

1st set

Mean radius of search coil = 0.7 cm.

Total number of search coil turns = 90

Primary current amp.	Deflection of Galvanometer (cm.) ON	OFF	Average deflection per amp.	Mean deflection of galvanometer amp.
2	21.5	21	10.6	
1	10.5	11	10.7	10.6
0.5	5	5.5	10.5	

Current through the electromagnet (amp.)	Deflection of galvanometer (cm) ON	OFF	Magnetic field (Gauss)
4.25	12	13	3044
4	11.8	12.6	2957
3.25	10.6	11	2630
2.5	9	9.8	2272
2.25	8.5	8.9	2110
2	7.7	7.9	1895
1.5	6.4	6.6	1580
0.75	3.5	3.9	907
0.5	2.3	2.6	590

2nd set.

Mean radius of search coil = 0.8 cm.

Total number of search coil turns = 100.

Current through the electromagnet (amp.)	Deflection of galvanometer (cm) ON	OFF	Magnetic field (Gauss)
4	17.3	18	2955
3.5	16	17	2760
3	14.8	15.2	2515
2.5	13.1	13.6	2230
2	11.2	11.4	1900
1.5	9	9.8	1575
1	6.7	7.1	1153
0.5	3.4	3.7	597
0.25	1.7	1.9	304

The calibration is repeated by means of a gaussmeter. The gaussmeter consists of a rectangular coil rotated along the axis passing through its plane by a synchronous motor of 50 c/s. When this rotating coil is placed perpendicular to an uniform magnetic field, the induced a.c. e.m.f. is generated in the coil which is measured by the C.R.O. The C.R.O. is calibrated previously by small a.c. voltage of 50 c/s applied from a source attached to the C.R.O. itself. The output induced voltage from the gauss meter for magnetic field strength of one gauss is taken from the data supplied by the manufacturer. During measurements the current through the electromagnet coil is gradually increased until the amplitude of the output a.c. voltage shows a discrete value. The current then is noted and the corresponding magnetic field from the C.R.O. calibration of amplitude length / volt is obtained.

Results :-

Amplitude of the output a.c. voltage / gauss of the gaussmeter supplied by the manufecturer " Rawson Electrical Instrument Co. Cambridge, Mass., U.S.A.

= 0.18 mv / gauss.

Calibration of oscilloscope screen :-

Applied voltage (50 c/s) to C.R.O. plate along y axis (volt).	Amplitude of wave form (cm.)	Amplitude /volt.	Mean amplitude volt.
0.5	10.2	20.4	
0.2	3.9	19.5	19.96
0.1	2	20	

Calibration of electromagnet :-

Current through the coil of the magnet (amp.)	Amplitude of the wave form (cm)	Magnetic field (gauss).
0.2	1	278
0.5	2	556
0.7	3	834
1	4	1112
1.3	5	1390
1.6	6	1668
2.1	7	1946
2.5	8	2224
3	9	2502
3.6	10	2780

A calibration curve is drawn of the magnetic field against current in the coil of the electromagnet fig. (4).

The measurements of the breakdown potential of the gas in radiofrequency field have been done following the procedure of Gill and Von Engel (1948) and Sen and Ghosh (1963) . The arrangement is shown in fig (5). The R.F. voltage is directly applied from the source to the electrodes by means of shielded cables. The r.m.s. value of the voltage is measured with the help of a V.T.V.M. constructed in the laboratory using a (6 SN 7) tube . The range of the V.T.V.M. is 500 volts r.m.s. The plate voltage of the oscillator is gradually increased and hence the r.f. applied voltage to the vessel also increases. At the point of breakdown of the gas the V.T.V.M. reading shows an abrupt fall of few volts and simultaneously a glow appears in the discharge tube. This point is taken as the breakdown point and the corresponding r.m.s. value of voltage indicated by voltmeter of V.T.V.M. is taken as the breakdown voltage. The whole experiment is performed in two ranges of pressure. The measurement of pressure in the range 0.5 mm. Hg. to higher pressure is done with the help of a mercury manometer. The manometer is connected to the system and its vapour is prevented from entering the discharge vessel by sorrounding its passage by a cold ice trap. The mercury level is measured by a telescope fitted with a vertical scale. This arrangement measured the pressure very accurately from a few millimeters of mercury upto 0.5 mm. of Hg. For pressures below 0.5 mm. Hg. to a few microns, the pirani portion of the Pirani Penning gauge supplied by Edward High Vacuum Ltd. Crawlay, Sussex, England, is used along with their calibration curves of the pirani meter for different gases. Penning gauge portion is also kept connected to the discharge vessel system to test the leak of the system. During investigation different gases are used as dielectric medium like air, oxygen, hydrogen, carbon-di-oxide, neon, helium, argon. The last three gases have been supplied by the British Oxygen Co. in glass cylinders. These gases are directly connected to the discharge tube via a stop cock. Air is passed

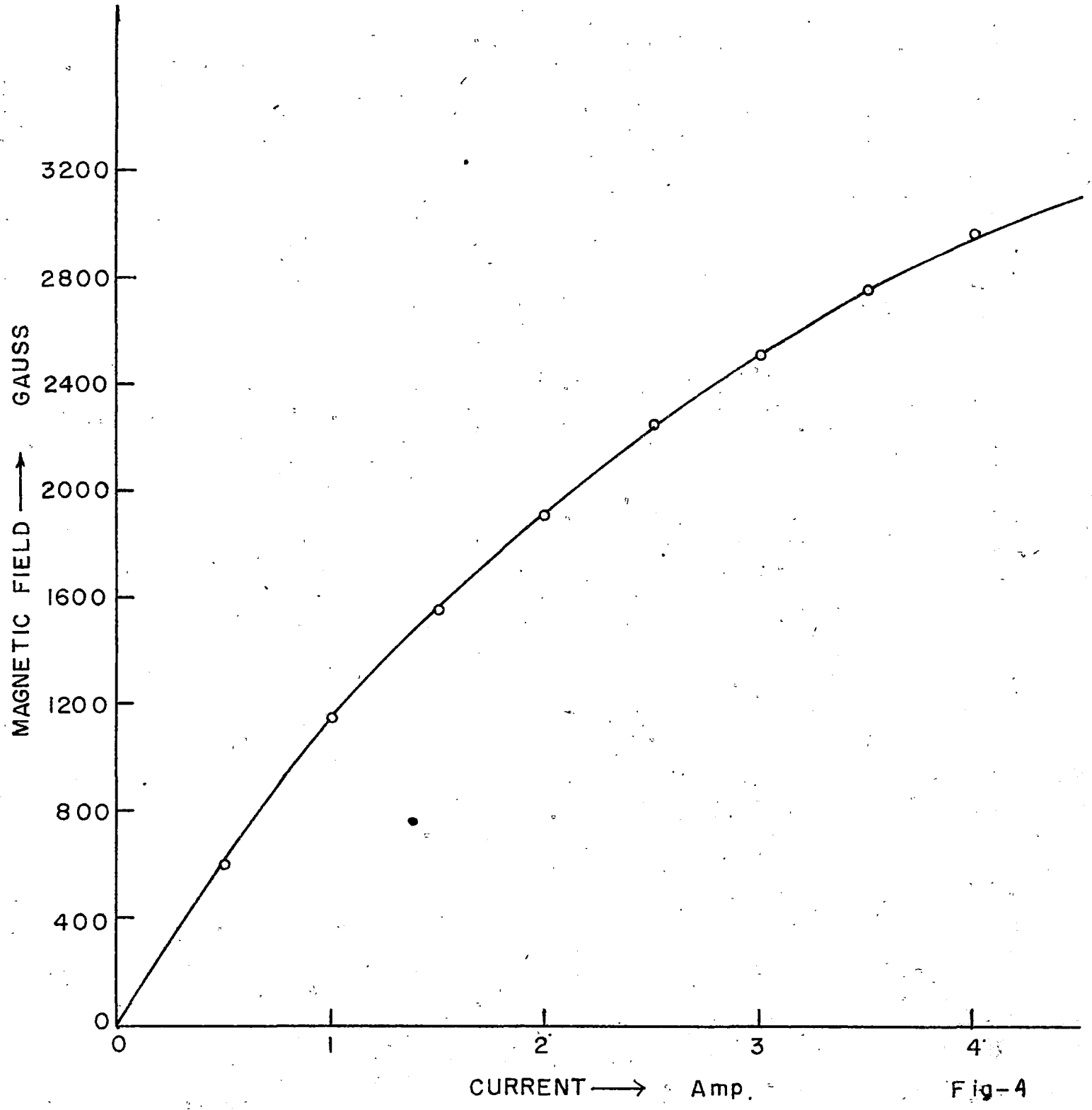
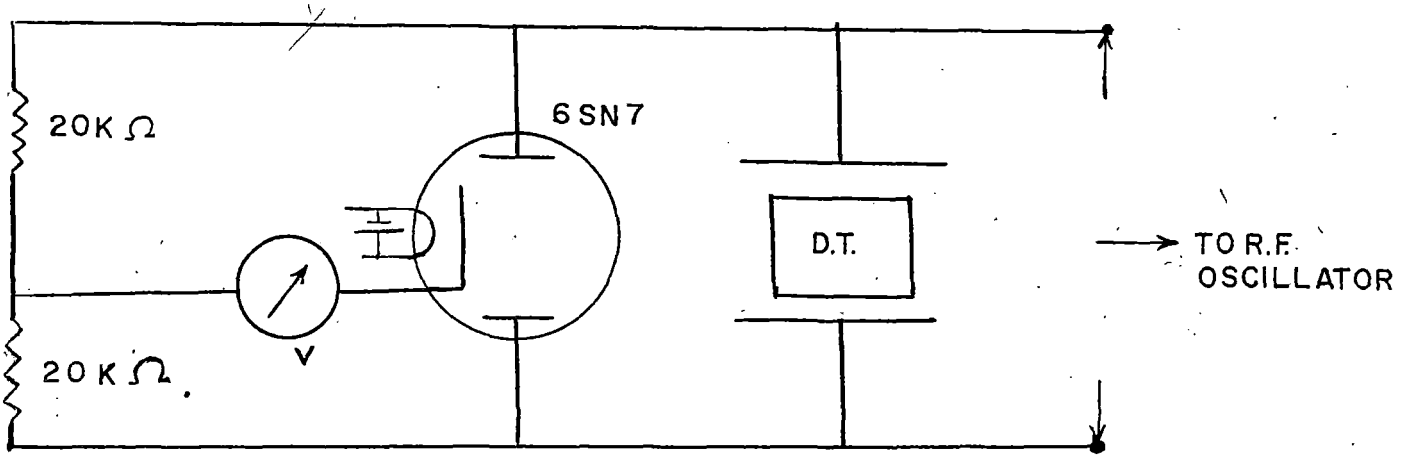

3200
2800
2400
2000
1600
1200
800
400
0
MAGNETIC FIELD ⟶ GAUSS
0
1
2
3
4
CURRENT ⟶ Amp.

Fig-4



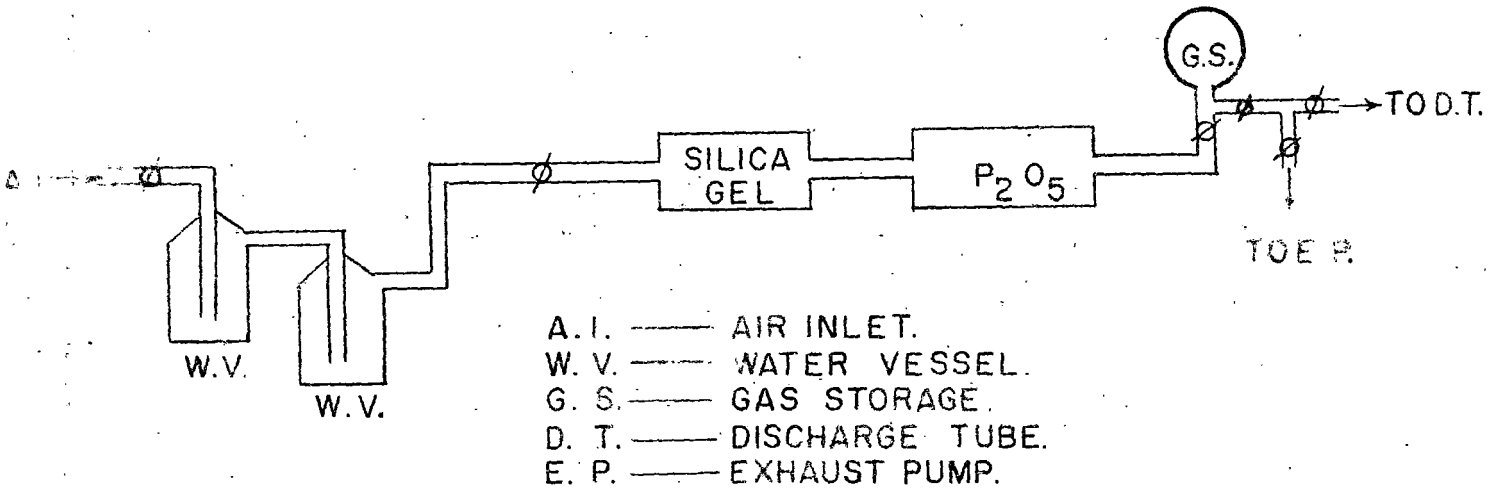
V——D. C. VOLTMETER.
6SN7——TWIN DIODE RECTIFIERS.
D. T.——DISCHARGE TUBE.
R. F.—— RADIO-FREQUENCY

Fig. (5) VACUUM TUBE VOLTMETER CONNECTED TO ELECTRODES OF DISCHARGE TUBE

through a series of cold water vessel to remove dust and organic matters and dried by silica gel and phosphorous pentoxide and is stored in a highly evacuated and clean glass vessel. Pure oxygen is prepared by the electrolysis of a concentrated solution of barium hydroxide with nickel electrodes in hard glass U tube. Oxygen is evolved at the anode. The gas is passed over red hot platinum to remove traces of hydrogen and dried by passing over pure phosphorouspentoxide and stored like air. Pure hydrogen is evolved at the cathode in the electrolysis, with nickel electrodes, of a warm concentrated solution of barium hydroxide in a hard glass U tube. The gas is passed over heated platinum gauge to burn out any oxygen and is dried by passing over broken pieces of potassium hydroxide, followed by purified phosphorouspentoxide which has been sublimed in oxygen. Storing is done in the previous manner. Pure carbon dioxide is obtained by the action of dilute sulphuric acid, boiled to free it from air, on pure sodium carbonate. The gas is passed through cold water to remove traces of acid and dried by passing over silica gel and phosphorous pentoxide and stored in the evacuated glass container keeping its mouth upward.

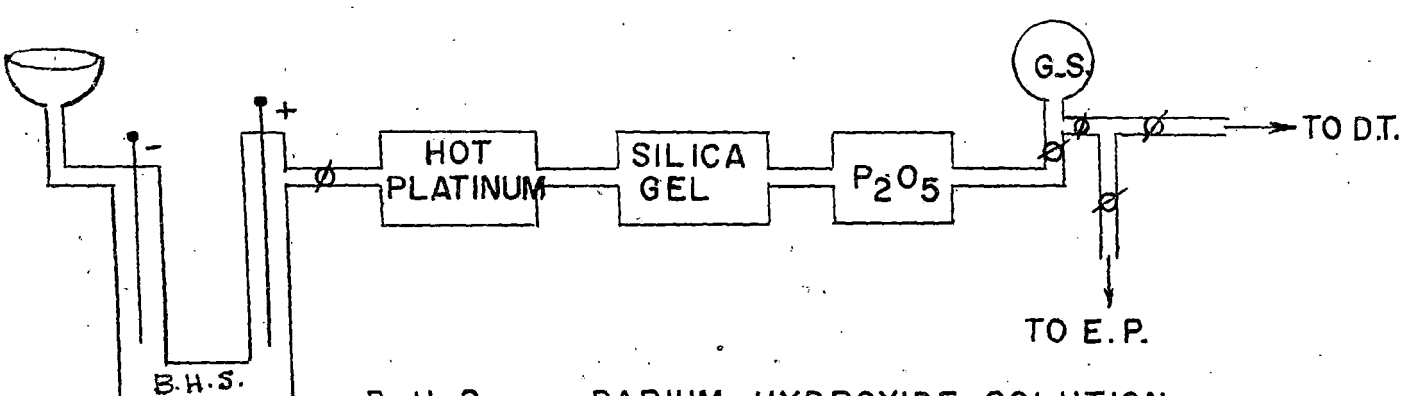
The whole arrangement of gas preparations in the laboratory is shown in fig. (6-a, b, c, d.). In all these preparations the whole system is connected to exhaust pump (Leybold pump). The maximum possible portion of the system is evacuated properly before any gas is allowed to pass through the system from the point of generation. Before making the final collection, a continuous operation of gas preparation and its exhaustion through the system is continued for a sufficiently long hours to ensure a complete atmosphere of the gas inside the system. All the gas containers are separately connected to the discharge vessel via stopcock during the ovservation. Throughout the experiment the Leybold rotary exhaust pump is used.

Before starting the measurements, the discharge vessel system is continuously evacuated and properly baked to remove occluded gas. The operation proceeds for a considerable period, after which the experimental gas is introduced in the system. The system is flushed a number of times with the gas from the



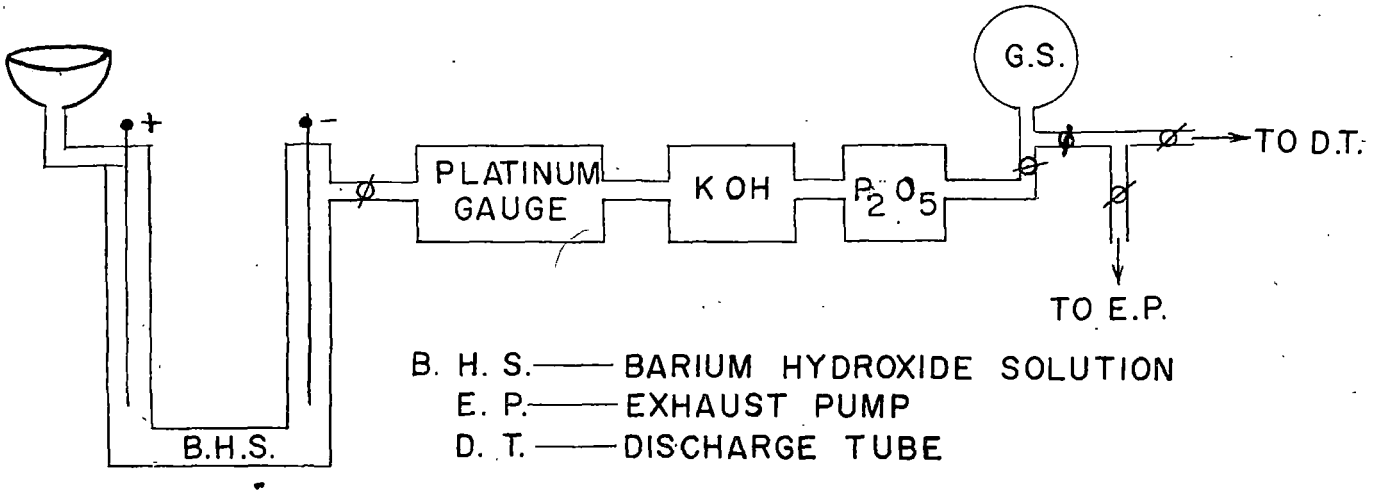
A. I. —— AIR INLET.
W. V. —— WATER VESSEL.
G. S. —— GAS STORAGE.
D. T. —— DISCHARGE TUBE.
E. P. —— EXHAUST PUMP.

FIG.(6 a) STORAGE OF DRY AIR.



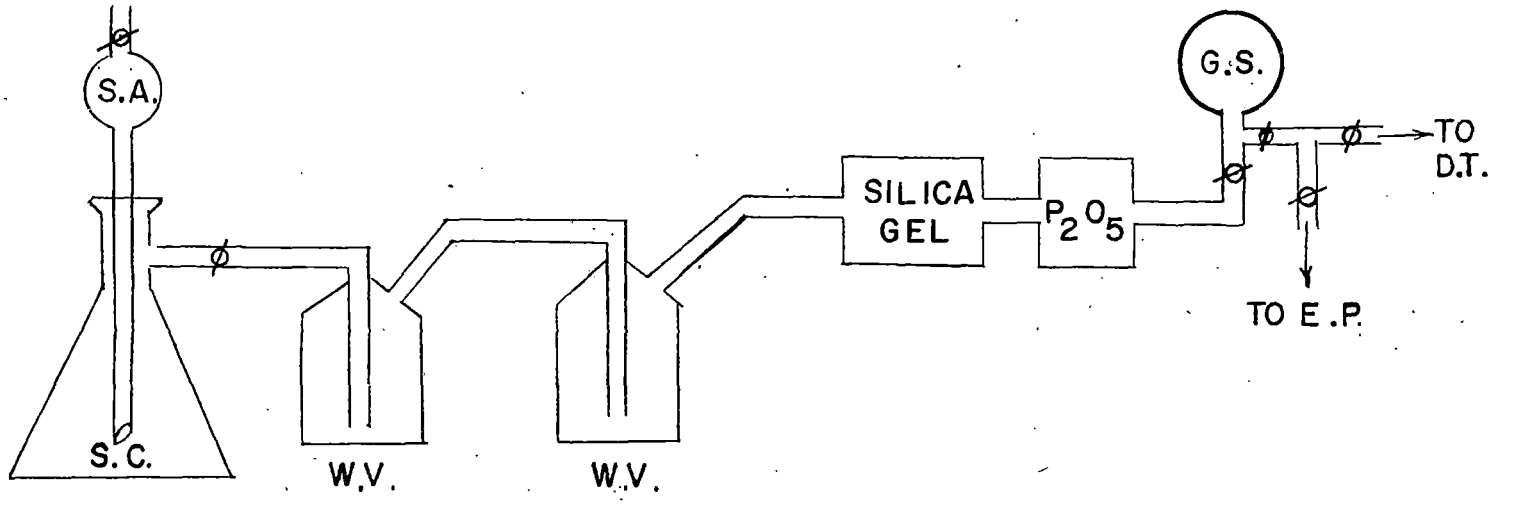
B. H. S —— BARIUM HYDROXIDE SOLUTION
G. S. —— GAS STORAGE.
E. P. —— EXHAUST PUMP.
D. T. —— DISCHARGE TUBE.

FIG.(6 b)PREPARATION OF OXYGEN.



B. H. S. —— BARIUM HYDROXIDE SOLUTION
E. P. —— EXHAUST PUMP
D. T. —— DISCHARGE TUBE

FIG. (6 C) PREPRATION OF HYDROGEN



S. A. —— DILUTE SULPHURIC ACID
S. C. —— GRANULS OF SODIUM CARBONATE
G. S. —— GAS STORAGE
E. P. —— EXHAUST PUMP.
D. T. —— DISCHARGE TUBE.
W. V. —— WATER VESSEL.

FIG. (6 d) PREPARTION OF CARBON-DI-OXIDE.

container to ensure the gas atmosphere inside the discharge vessel. Keeping the pressure fixed by proper manipulation of stop cock, the breakdown voltage is measured by the V.T.V.M. (Internal impedence 20 K ohm) as stated earlier. Observation at different pressures is repeated for several times and the mean values of breakdown potential is noted against the corresponding pressure. The mean value does not deviate more than $\pm$ 2 volts for all the observed values at the corresponding pressure.

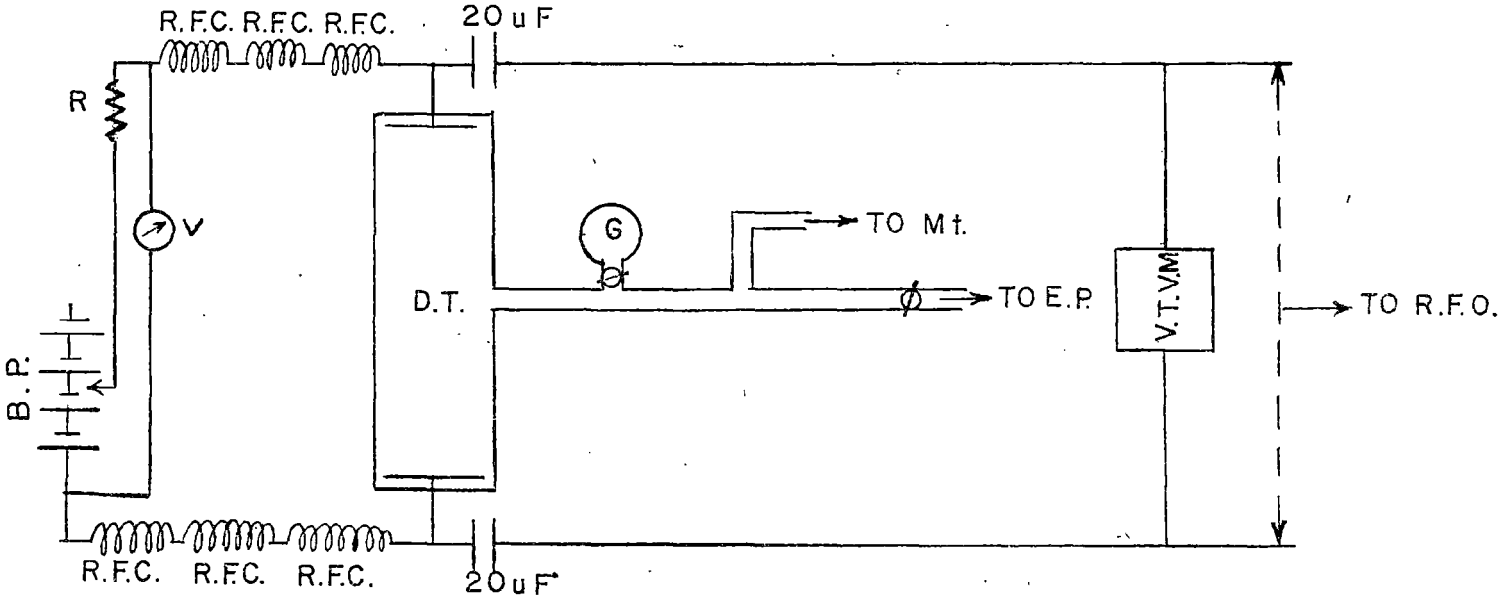
The same process is repeated for all the gases mentioned earlier and the respective breakdown potential data are noted for different pressures. Breakdown potential measurements above the pressure 0.5 mm. Hg. are done with air, oxygen, hydrogen and carbondioxide using a single discharge vessel. And for pressures below 0.5 mm. Hg. another discharge vessel (both of cylindrical shape but of different dimension) is used. In this low pressure range the gases neon, helium and argon are used as dielectric medium.

Measurements with cross steady magnetic field :- The above mentioned procedure has again been repeated for all the gases in crossed magnetic field. The uniform magnetic field which was calibrated at the begining of the experiments is placed perpendicular to R.F. electric field. The current of the coil of electromagnet is supplied from a metal rectifier fitted with proper filter circuits. Keeping the magnetic field at a fixed value, the pressure is gradually changed and the corresponding breakdown potentials are noted. The same procedure is repeated for different values of the magnetic field. The process is repeated several times and mean breakdown potentials are taken. Breakdown potentials corresponding to the same magnetic field but different pressures then constitute one set of reading. In this way different sets are obtained for different descrete values of magnetic field. Repeation of the process has been made with all the gases mentioned as dielectric medium.

B. R.F. Breakdown in superimposed D.C. Field.

Apparatus :-

(1) R.F. electrical excitation source (2) D.C. voltage source (3) Gas generation and purification system (4) Exhaust pump (5) Mercury manometer (6) Discharge tubes filled with rare gases. The whole experimental arrangement is shown in fig. (7). The r.f. excitation source used in this experiment was the one described in the previous arrangement. The r.f. voltage is applied to the highly polished and clean parallel electrodes fitted in a thick glass cylindrical vessel, through two oil filled condensers each of 10μF capacity and capable of sustaining a potential difference of 3 K.V. These two condensers act as blocking condenser to the applied d.c. voltage. As the impedence of these two condensers in radiofrequency is very small ($<< 1$) so the V.T.V.M. terminals are connected towards the r.f. source end of the condensers as precautionary measure to protect the valve of the V.T.V.M. The V.T.V.M. that is used in this experiment has been described in the previous experimental arrangement. The source of d.c. voltage is a package of dry batteries connected in series and capable of change of voltage by steps of 90 volts. The d.c. source is connected to the electrodes of the discharge vessel via some r.f. chokes connected in series. A high value resistance is connected in series with batteries to control the current when the vessel becomes conducting. A switch system disconnects the d.c. source from the vessel. The experiment is performed in two ranges of d.c. volts/cm. The whole experiment is performed in the range of pressure 0.5 mm. Hg. to a few mm. Hg. The measurement of this pressure where necessary is done by the mercury manometer in the same manner as described in previous arrangement.



B. P. —— DRY BATTERY PACKAGE
R. F. C. —— RADIO FREQUENCY CHOKE
V —— D.C.VOLTMETER
D.T. —— DISCHARGE TUBE.
G —— GAS CONTAINER.
Mr. —— MERCURY MANOMETER
E.P —— EXHAUST PUMP
V.T.V.M. —— VACUUM TUBE VOLT METER.
R.F.O. —— RADIO FREQUENCY OSCILLATOR
R. —— HIGH RESISTANCE

FIG-7

Before starting the actual experiment with variable pressure and high d.c. volt/cm the whole system of discharge vessel is exhausted by the Leybold oil exhaust pump and simultaneously baked for a considerable period. After that the system is flushed several times by the experimental gas to ensure the atmosphere of this gas only throughout this system. The same procedure is followed for all the gases studied. The d.c. voltage is applied to the electrodes and the r.f. voltage is gradually increased until the gas of the container shows signs of breakdown. At this moment the d.c. source is disconnected to prevent the damage of the polish of the electrode surfaces. By changing the applied d.c. voltage in steps of 90 volts the corresponding r.f. breakdown potentials are measured. The experiment is repeated several times and mean values of the breakdown potentials are taken. The whole experiment is performed for several discrete values of pressure.

Identical procedure, as described above, is followed for different experimental gases and the corresponding observations made at different pressures. The gases used in this experiment as dielectric medium are dry pure air, oxygen, hydrogen, carbon-di-oxide, helium, neon and argon. The preparations and storing of the first four gases have been described previously. Helium, neon and argon have been supplied by the manufacturing company in Geisler tube fitted with aluminium electrodes. These tubes are directly used as discharge vessels. The pressures of the gases inside the tube are given by manufacturer. The experiment with these vessels give results for small superimposed d.c. volts per cm. at constant pressure since here the length of the discharge column was large. Other gases are treated in a small discharge vessel to get the result at high applied d.c. volt/cm and at different pressures.

C. Low pressure gas breakdown by secondary electron resonance (a) Witout magnetic field (b) With magnetic field.

Apparatus :-

(1) R.F. source of variable frequency (2) Diffusion pump with rotary exhaust pump (3) Gas preparation and purification system (4) Electromagnet (5) Pirani Penning Gauge (6) Discharge tubes. The diffusion pump used in the present experiment is an oil diffusion pump made of leak proof metal body. The Leybold exhaust pump decribed earlier acts as fore pump stage of the diffusion pump. Siliconeoil is used in the diffusion pump. The R.F. excitation source and the V.T.V.M. to measure the r.m.s. value of the voltage of excitation are the same described in the previous arrangement. The same is the case for electromagnet and Pirani-Penning gauge. The Pirani section of the gauge can read pressure upto few microns of Hg. for different gases and penning section has the range down to 10^{-5} mm. Hg. for pressure measurement. During the experiment the discharge containers used are all of cylindrical geometry having different dimension of length and same radius and made of pyrex glass. All measurements were made with parallel external electrode systems placed perpendicular to the axis of cylindrical vessel. Before using the discharge vessels, they are thoroughly cleaned by concentrated acids and alkali solutions and baked under evacuated condition for some time to remove all contaminations. The experimental container is connected to the diffusion pump and their junction is sorrounded by solid ice to prevent oil vapour to enter the discharge vessel. An "Y" connection is joined here with the discharge tube. The other ends of the connections are fitted to penning head and gas system respectively. For the present experiment only hydrogen and air are used, the preparations and storage of these two gases have been discussed in the previous chapters. The mercury cup stopcock controls the gas flow. The whole experimental arrangement is shown in fig. (8).

Before starting the original experiment, it is necessary to test the exhaust capacity of the diffusion pump. For this purpose the discharge tube system is dismantled and instead Penning head is directly connected to the diffusion pump. The run of rotary pump for a few hours lowers the pressure of the system to about 10μHg. pressure. The diffusion pump is then started by switching the heating coil and running cold water through the cooling pipes of the diffusion pump. After about five to six hours the pressure reading in the Penning gauge shows a steady valve of 5×10^{-5} mm. Hg. which is then maximum exhaustion capacity of this diffusion pump. However by connecting the whole discharge tube system during the actual experiment, the pressure could be lowered to a steady value upto 15×10^{-4} mm. Hg. at best by properly baking the system and operating the diffusion pumps for about then hours. At this stage of pressure the whole experiment is performed keeping the exhaust system in operation throughout the observation.

During the experiment it is proposed first to see that the mechanism of secondary electron resonance breakdown is operative in the present setup.

Measurements without magnetic field :-

The most distinguishing characteristic of the secondary electron resonance breakdown mechanism is that the breakdown voltage must be independent of the nature of the gas in the same vessel. Hydrogen and air are used as two different gases for this purpose. Starting the experiment, the whole system is continously flashed for sometime by the experimental gas with the help of rotary exhaust pump to create the atmosphere of the gas in the discharge vessel. Then the actual operation of exhaustion is started in the manner stated earlier. When the penning gauge shows the steady pressure near one micron mercury, the vessel is set for taking observations. Keeping the whole exhaust system in the run, the r.f. breakdown voltage of the dielectric medium of the vessel is measured, which is indicated only through apperance of glow in the vessels but

no fall of voltage generally taken place as stated earlier. By varying the frequency of the oscilator, the breakdown voltage measurements is repeated until the cut-off frequency is obtained. At frequencies lower than the cut off frequency, the dielectric medium behaves like an insulator to any amount of r.f. voltage. The whole experiment is repeated for hydrogen and air. The two curves obtained by drawing breakdown potentials against frequency for two gases should be identical if the secondary electron resonance mechanism is operative. Once this is varified, the later part of the experiment is performed using only air as dielectric medium.

Using the cylindrical shaped discharge tubes of different lengths and same radius and each one properly treated for cleaning as described earlier, the breakdown potential measurement is made for all tubes one after another for different frequencies available in the present setup. The measurements are limited by r.f. output voltage in the highest frequency end which is approximately 40 Mc/s. In each case the measurements are continued upto the frequency slightly lower than the respective cut-off frequencies which are different for different lengths of the discharge tubes. The cylindrical vessels used are all of same diameter (diameter 3.5 cm.) and lengths cm, 5 cm, 7 cm. and 15 cm. The oscillator frequency and corresponding limited output voltage allows only to measure the linear portion of frequency vs. breakdown potential curves for all the discharge tubes mentioned above. It was only possible to get one or two points beyond the cut-off frequency region due to limited r.f. output voltage. However the glow at breakdown in this region is very faint and only appears on the glass surface unlike the normal state where glow appears in the central portion of the discharge vessel.

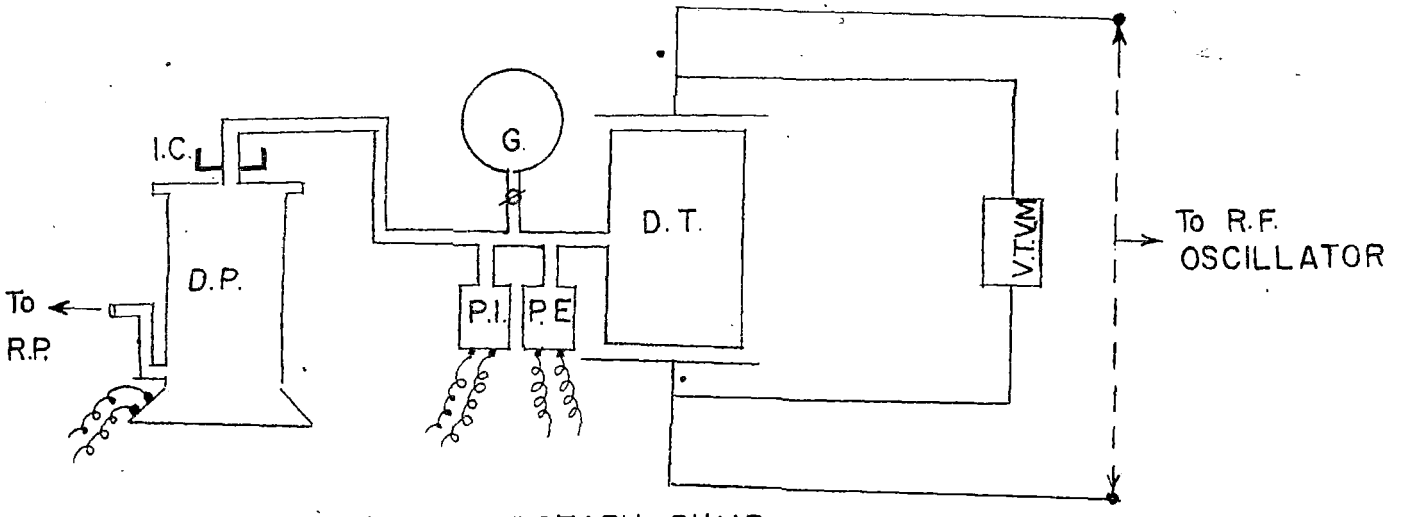
Experiment with magnetic field :- The uniform magnetic field is placed perpendicular to the axis of the cylindrical vessel of length 5 cm. and covering the whole length of the tube in the uniform lines of force. The arrangement makes the magnetic field perpendicular to r.f. electrical excitation field.

As the dimensions of the pole faces of the magnet are 7.5 cm. x 4.5 cm. and the length of the discharge tube is 5 cm., the tube lies entirely within the pole faces. To investigate the effect of uniform magnetic field on the breakdown potential and corresponding cut-off frequency in the secondary electron resonance breakdown mechanism, the single discharge vessel mentioned above is chosen for the whole experiment. Keeping the magnetic field steady at some value, the same procedure, as adopted in the measurements without magnetic field, is followed and frequency versus breakdown potential curve slightly beyond the cut-off frequency is obtained. By increasing the magnetic field by some discrete amount, different such curves are obtained. It is observed that with the increase of magnetic field, the breakdown potential at identical frequency increases and correspondingly the cut-off frequency is shifted towards the lower frequency value, but curves are identical in nature among themselves and also with the curve without magnetic field. The observations were made for higher and higher magnetic field until further observations could not be taken due to limitation in the output power of the tube. It is to be noted that every observation of breakdown potential whether without magnetic field or with magnetic field is repeated several times, and the mean value is taken. It is observed that the breakdown potential never deviates more than $\pm$ 2 volts (r.m.s.) from each other in repeated observations.

D. Effect of magnetic field on the light intensity of r.f. discharge column.

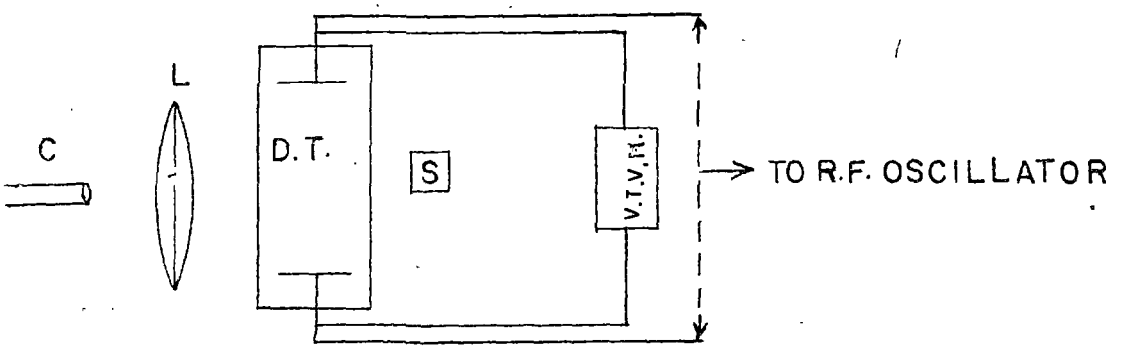
Apparatus :-

(1) R.F. excitation source (2) Discharge tube filled with rare gases (3) Spectrograph (4) Photosurface (5) Microammeter (6) Electromagnet. The R.F. electrical excitation source is the same as before. The discharge tubes are cylindrical tubes fitted with electrodes and filled with rare gases such as neon, argon, helium at pressures of 10 mm. Hg. A constant deviation spectrograph with arrangement to measure the wavelength of the spectral lines directly has been



R. P. ——— ROTARY PUMP
D. P. ——— DIFFUSION PUMP
P. I. ——— PIRANI HEAD
P. E. ——— PENNING HEAD
G. ——— GAS CONTAINER
D. T. ——— DISCHARGE TUBE
V. T. V. M. ——— VACUUM TUBE VOLTMETER.
I. C. ——— ICE CONTAINER
R. F. ——— RADIO FREQUENCY

Fig. 8



C. ——— COLLIMATOR OF SPECTROGRAPH
L. ——— CONVERGING LENS SYSTEM
D.T. ——— DISCHARGE TUBE
S. ——— PHOTO VOLTAIC SURFACE
V.T.V.M. ——— VACUUM TUBE VOLTMETER

Fig. 9

used. The photoelectric cell supplied by Evel serves as a photosurface which yields photo electron current on exposure to light. This is used to measure the direct intensity of the beam by the amount of current that flows. No external voltage is necessary to collect the photoelectrons. When the two electrodes are connected through a microammeter, current flows depending upon the intensity of the light. In the present experiment the surface is always exposed to the ~~monochromatic~~ whole beam from the discharge tube and ~~constant deviation spectrometer~~ comparison of intensities is made without and with the magnetic field. The same electromagnet described earlier is used here. The whole experimental arrangement is shown in fig. (9).

The experiment is performed in two ways. The discharge tubes are excited by r.f. electrical excitation source applying power directly to electrodes. The tubes are used as source to the spectrograph. The magnetic field is placed perpendicular to the axis of the tubes and so perpendicular to the r.f. electric field. Viewing through the telescope, some lines are chosen serially from the spectrum and their wavelengths are obtained from the calibration in the spectrometer. Replacing the eyepiece by a photographic camera, exposures are taken on a photographic plate of those spectral lines. The magnetic field is then established to some discrete values and in each case the spectrum of the same lines are taken exposing the photographic plate by the same amount of time as before. All the exposures were taken in the same photographic plate to ensure uniform developing of all the spectra taken at different magnetic fields. The plates were scanned by microphotometer to get the intensity profiles of all the lines at different magnetic field condition. Some intense lines which were photographed as very dark lines in all the spectra, could not be scanned for change of intensity by the present photometer. Besides these, in all other lines there is a marked increase of intensity with increase of magnetic field.

In the next part of the experiment, the spectrograph is removed and the photo surface is placed before the discharge tube. The R.F. excitation is put off and magnetic field is increased to investigate if there is any effect of the magnetic field on the photosurface. No such effect was found. The tube is excited and the magnetic field is increased. The photocurrent shows a gradual increase with magnetic field. By changing the position of the photosurface with respect to discharge tube and magnetic field the same result is obtained. Hence keeping the photosurface at the same position observations were made for three discharge tubes in the manner described above. Here the photocurrent yield is taken proportional to the intensity of light. It is necessary to mention here that on application of magnetic field in the said manner, the whole discharge column is found to be visibly constricted. This was general in case of all the gases studied.

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1. Gill, E.W.B. and Von Engel, A. (1948) Proc. Roy. Soc. A192 446

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

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)

S E C T I O N - A.

I N T R O D U C T I O N.

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 (1947)[8] 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 incroporate 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 300 μ 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 chapterIII. 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 0.4 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

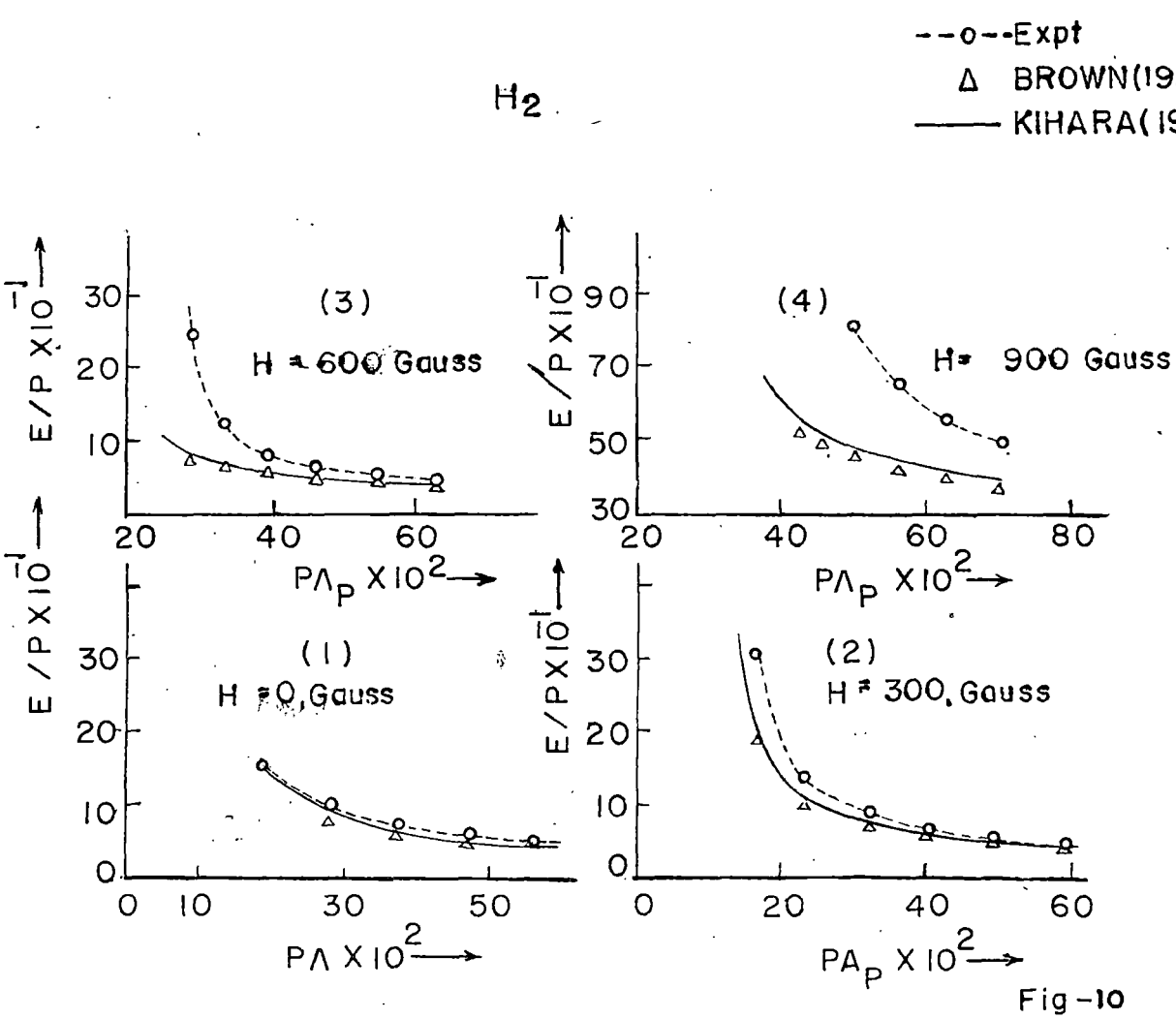
--o--Expt
Δ BROWN(1959)
KIHARA(1952)
H_2
(3)
H = 600 Gauss
(4)
H = 900 Gauss
(1)
H = 0, Gauss
(2)
H = 300, Gauss
E/P X10
$P\Lambda_P$ X10^2
$P\Lambda$ X10^2
PA_P X10^2

Fig-10

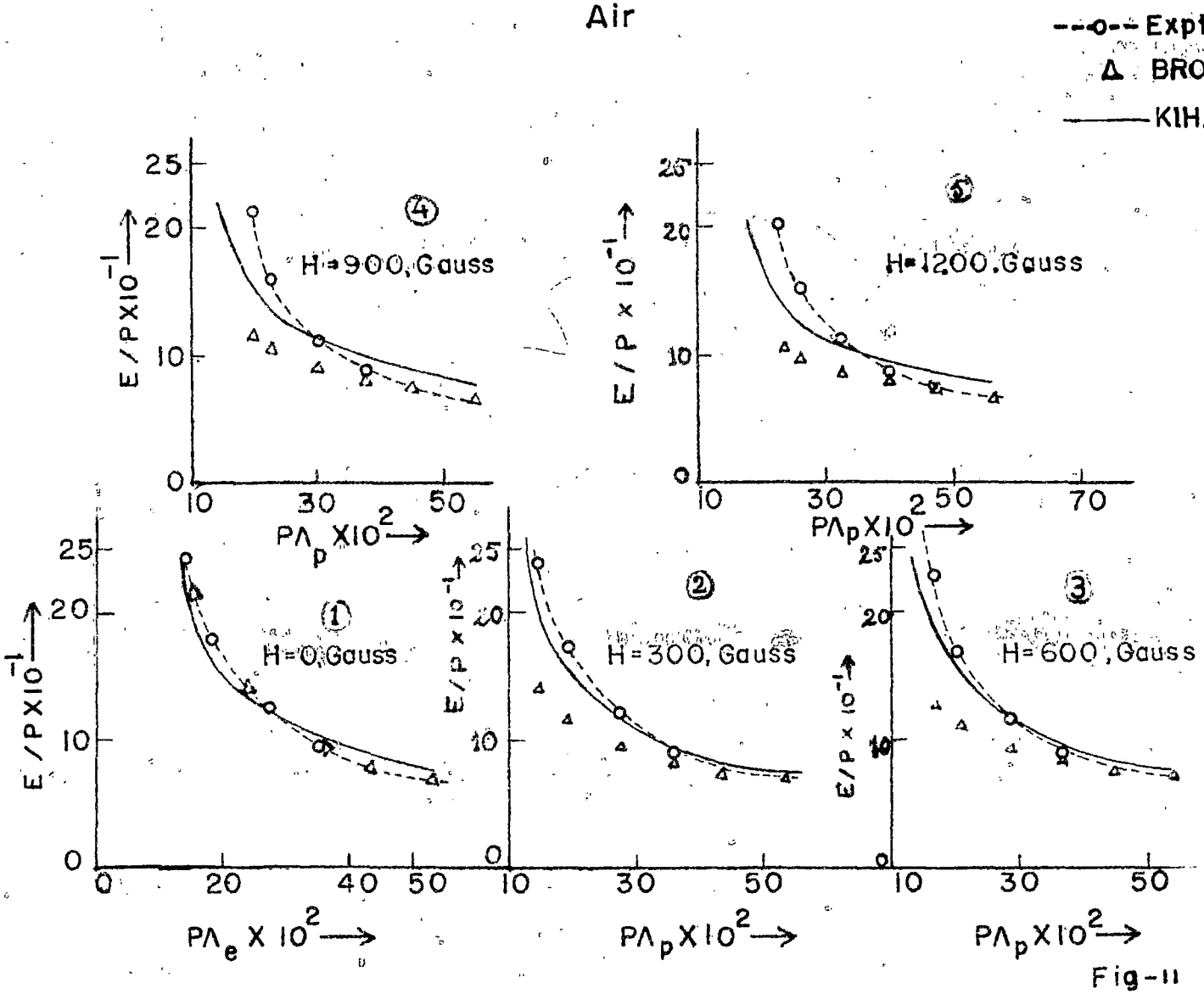
Air
---o--- Expt
Δ BROWN(1959)
——— KIHARA(1952)
④
H=900, Gauss
⑤
H=1200, Gauss
①
H=0, Gauss
②
H=300, Gauss
③
H=600, Gauss
E/P X10⁻¹
PΛp X10²
PΛe X 10²

Fig-11

O_2

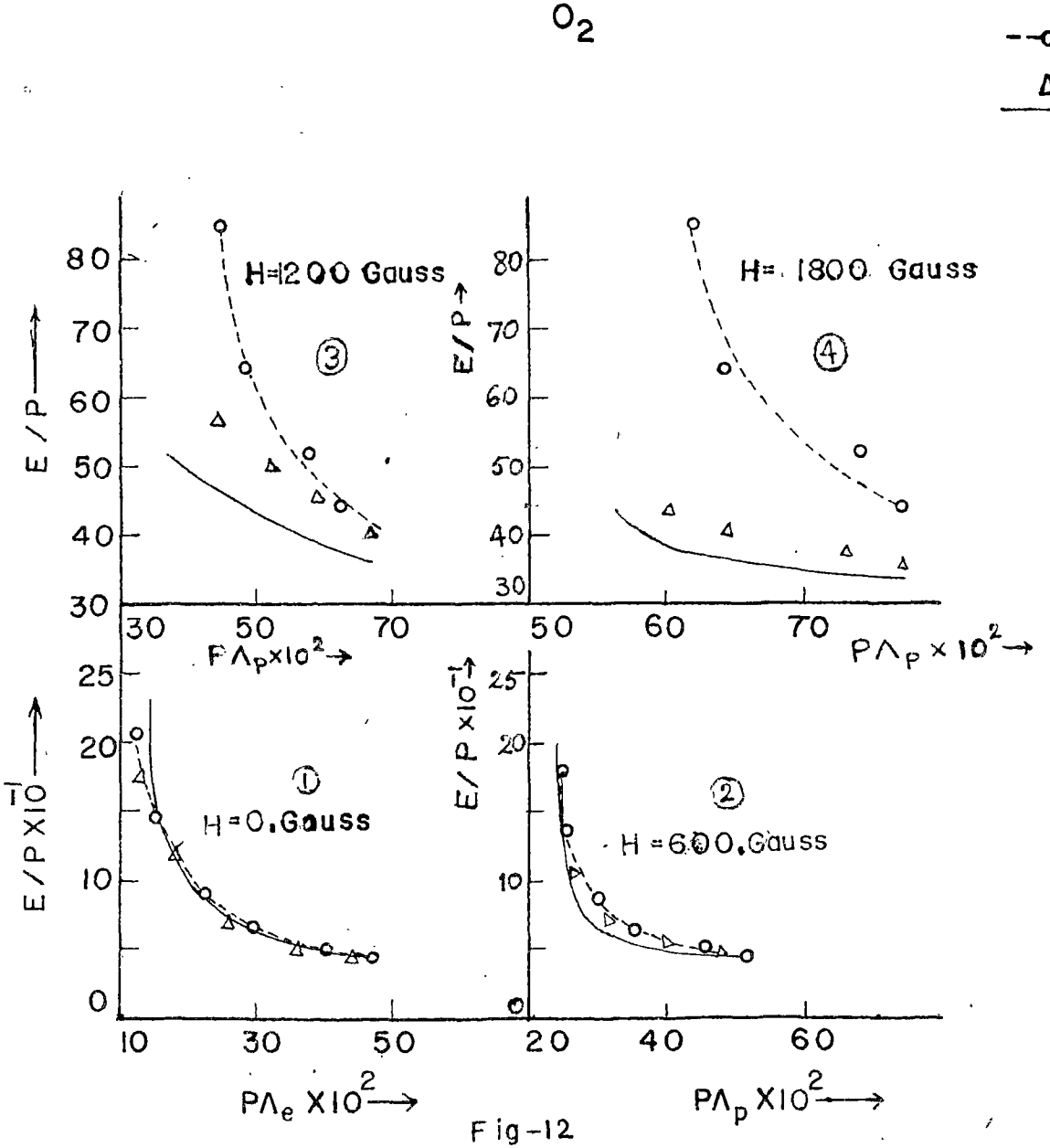
Expt
BROWN(1959)
KIHARA(1952)
H=1200 Gauss
③
H= 1800 Gauss
④
E/P
PΛp×10²
PΛp × 10²
E/P X10⁻¹
①
H=0. Gauss
②
H=600. Gauss
PΛe X10²
PΛp X10²

Fig-12

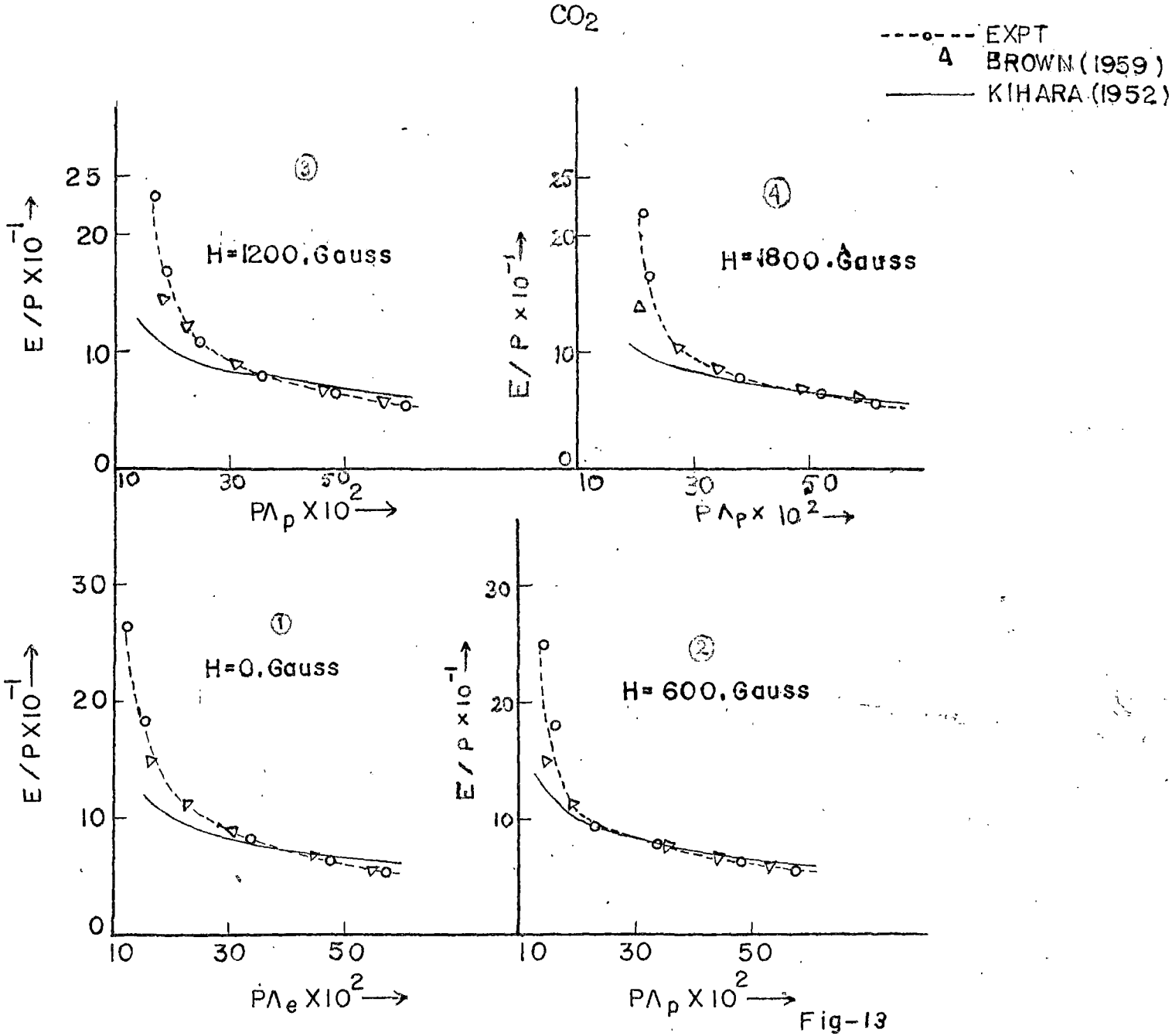
CO_2
EXPT
BROWN (1959)
KIHARA (1952)
③
H=1200, Gauss
④
H=1800. Gauss
①
H=0, Gauss
②
H= 600, Gauss
E/P X10⁻¹
PΛp X10²
PΛe X10²

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 0.4 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

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

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 $\eta = \alpha \bar{K} E$ 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

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

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

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)

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

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

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

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

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

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,

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

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

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

$$KT_e = \frac{e}{N} \cdot \frac{E_0}{\sqrt{2}} \cdot \frac{1}{(3\lambda\beta)^{1/2}} \cdot \left[1 + \frac{\omega^2}{N^2\lambda^2}\right]^{-1/2}$$

where β 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 $Q = \beta c$ which means that the total cross section is proportional to the speed of the colliding electron. Putting the value of KT_e we get,

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

$$\text{then} \quad \frac{B_0 P}{E}\left[1 + \left(\frac{C_1}{A_1 P \bar{\lambda}}\right)^2\right]^{1/2} = 2\log\left(A_1 P \pi \Lambda\right) \qquad \ldots(4.12)$$

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

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

and

$\bar{\lambda}$ is the wavelength of the exciting r.f. field and $B_0 = \frac{N}{P} \cdot \frac{mc_i^2}{2e} \cdot (3\lambda\beta)^{1/2}$ and B_0 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 $\left(\frac{C_1}{A_1 P \bar{\lambda}}\right)^2$ becomes negligible compared to unity and the equation can be further simplified

$$\frac{B_0 P}{E} = 2 \log (A_1 P \pi \Lambda)$$

$$\text{or} \quad E/P = \frac{B_0}{2 \log (A_1 P \pi \Lambda)} \qquad \ldots(4.13)$$

Calculation of A_1

The value of the constant A_1 can be calculated according to Kihara from the constants A_0 and B_0, the Townsend's constants, as follows. Kihara has shown that

$$A_0 = \frac{N}{P} \cdot \frac{\sigma}{c_i} \cdot \left(\frac{3\lambda}{f}\right)^{1/2} \; ; \quad B_0 = \frac{N}{P} \cdot \frac{m c_i^2}{2e} \cdot (3\lambda f)^{1/2}$$

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

$$\text{then} \qquad \frac{3\sigma\lambda}{c_i} = A_0 B_0 \frac{P^2}{N^2} \cdot \frac{2e}{m} \cdot \frac{1}{c_i^2}$$

$$\text{and} \qquad c_i = 0.8 \left(\frac{2eV_i}{m}\right)^{1/2}$$

$$\text{then} \qquad A_1 = \frac{1}{\pi} \left\{ \frac{A_0 B_0}{0.64\, V_i} \right\}^{1/2}$$

$$\ldots(4.14)$$

where V_i denotes the ionization potential of the gas. The values of A_0 and B_0 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_0 and B_0 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_0 and B_0 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	B_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 (4.15) 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 Deas and Emelius (1949) where the experimental variation of τ_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,

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

$$\text{or} \quad N^2 \cdot \frac{3.\sigma}{c_i} \cdot \lambda \cdot \exp\left(-\frac{m c_i^2}{2KTe}\right) = \left(1/\Lambda^2\right) + \frac{\nu_a m N \lambda}{KTe} \qquad \ldots(4.17)$$

$$\text{and} \quad \frac{\nu_a m N \lambda}{KTe} = \frac{(\alpha_a/p)(E_a/p)\bar{K} p^2 m N \lambda}{e E_a / \{(3\lambda\rho)^{1/2} \cdot N\}} \qquad \ldots(4.18)$$

and from Kihara's theory

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

$$\text{then} \quad \frac{\nu_a}{KTe/mN\lambda} = (\alpha_a/p) \cdot p^2 \cdot (3\lambda\rho)^{1/2} \cdot \frac{N}{p} = 1/\Lambda_a^2$$

the breakdown voltage will now be given by

$$\frac{B_0 P}{E_a}\left[1 + \left(\frac{c_1}{A_1 P \bar{\lambda}}\right)^2\right]^{1/2} = 2 \log (A_1 P \pi \Lambda_e) \qquad \ldots(4.19)$$

where

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

or as before neglecting $\left(\frac{c_1}{A_1 P \bar{\lambda}}\right)^2$ 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)

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

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 U_{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 incase 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 $\left(eL/m v_r\right)^2 = C$ 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)

$$E_H/P = \frac{B_o}{2 \log (A_1 P \pi \Lambda_P)} \qquad \text{... (4.26)}$$

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_o (Townsend 1948). 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 magnetic 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

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

$$A_0 \exp(-B_0 P/E) \cdot N P (3\lambda\rho)^{1/2} = 1/\Lambda^2$$

and according to Kihara $A_0 = \left(\frac{N}{P}\right)\left(\frac{\sigma}{c_i}\right)\left(\frac{3\lambda}{\rho}\right)^{1/2}$

then $N^2 \cdot \frac{3\sigma\lambda}{c_i} \cdot \Lambda^2 = \exp(B_0 P/E)$

or $\frac{N^2}{\pi^2} \cdot \frac{1}{P^2} \cdot \frac{3\sigma\lambda}{c_i} \cdot P^2 \pi^2 \Lambda^2 = \exp(B_0 P/E)$

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

$$A_1^2 P^2 \pi^2 \Lambda^2 = \exp(B_0 P/E)$$

or $$E/P = \frac{B_0}{2 \log (A_1 P \pi \Lambda)} \qquad \ldots(4.27)$$

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)

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

$$\text{or} \quad \Lambda_P/\Lambda = \left(A_1 P\pi \Lambda\right)^{(E/E_H - 1)} \qquad \ldots(4.28)$$

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

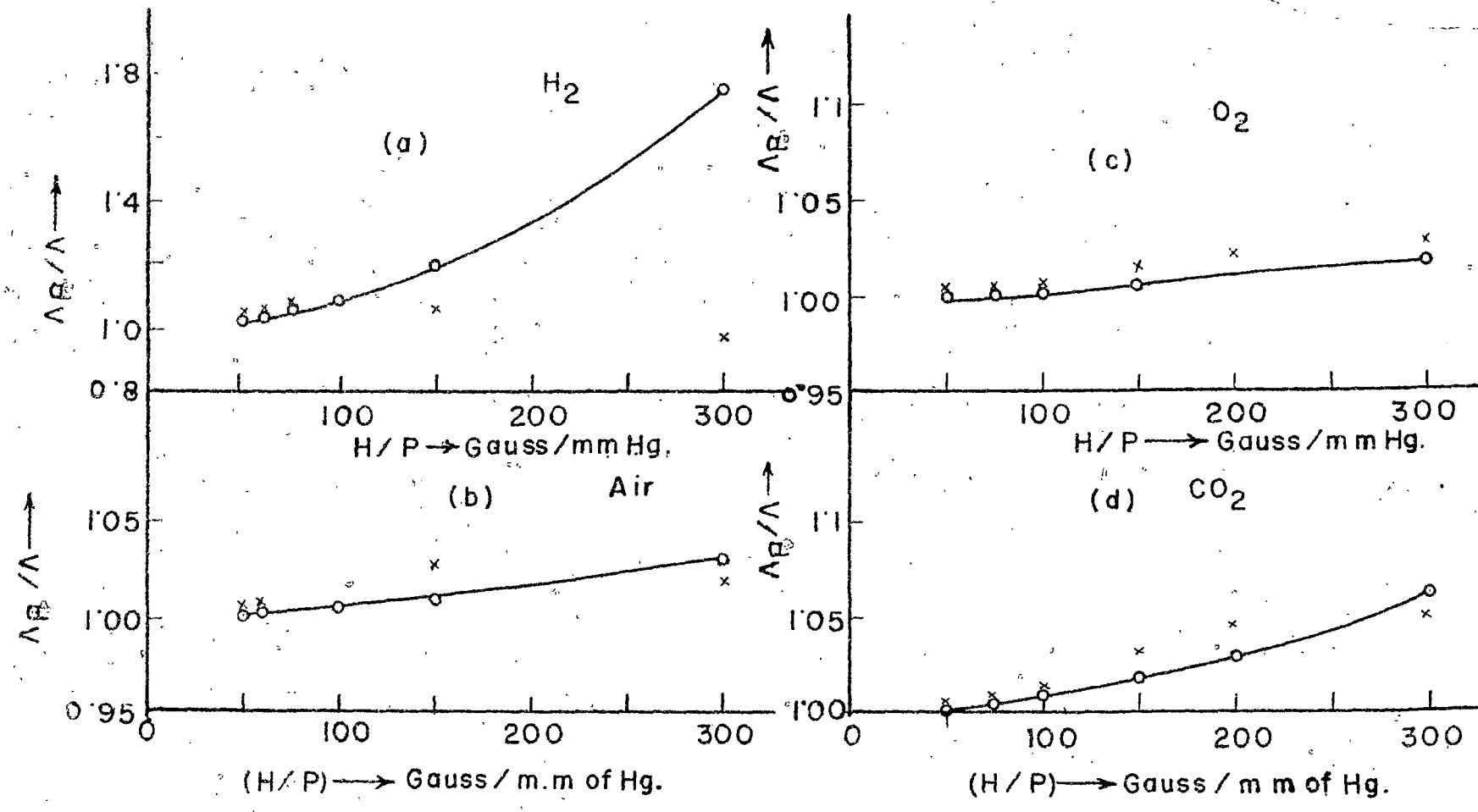
(a)
H_2
1·8
1·4
1·0
0·8
100
200
300
H/P → Gauss/mm Hg.
(b)
Air
1·05
1·00
0·95
0
100
200
300
(H/P) → Gauss/m.m of Hg.
(c)
O_2
1·1
1·05
1·00
·95
100
200
300
H/P → Gauss/m m Hg.
(d)
CO_2
1·1
1·05
1·00
0
100
200
300
(H/P) → Gauss/m m of Hg.
THEOR.
EXPT.

Fig.14

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

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S E C T I O N - B.

I N T R O D U C T I O N.

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 breakdown 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 $\pm$ 2 volts, where E is the breakdown voltage per cm and L denotes the length of the tube.

R E S U L T S 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

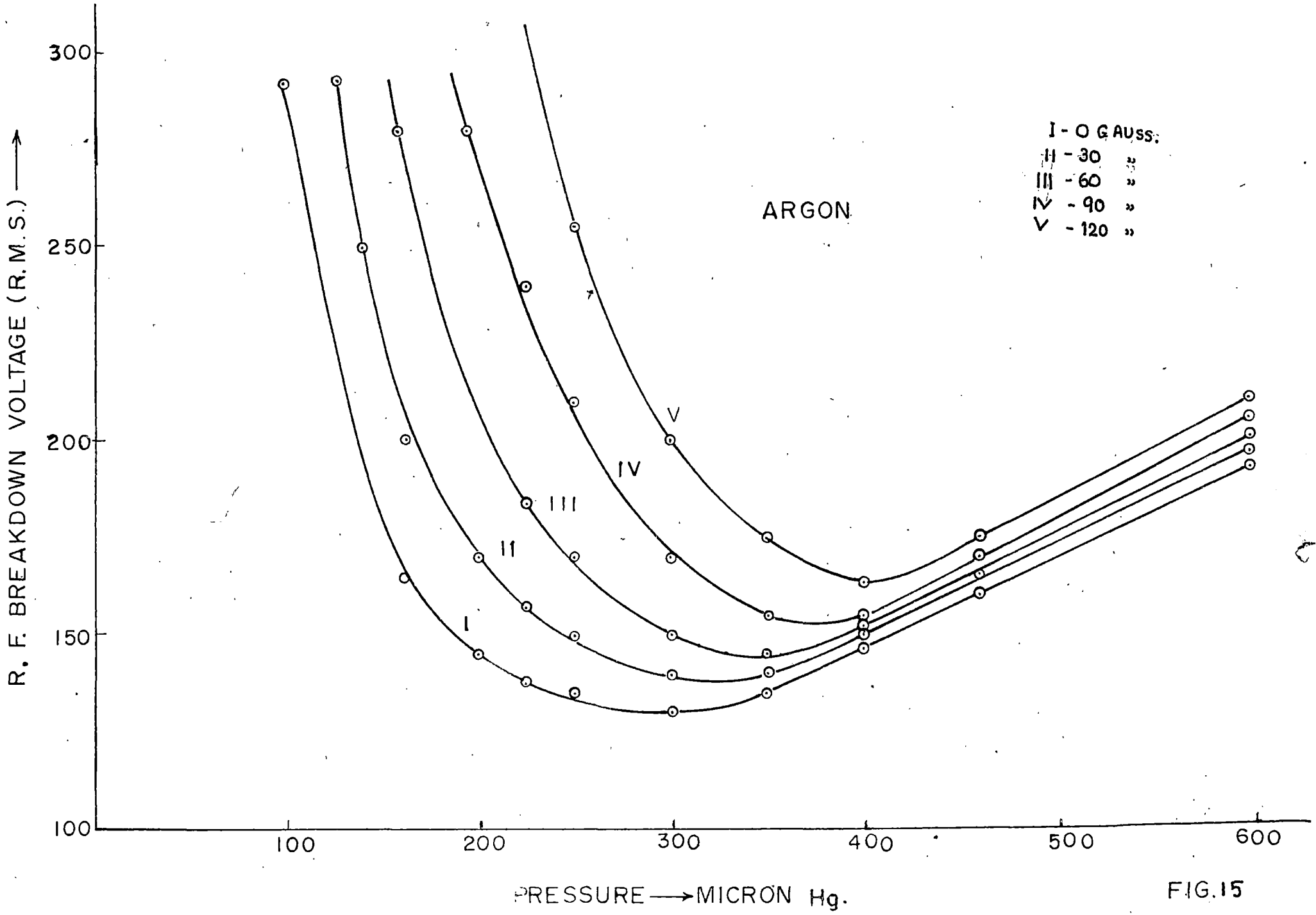
ARGON
I - 0 GAUSS.
II - 30 »
III - 60 »
IV - 90 »
V - 120 »
I
II
III
IV
V
R. F. BREAKDOWN VOLTAGE (R.M.S.) ⟶
300
250
200
150
100
100
200
300
400
500
600
PRESSURE ⟶ MICRON Hg.

FIG. 15

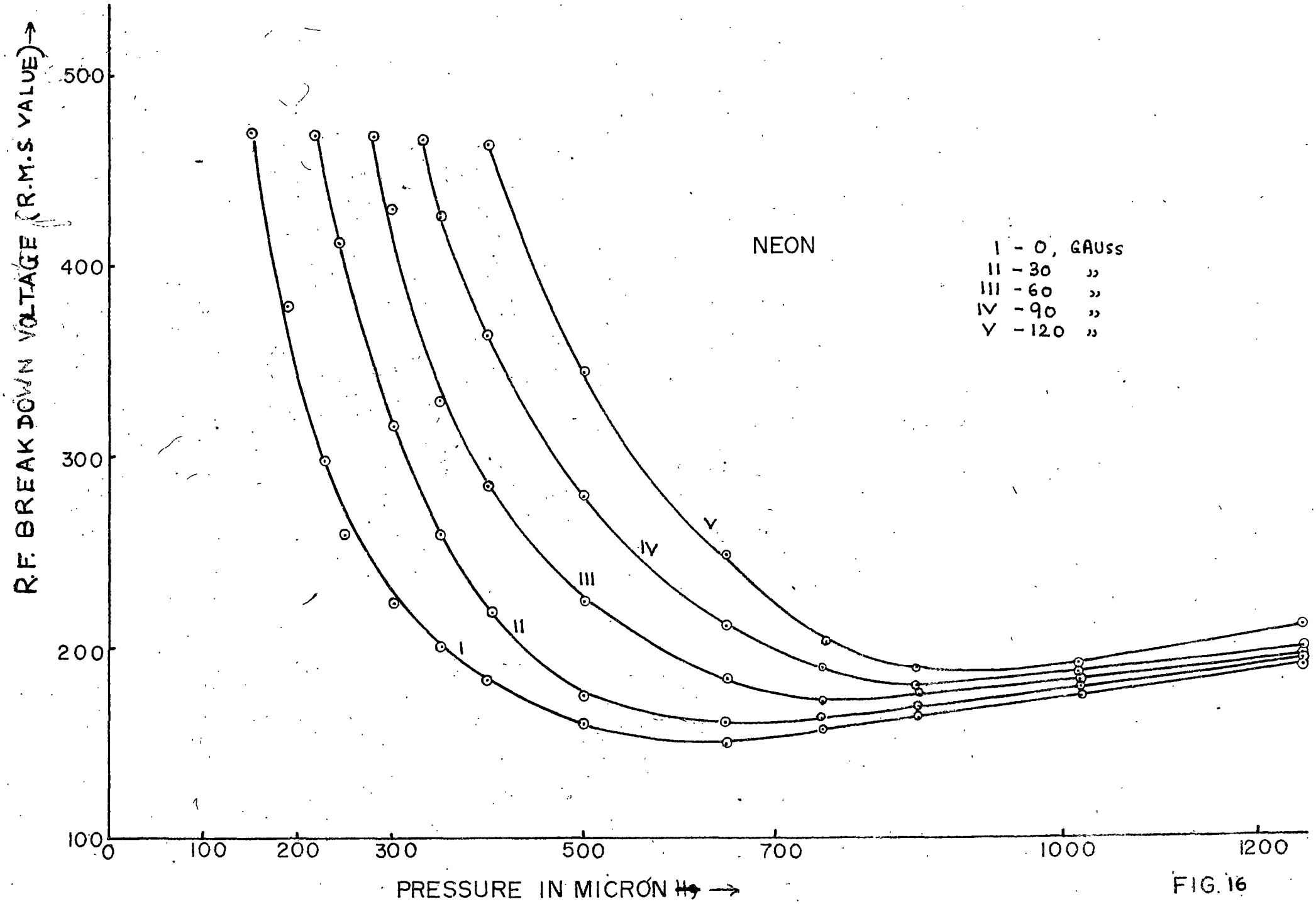
R.F. BREAK DOWN VOLTAGE (R.M.S VALUE) →
500
400
300
200
100
0
100
200
300
500
700
1000
1200
PRESSURE IN MICRON Hg →
NEON
I - 0, GAUss
II - 30 „
III - 60 „
IV - 90 „
V - 120 „
I
II
III
IV
V

FIG. 16

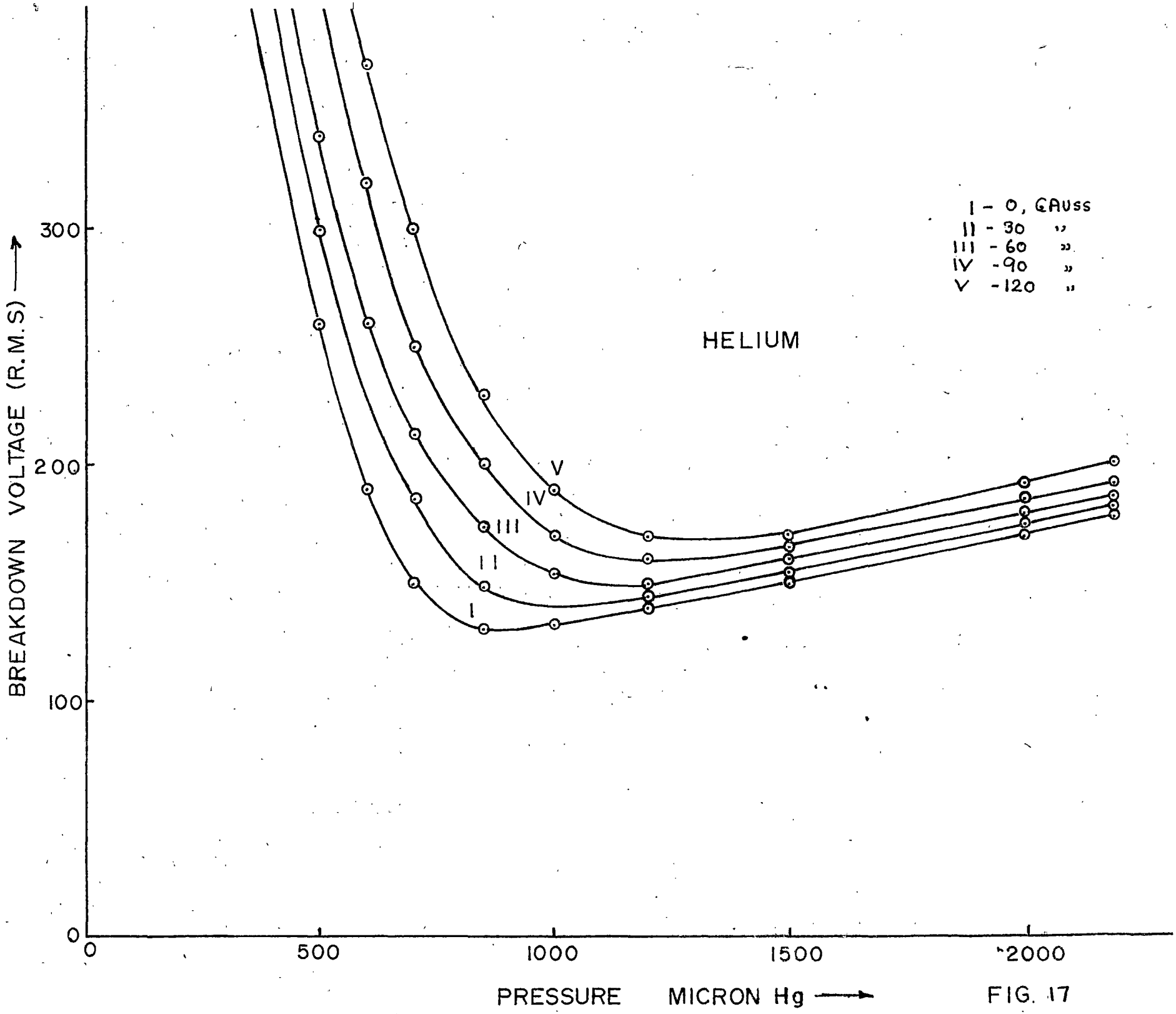
I - 0, GAuss
II - 30 "
III - 60 "
IV -90 "
V -120 "
HELIUM
BREAKDOWN VOLTAGE (R.M.S) ⟶
300
200
100
0
V
IV
III
II
I
0
500
1000
1500
2000
PRESSURE MICRON Hg ⟶

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.
Argon	130	0	·285	·226	
	140	30	·325	·251	·252
	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.
Neon	150	0	·625	·595	·654
	160	30	·675	·651	·710
	170	60	·750	·704	·762
	180	90	·850	·735	·812
	190	120	·925	·768	

T A B L E - 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 $L' = 1/A_o$ where A_o is the constant introduced by Townsend in his theory of electric 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_o given by Brown (1959).

T A B L E - IV.

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

To 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

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

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

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

Putting the values of E_p = 13 volts/cm, $\omega = 6.28 \times 6.4 \times 10^6$ 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 μ the numerical value of the term $\left(C_1/A_1 P\lambda_0\right)^2$ becomes negligible in comparison to unity and the pressure at which the breakdown voltage becomes minimum can be calculated to be

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

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 $\omega/N\lambda \gg 1$ 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 15μ because when the values of ω, N and λ are inserted, the left hand side of the equation becomes greater than unity when P is smaller than 15μ. Further it has been shown by Kihara that the breakdown voltage E is given by

$$\exp\left(B_0 P/2E\right) = A_1 PL\left[1 - \frac{E/B_0 P}{C_2 L/\lambda_0}\right] \qquad \ldots(4.33)$$

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

$$P_{min} = \left(2E_{min}/B_0\right)\log\left(2A_1 LE/B_0\right) \qquad \ldots(4.34)$$

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

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

and the breakdown condition is given by

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

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 $\nu_c \gg \omega$ the effective field becomes E and the equivalent diffusion length becomes

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

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

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

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

we get

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

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 $\alpha = (3/4)(N/P)^2 \lambda.f.$ 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

$$\exp\left[\frac{B_0 P}{2E_H} \left(1 + CH^2/P^2\right)^{1/2} \right] = A_1 PL \left(1 + CH^2/P^2\right)^{1/2} \left[1 - \frac{E_H/B_0 P}{(c_2 L/\lambda)\left(1 + CH^2/P^2\right)} \right] \quad \ldots (4.40)$$

and

$$\exp\left[\frac{B_0 P}{2E_H} \left(1 + CH^2/P^2\right)^{1/4} \right] = A_1 PL \left(1 + CH^2/P^2\right)^{1/4} \left[1 - \frac{E_H/B_0 P}{(c_2 L/\lambda)\left(1 + CH^2/P^2\right)^{1/2}} \right] \quad \ldots (4.41)$$

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'	$c_i \times 10^{-5}$ 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 $\exp(B_0 P/2E)$ against E and also for $A_1 PL\left[1 - \frac{B_0 P/2E}{C_2 L/\lambda}\right]$ 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: $\exp(B_0 P/2E)$

II: $A_1 PL\left[1-\frac{B_0 P/2E}{C_2 L/\lambda}\right]$ AGAINST E

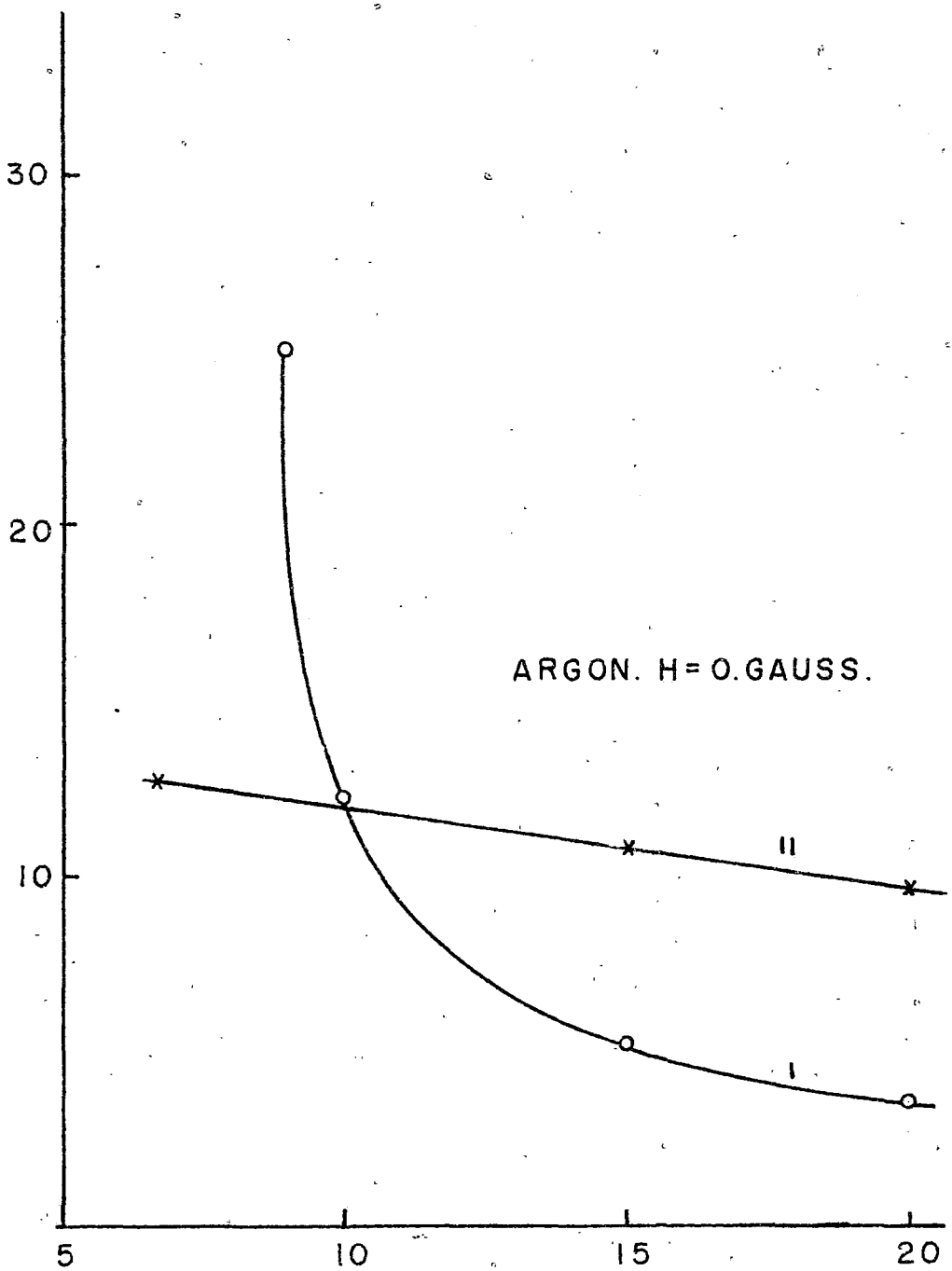

FIG-18a

VARIATION OF

I: $\exp(B_0 P/2E)$

II: $A_1 PL\left[1-\frac{B_0 P/2E}{C_2 L/\Lambda}\right]$ AGAINST E

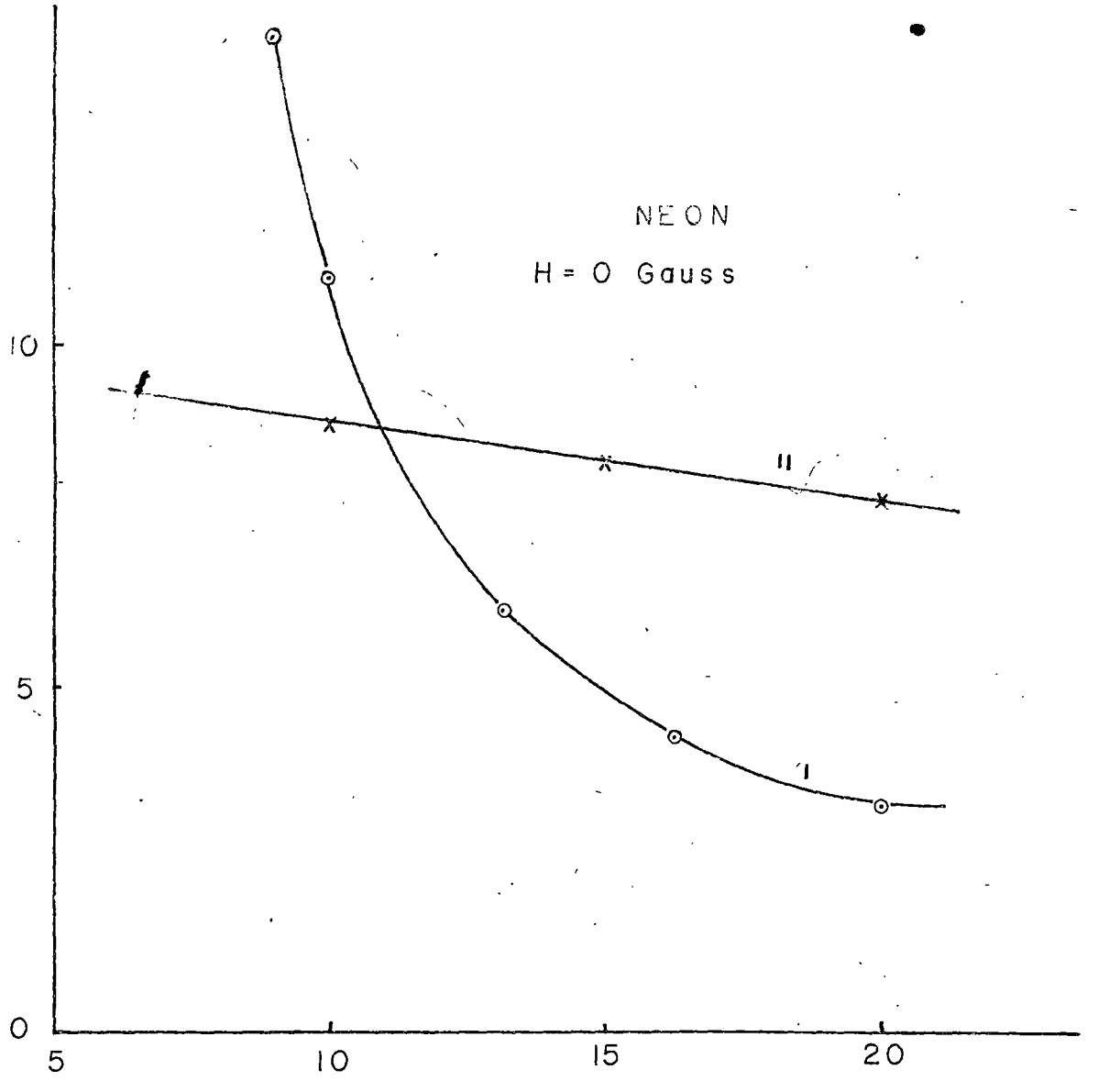

Fig. 18b

VARIATION OF

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

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

AGAINST E

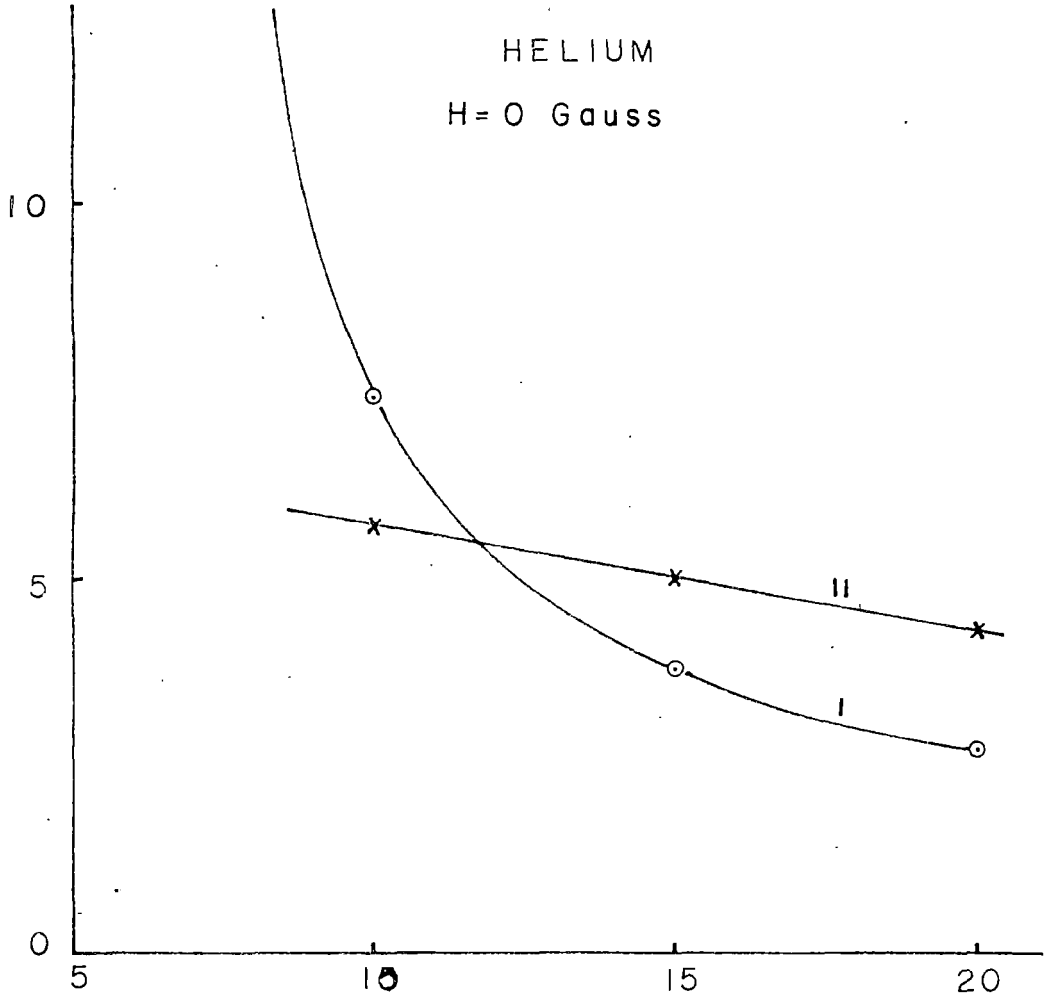

Fig.18c

VARIATION OF

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

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

AGAINST E

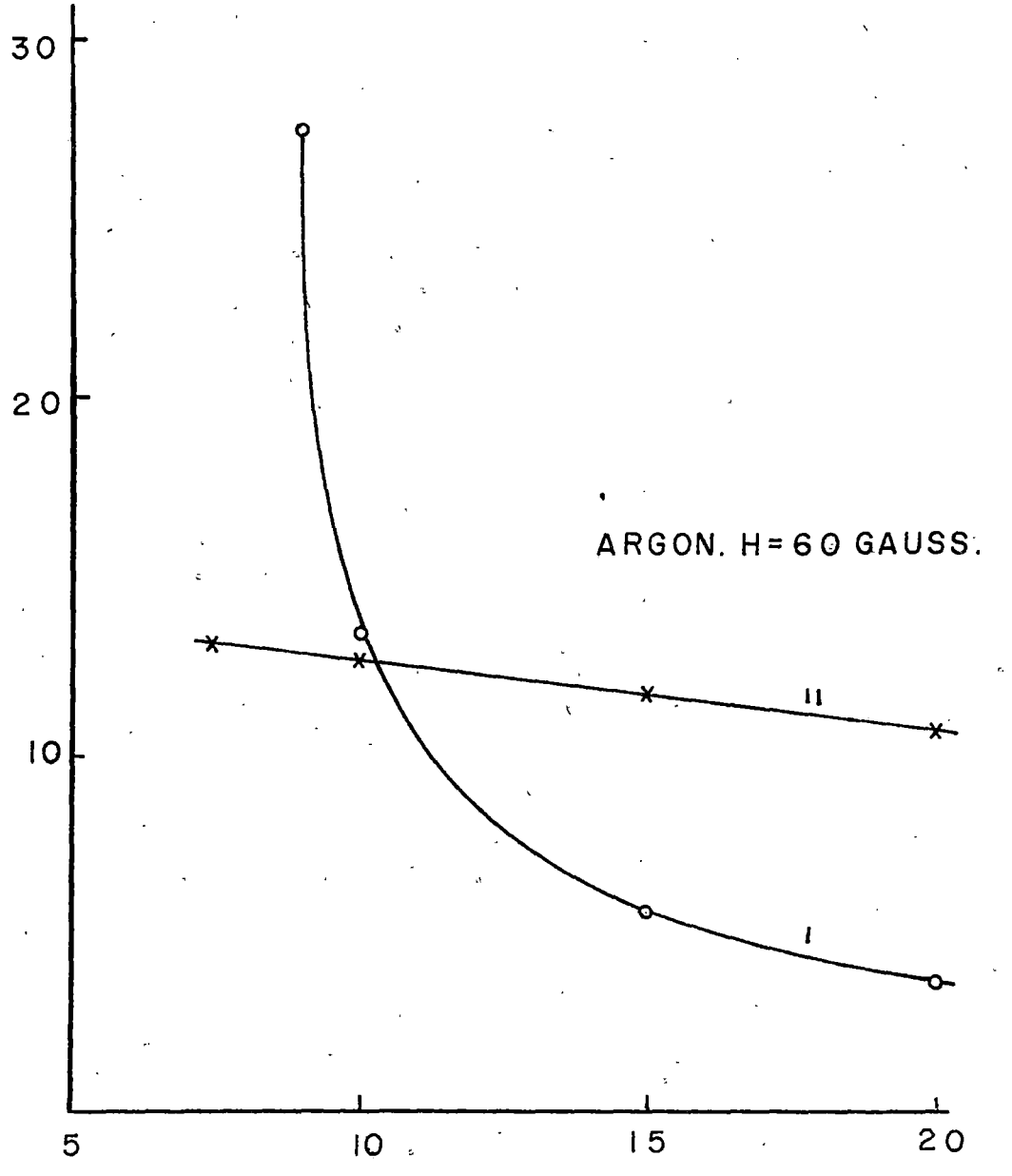

FIG. 19α

VARIATION OF

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

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

AGAINST E

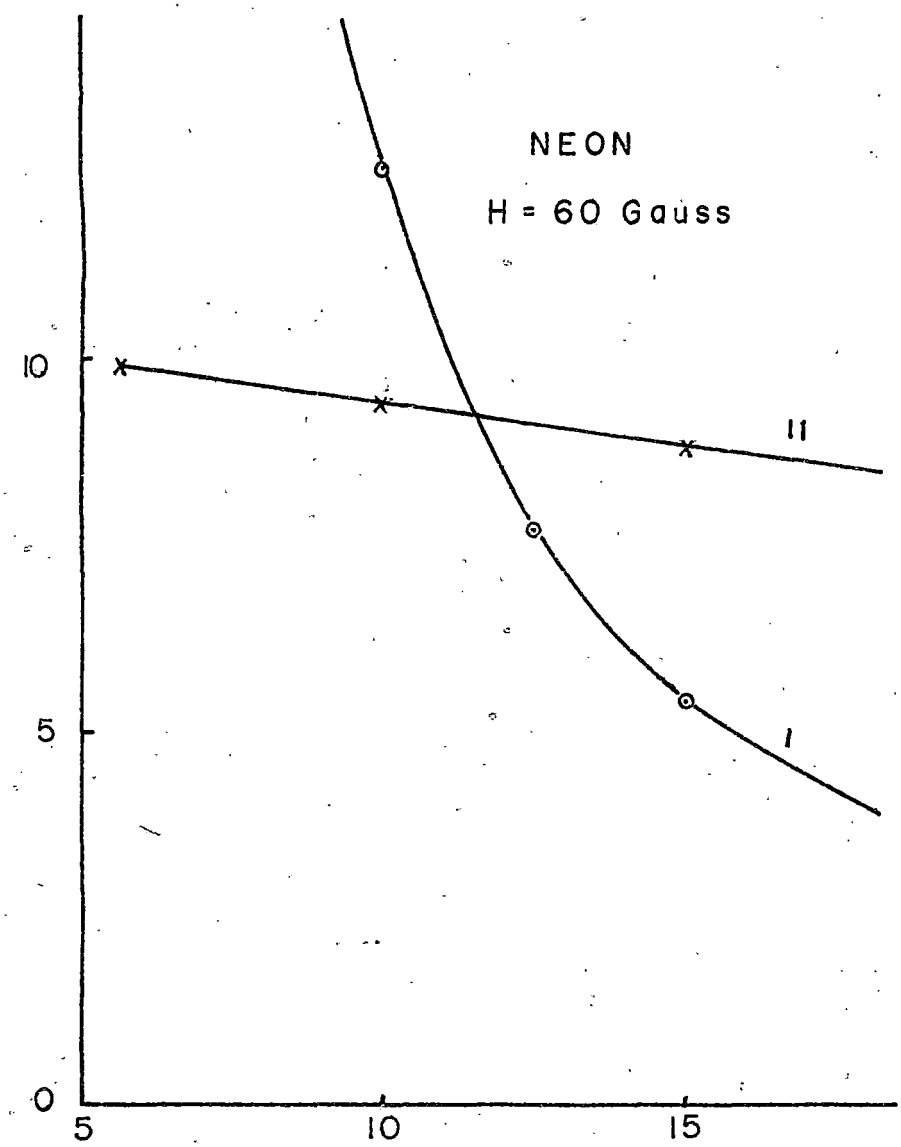

Fig 19b

T A B L E - 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	11.5	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

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

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

.... (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

$$(P_H)^2_{min} = \frac{4(E_H)^2_{min}}{B_o}\left[\log \frac{2(E_H)_{min} A_i L}{B_o}\right]^2 - C H^2$$

...(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

$$(P_H)^4_{min} + C H^2 (P_H)^2_{min} - \left[\frac{2(E_H)_{min}}{B_o} \log \frac{2(E_H)_{min} A_i L}{B_o}\right]^4 = 0$$

...(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 than 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 [1] , 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

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

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 (Hoh 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 drawbacks 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.

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C H A P T E R - V.

BREAKDOWN OF GASES BY RADIO FREQUENCY ELECTRIC FIELD IN THE PRESENCE OF A SUPERIMPOSED PARALLEL D.C. ELECTRIC FIELD.

I N T R O D U C T I O N.

Varela (1947) observed that the breakdown potential in a discharge excited by a radiofrequency source increased when a d.c. potential less than the radiofrequency breakdown voltage was applied across the discharge tube. The discharge tube had aluminium electrodes in an atmosphere of 5 cm. hydrogen with an admixture of 20% argon. It was expected however, that the presence of the d.c. field would hasten ionisation with a given radiofrequency potential by virtue of higher peak electron velocities and that a residual potential following the discharge would hasten deionisation; but the results were contrary to what was expected. Almost the same results were obtained earlier by Kirchner (1925, 1947) while studying the breakdown in gases by an r.f. field in the presence of a d.c. potential.

Varnerin and Brown (1950) calculated theoretically the distribution function of electrons in an ionised gas in the presence of both radiofrequency and d.c. fields. It is generally known that the gas in the cavity will breakdown when the losses of electrons to the walls of the cavity are replaced by ionisation in the body of the gas. When an a.c. field is applied, electrons are lost by diffusion; when, in addition, a d.c. field is applied, electrons are lost both by diffusion and mobility. It has been shown by Varnerin and Brown that the new effective diffusion length $L_{d.c.}$ of the vessel in the presence of the d.c. field is shorter than its undisturbed diffusion length L according to the equation

$$1/L_{d.c.}^2 = 1/L^2 + \left\{ \bar{K} E_{d.c.} / 2D \right\}^2 \qquad \ldots(5.1)$$

where $\bar{K}$ denotes the mobility of the electron and D the diffusion coefficient. They thus concluded that the only difference between the breakdown condition

in the a.c. - d.c. case and the pure a.c. case is the substitution of a modified diffusion length $L_{d.c.}$ for the characteristic diffusion length L. That a greater breakdown field is necessary when the d.c. voltage is superimposed on the radiofrequency field was shown by Brown (1956) in the case of air at a pressure of 38 mm. of mercury where a d.c. field upto 200 volts/cm was applied.

No, systematic study of the breakdown of gases under the simultaneous action of the a.c. and d.c. fields has so far been reported. It is expected that this study will throw more light on the mechanism of breakdown.

The object of the present investigation is to determine the breakdown voltage in some gases in a superimposed radiofrequency and d.c. field and to present a theory capable of explaining the observed results. The whole investigation is divided in to two parts. In the first part the breakdown voltage under the simultaneous action of radiofrequency and d.c. field is measured for some rare gases (He, Ne, A) and oxygen at a constant pressure of 10 m.m. mercury. The applied d.c. voltage is varied from zero to 70 volts/cm . It has been found that the breakdown voltage is higher when both the fields are present than when the gas is excited by a radiofrequency field alone and the breakdown voltage gradually increases with the increase of the d.c. field. A theoretical expression for the breakdown voltage in the presence of d.c. and radiofrequency field was deduced from the theory of electrical discharge by Kihara (1952) utilising the expression for equivalent length deduced by Varnerin and Brown. The expression thus deduced was utilised to explain the experimental results. However this treatment did not include the contribution to ionisation made by the d.c. field because the field applied was small compared to the radiofrequency breakdown field. It was evident however from the experimental results obtained that the rate of rise of breakdown field with the applied d.c. field gradually becomes smaller as the value of the d.c. field is

increased. From this it was evident that the contribution to ionisation by the d.c. field was becoming dominant with higher d.c. fields and naturally if the d.c. field be sufficiently increased then the contribution to ionisation by the d.c. field will be considerable and the radiofrequency voltage to cause breakdown will gradually decrease. At this point a second set of experiments is performed on a.c. - d.c. combined breakdown phenomena to verify the above conclusion. The gases used were oxygen, air, carbon-di-oxide and hydrogen and results were obtained for different pressures in each gas (a few m.m. mercury) by gradually increasing the d.c. voltage at regular steps. The maximum d.c. voltage used is 240 volts per cm. The variable voltage radiofrequency field had the frequency 10.3 Mc/sec. In all cases studied, the radiofrequency voltage initially increases with applied d.c. voltage attains a maximum and then with the continous increase of d.c. field, the r.f. breakdown voltage gradually decreases.

Obviously the theoretical expression deduced to explain the results of first set of experiments was a partial success. It was pointed out that the discrepancy might be due (a) to uncertainty in the values of the molecular constants introduced by Kihara and (b) the effect of d.c. ionisation was not taken into consideration. Varnerin and Brown in finding the effect of d.c. field only considered the effects of increased diffusion and mobility but at high values of d.c. field the contribution due to d.c. ionisation should also be taken into consideration. Consequently a modified theoretical expression is deduced to explain the experimental results of the second set.

EXPERIMENTAL SETUP.

In the first part of the experiment, the discharge tubes of helium, neon, argon and oxygen have been supplied by the manufacturers in sealed condition at a certain pressure and each discharge tube is fitted with aluminium electrodes. The r.f. voltage and d.c. voltage are simultaneously applied to the discharge

tubes through series connected condensers and series connected r.f. chokes respectively as explained in chapter III. The d.c. field is varied from 5 volts/cm to 70 volts/cm. The length of the discharge tubes are as follows : helium-13 cm., neon -15 cm., argon - 13.2 cm., oxygen- 13 cm.

The second part of the experiment has got the identical setup as the previous one. The discharge tube is of length 3cm. and diameter 1.25 cm and fitted with two platinum electrodes with arrangement of stopcock to control the pressure of the gas enclosed. The gases studied in this investigation are oxygen, air, hydrogen and carbon-di-oxide. Air, oxygen and carbondioxide have been chosen in order to study the effect of electron attachment and the pressure is of the order of a few mms of mercury which has been measured with the help of a mercury manometer. The radiofrequency voltage has the frequency 10.3 Mc/s and the d.c. voltage applied is from few volts/cm to 240 volts/cm. Hydrogen and oxygen have been prepared by electrolysis of barium hydroxide solution. Carbon-dioxide has been obtained by the action of dilute sulphuric acid on sodium carbonate.

RESULTS AND DISCUSSION.

1st Part :- The variation of the ratio E_1/E_o (where E_1 is the breakdown voltage per cm in the presence of both the radiofrequency and d.c. fields and E_o is the breakdown voltage per cm in the presence of the radiofrequency field only) against $E_{d.c.}$ the applied d.c. voltage per cm is shown in figs.20-a, b, c, d. There is no detectable change in radiofrequency breakdown voltage for small d.c. voltages, which was less than 5 v/cm for all the gases studied; it is clear that with the application of d.c. field, the radiofrequency breakdown voltage increases and the nature of variation of E_1/E_o with $E_{d.c.}$ is practically the same for all the gases studied. The nature of the variation is the same as that observed by the previous workers.

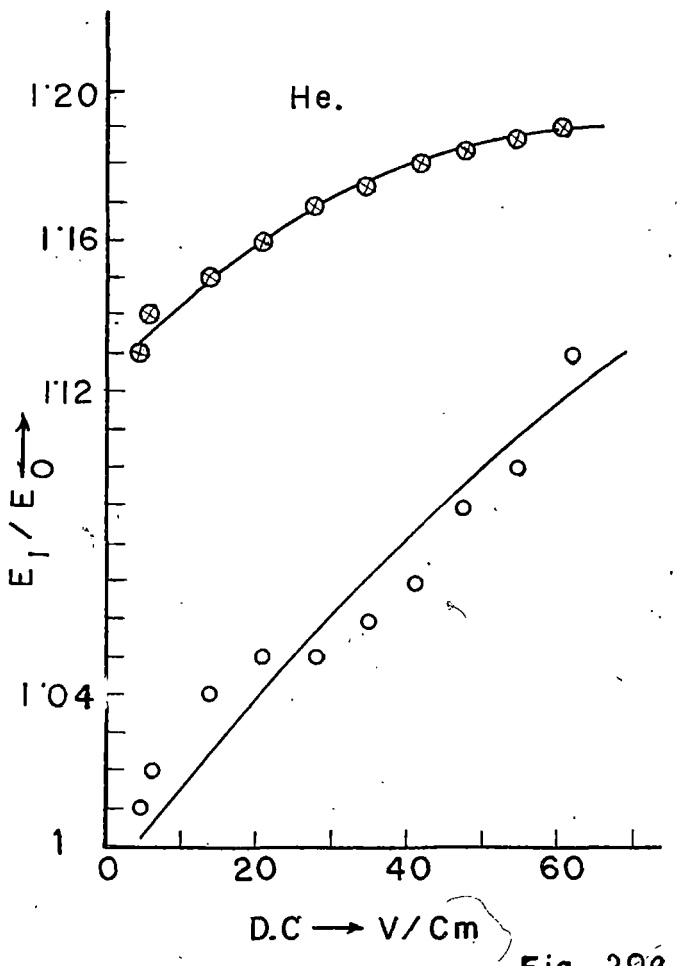

Fig-20a

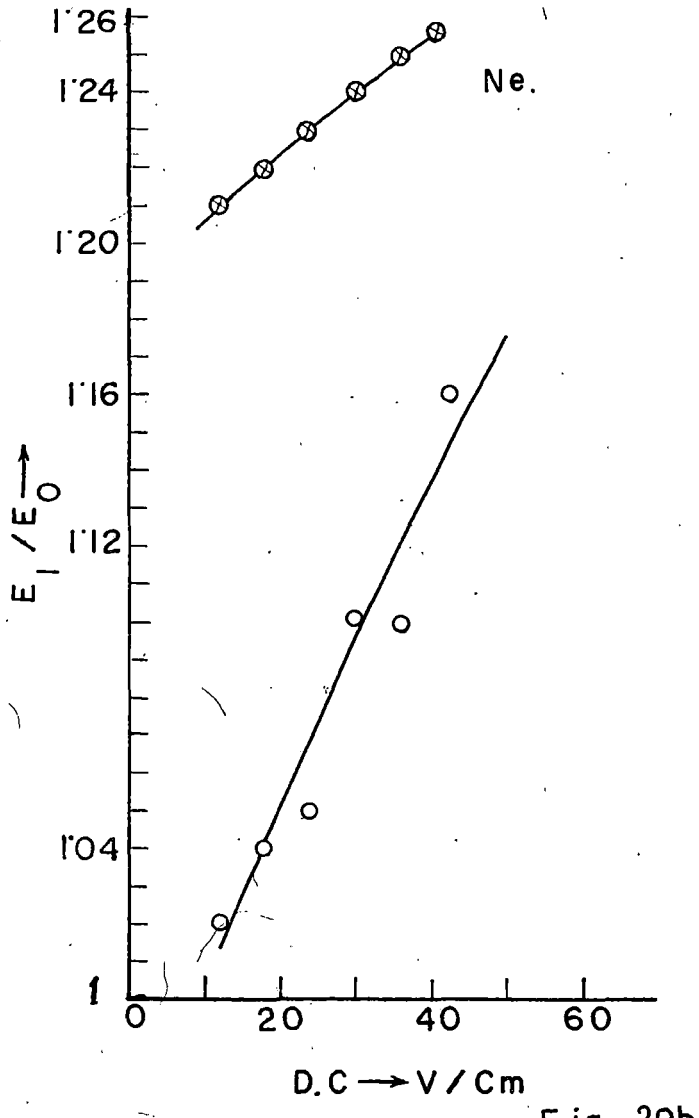

Fig-20b

[O : EXPERIMENTAL POINTS.]

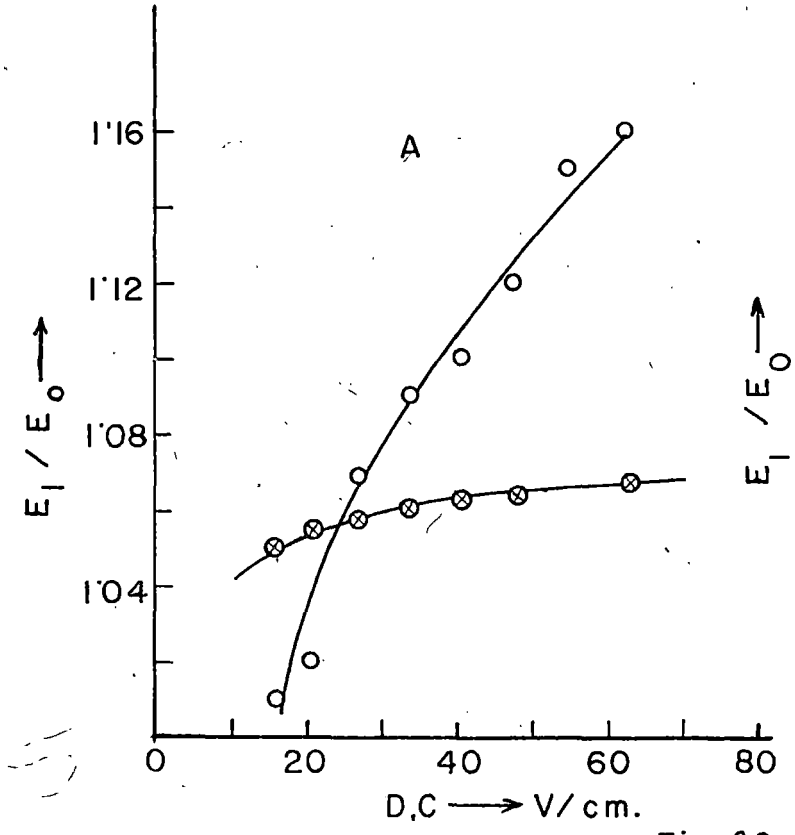

Fig-20c

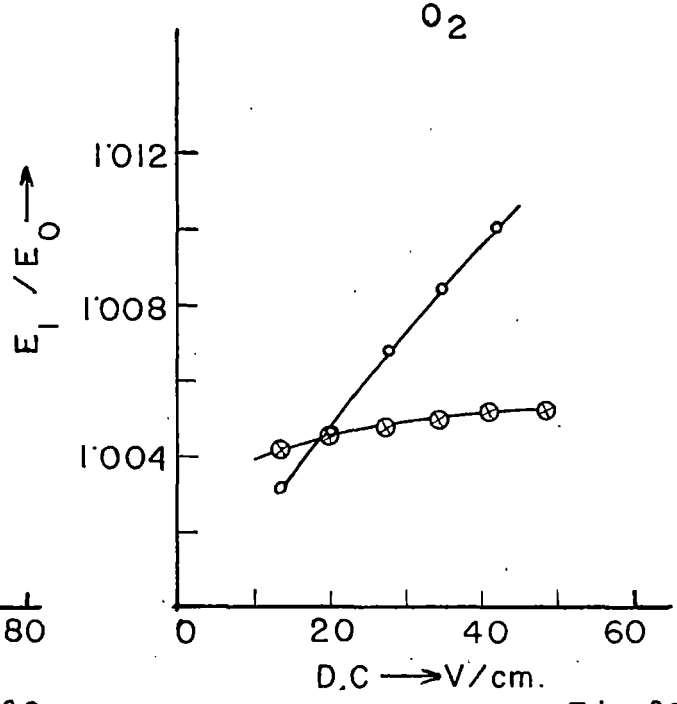

Fig-20d

[O : EXPERIMENTAL POINTS]

The physical significance of these results is at once apparent. In a r.f. field, breakdown occurs when the loss of electrons by diffusion and mobility is compensated by the generation of electrons by ionisation. The application of the d.c. field further increases the loss due to diffusion and mobility and hence a larger electric field must be applied to produce more ionisation to compensate for this increased loss. In the analysis which follows use has been made of the equations deduced by Kihara (1952) with the new diffusion length $L_{d.c.}$ introduced by Varnerin and Brown (1950).

If L_o denotes the equivalent length with the radiofrequency field alone, then according to Kihara (1952)

$$1/L_o^2 = (1/\pi^2)(\nu_o/D_o) \qquad \ldots (5.2)$$

where ν_o is the ionisation coefficient and D_o is the diffusion coefficient. When both the r.f. and d.c. fields are present, the breakdown condition is given by

$$1/L_{d.c.}^2 = (1/\pi^2)(\nu/D) \qquad \ldots (5.3)$$

where $$1/L_{d.c.}^2 = 1/L_o^2 + \left\{\bar{K} E_{d.c.}/2D\right\}^2 \qquad \ldots (5.4)$$

then $$1/L_o^2 + \left\{\bar{K} E_{d.c.}/2D\right\}^2 = (1/\pi^2)(\nu/D) \qquad \ldots (5.5)$$

where ν and D represent the quantities for the new breakdown field. According to Kihara (1952)

$$\nu_o/D_o = (3.\sigma.N^2\lambda/c_i)\exp\left[-mc_i^2/2K(T_e)_o\right]$$

$$\nu/D = (3.\sigma.N^2\lambda/c_i)\exp\left[-mc_i^2/2KT_e\right]$$

where σ, λ and c_i are the molecular constants introduced by Kihara and N is the number of molecules per c.c. at the pressure of the gas, K is the Boltzman constant, "m" is the mass of the electron and (T_e) is the electron temperature, which will be different for two breakdown voltages. Consequently, from equations (5.3) and (5.4) we get

$$\frac{1/L_o^2}{(1/L_o^2) + (\bar{K} E_{d.c.}/2D)^2} = \exp\left[(mc_i^2/2K)\left\{\frac{1}{T_e} - \frac{1}{(T_e)_o}\right\}\right] \quad \ldots(5.6)$$

Assuming that $T_e \approx (T_e)_o$ we get

$$\log\left[1 + \left(\bar{K} E_{d.c.} L_o/2D\right)^2\right] = -(mc_i^2/2K)\left\{\frac{(T_e)_o - (T_e)}{(T_e)_o^2}\right\} \quad \ldots(5.7)$$

But according to Kihara (1952)

$$\bar{K}/2D = e/K(T_e)_o$$

and $$K(T_e)_o = eE_o/N(6\lambda\rho)^{1/2}$$

where E_o = Peak r.f. breakdown voltage = (r.m.s. voltage). $2^{\frac{1}{2}}$

and similarly $$KT_e = eE_1/N(6\lambda\rho)^{1/2}$$

where E_1 = Peak r.f. breakdown voltage = (r.m.s. voltage) . $2^{\frac{1}{2}}$

Putting these values into equation (5.6) we get

$$\log\left[1 + \left\{eL_o E_{d.c.}/2K(T_e)_o\right\}^2\right] = N(6\lambda\rho)^{1/2}\left\{(E/E_o) - 1\right\} \quad \ldots(5.8)$$

According to Kihara $$L_o = L' - (2\bar{K}/\omega)E_o \quad \ldots(5.9)$$

where L′ is the length of the discharge tube and " ω " is the angular frequency of the applied r.f. field. Hence

$$\log\left[1+\left\{\frac{e\left[L'-(2\bar{K}/\omega)E_0\right]E_{d.c.}}{2K(T_e)_0}\right\}^2\right] = N(6\lambda\rho)^{1/2}\left\{(E_1/E_0)-1\right\}$$

$$\therefore\ E_1/E_0 = 1 + \frac{\log\left[1+\left\{\frac{e\left[L'-(2\bar{K}/\omega)E_0\right]E_{d.c.}}{2K(T_e)_0}\right\}^2\right]}{N(6\lambda\rho)^{1/2}}$$

.....(5.10)

Since the radiofrequency breakdown voltage is known from experimental results, $(T_e)_0$ can be calculated from the relation (Kihara 1952).

$$K(T_e)_0 = eE_0/N(6\lambda\rho)^{1/2}$$

The values of the mobility coefficient $\bar{K}$ for the value E_0/p have been obtained from the results reported by Brown (1959). In order to calculate the right hand side of equation (5.10), the following values have been calculated from the data of molecular constants given by Kihara (1952).

T A B L E - I.

$N = 3.55 \times 10^{17}$ P = 10mm. Hg. f = 10Mc/sec $\omega = 6.28 \times 10^7$ radians.

Gas	$\lambda\times10^8$ Cm^3/sec	$\rho\times10^{24}$ Cm.Sec.	$N(6\lambda\rho)^{1/2}$	E_0 Volts/cm	$K(T_e)_0\times10^{12}$	L' cm.	$\bar{K}\times10^{-6}$	$\frac{e[L'-(2\bar{K}/\omega)E_0]}{2K(T_e)_0}$	$(\lambda\rho)\times10^{32}$ cm^4
Argon	7.8	1.35	282.1	16.28	0.0953	13.3	0.0568	114.1	
Helium	4.4	0.20	81.58	14.61	0.2902	13	0.0821	36.17	
Neon			52.96	17.3	0.517	15	0.1329	22.86	0.3710
Oxygen			726.6	23	0.0512	13	0.1304	203.8	8.356

The right hand side of equation (5.10) can thus be calculated for different values of $E_{d.c.}$. The results are plotted side by side with the experimental curves. The quantitative agreement is not satisfactory except for argon and oxygen and also for values of $E_{d.c.}$ near about 20 v/cm. There is no agreement at all for helium and neon. The quantitative disagreement can be attributed partly to constants introduced by Kihara. The nature of the theoretical curve resembles the experimental curve to a certain extent, but the rate of rise as predicted from the theoretical deduction is smaller than that obtained experimentally. It should be noted however, that in the above deduction two effects have not been considered viz. (a) increased loss due to diffusion because of the presence of positive ions and (b) the possible ionisation contributed by the d.c. field itself. The contribution by the second factor to the theoretical computation of breakdown voltage would, however, decrease the actual value, because if there is any ionisation caused by the d.c. field, it would tend to lower the value of breakdown field. Whereas this factor may lower the values of (E_1/E_0) somewhat in the case of helium and neon, it will reduce still further the values of (E_1/E_0) in the case of argon and oxygen where the theoretical values are actually lower than the experimental values. Further more in the case of oxygen the contribution due to the attachment of electrons have not been taken into consideration, and this actually modifies the expression for breakdown voltage. The increased loss due to diffusion in the presence of positive ions may be responsible for the higher values obtained experimentally.

The theoretical and experimental results point, however, to the fact that in a discharge excited by the simultaneous action of radiofrequency and d.c. voltage, the loss of electrons is due both to diffusion and to mobility and by employing the deductions of Kihara with the expression for the equivalent length as deduced by Varnerin and Brown, it has been possible to deduce results which can be compared with the experimentally observed values. Though the evobe

treatment is incomplete in many sense, yet its success with so many uncertainities could not be ignored. So in the second part of the experiment, attention was paid to different drawbacks in this theoretical expression and the theory has been modified in the light of knowledge gathered by this result.

2nd Part :- In continuation of work done in the first part the variation of radiofrequency breakdown voltages with the applied d.c. field has been plotted in Figs. 21, 22, 23, 24, in case of air, hydrogen, oxygen and carbon-di-oxide respectively. The ordinate represents the ratio E_2 / E_o where E_2 is the radiofrequency breakdown voltage when both the radiofrequency and d.c. fields are present and E_o is the breakdown voltage when only the radiofrequency voltage is present. It is seen from the nature of the curves that the breakdown voltage gradually increases with the increase of d.c. field, then attains a maximum at a certain d.c. field which is different for different gases, and then falls as the d.c. field is further increased. A well defined maximum is obtained in each case and the variation of breakdown voltage with the d.c. field is quite general as it has been observed for all the four gases studied. It is thus quite apparent that whereas the theory of Varnerin and Brown (1950) can explain the increase of breakdown voltage when the d.c. field is small as due to increased loss due to mobility in the presence of d.c. field, the occurance of maxima and the consequent fall in breakdown voltage show that other mechanisms are also operating.

To explain the observed results it is therefore suggested that, whereas for small d.c. fields, d.c. ionisation can be neglected, the effect of d.c. ionisation has to be taken into consideration when the d.c. voltage is of the order employed in the present investigations. The effect of d.c. voltage is also to increase the mobility and thereby cause an increased loss of electrons. In the calculation which follows, it will first be considered that the ionisation

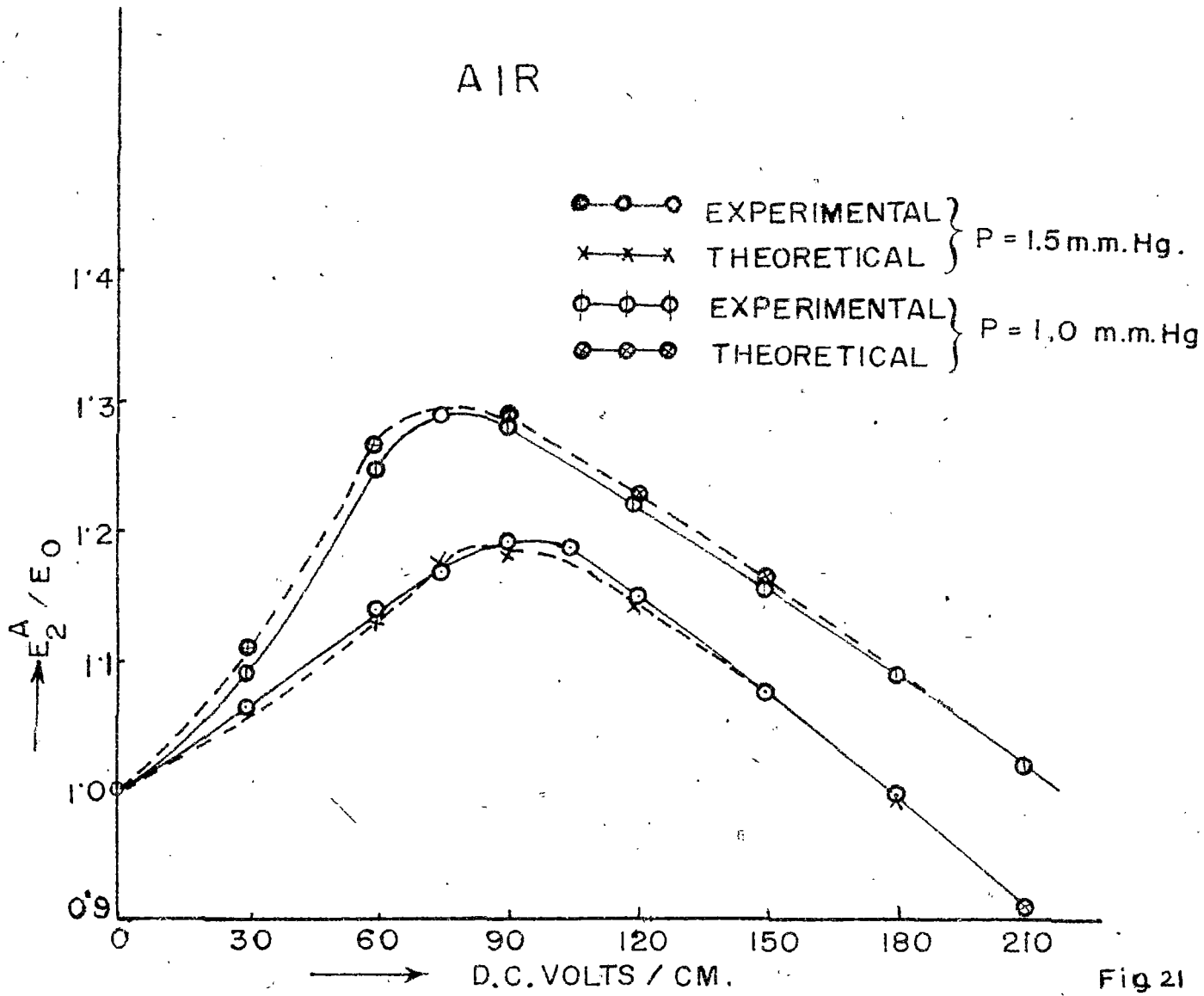
AIR
EXPERIMENTAL
THEORETICAL
P = 1.5 m.m.Hg.
EXPERIMENTAL
THEORETICAL
P = 1.0 m.m.Hg.
1·4
1·3
1·2
1·1
1·0
0·9
E_2^A / E_0
0
30
60
90
120
150
180
210
D.C. VOLTS / CM.

Fig. 21

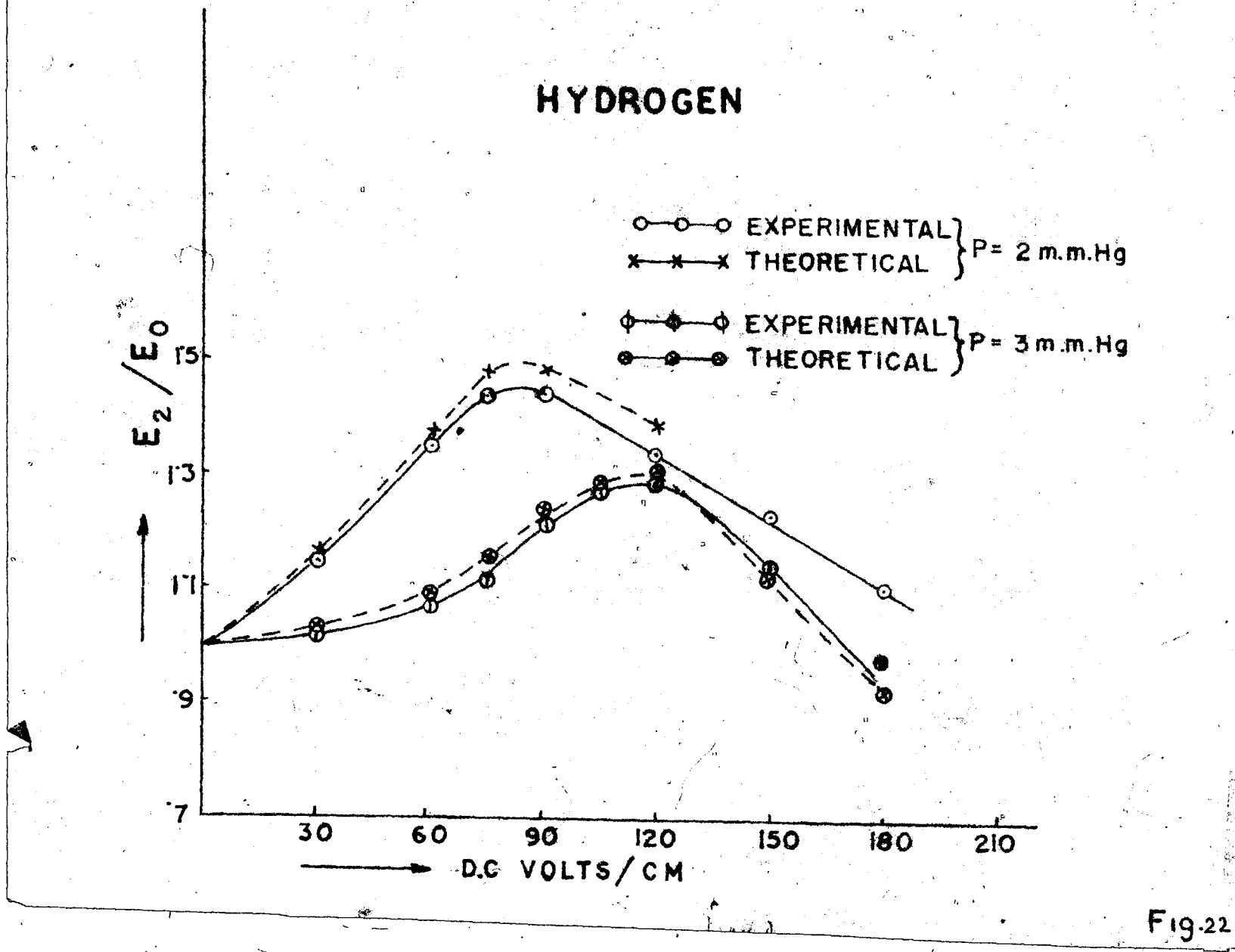
HYDROGEN
EXPERIMENTAL
THEORETICAL
P= 2 m.m.Hg
EXPERIMENTAL
THEORETICAL
P= 3 m.m.Hg
E2 / E0
1·5
1·3
1·1
·9
·7
30
60
90
120
150
180
210
D.C VOLTS / CM

Fig 22

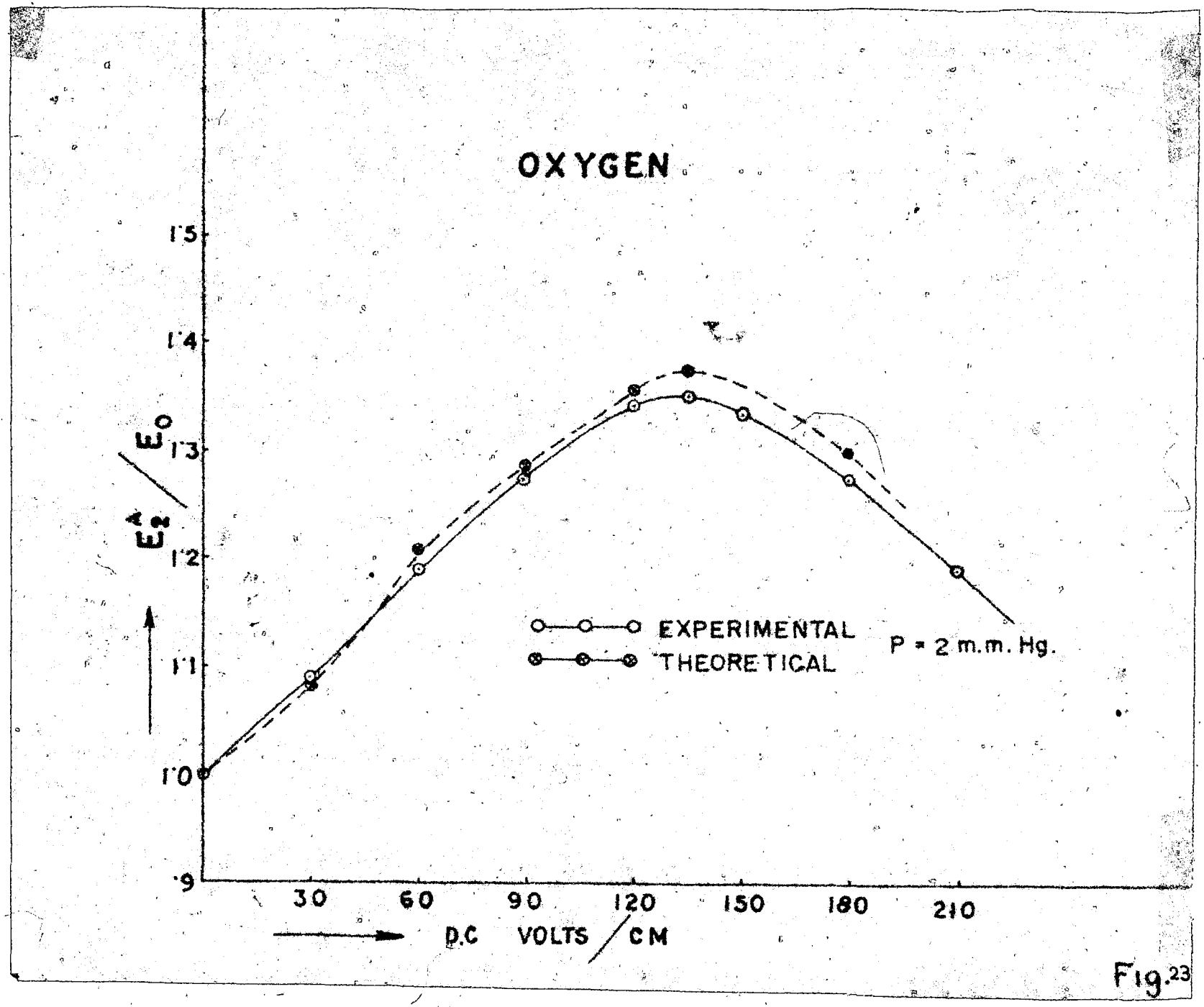
OXYGEN
1·5
1·4
1·3
1·2
1·1
1·0
·9
E^A / E^0
EXPERIMENTAL
THEORETICAL
P = 2 m.m. Hg.
30
60
90
120
150
180
210
D.C VOLTS / CM

Fig.23

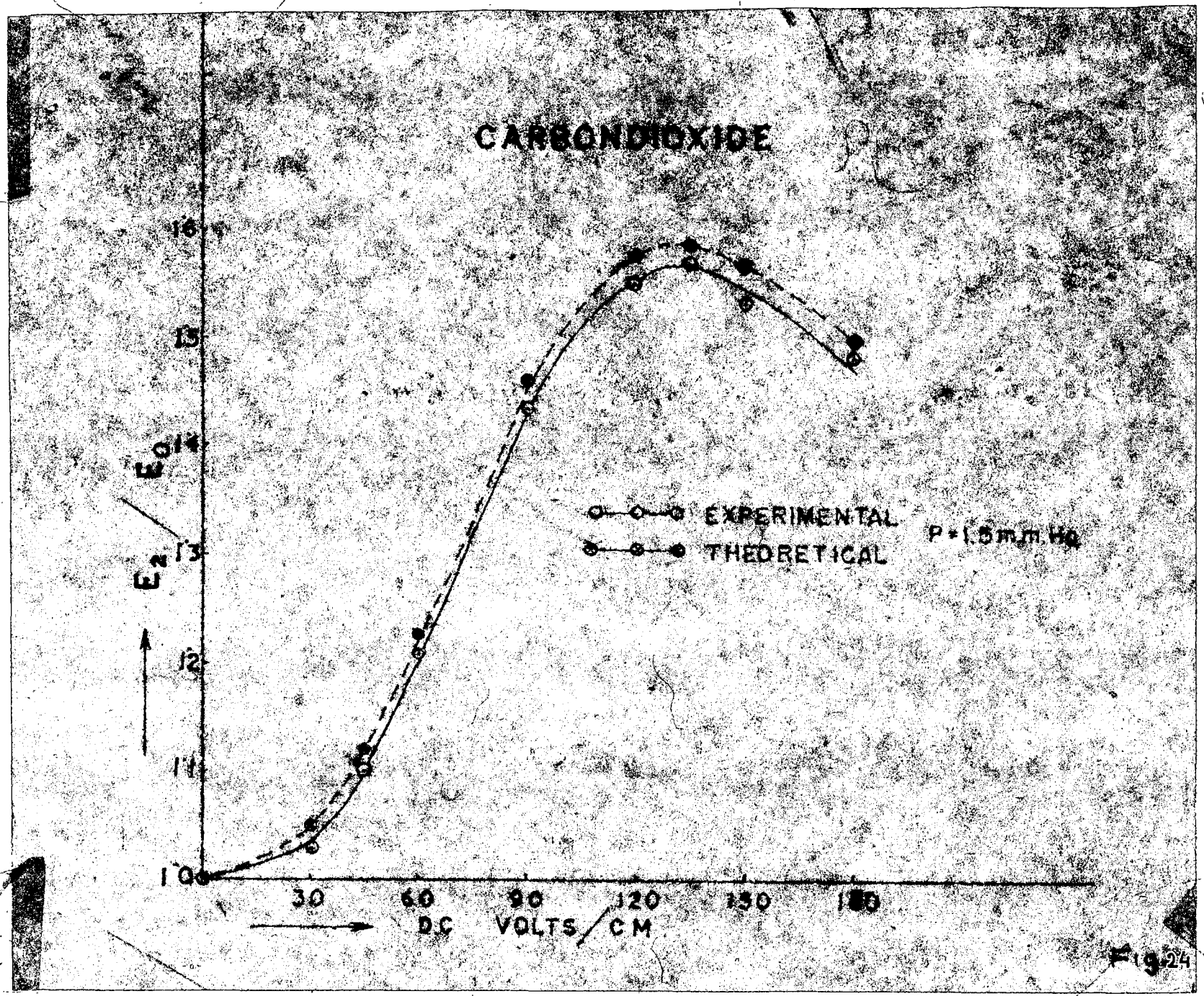
CARBONDIOXIDE
16
15
14
13
12
11
10
E_{CO_2}
E_{N_2}
EXPERIMENTAL
THEORETICAL
P = 1.5 m.m. Hg
30
60
90
120
150
180
D.C VOLTS / C M

Fig 24

due to d.c. field is absent and only the loss due to mobility to be effective. It will be then found out how this breakdown field changes when the d.c. ionisation is taken into consideration. In the presence of radiofrequency field the breakdown condition is given by

$$\nu_0/D_0 = 1/\Lambda^2 = \left(2{\cdot}405/a\right)^2 + \left(\pi/L_0\right)^2 \qquad \ldots(5.11)$$

where Λ is the diffusion length

where

$$L_0 = \left(L - 2\bar{K} E_0/\omega\right) \qquad \ldots(5.12)$$

Here ν_0 is the ionisation coefficient and D_0 is the diffusion coefficient. E_0 is the breakdown field in absence of d.c. field, L the length of the discharge tube, " a " is the radius of the tube, and $\bar{K}$ the mobility and ω the angular frequency of the applied field. When the d.c. field is also present, it has been shown by Varnerin and Brown (1950) that the breakdown condition is given by

$$\nu_1/D_1 = \left(2{\cdot}405/a\right)^2 + \left(\pi/L_0\right)^2 + \left(\bar{K} E_{d.c.}/2D\right)^2 \qquad \ldots(5.13)$$

From equations (5.11), (5.12) and (5.13)

$$\frac{\nu_0/D_0}{\nu_1/D_1} = 1/\left(1 + \beta E_{d.c.}^2\right) \qquad \ldots(5.14)$$

where $\beta = \dfrac{\left(\bar{K}/2D\right)^2}{\left(2{\cdot}405/a\right)^2 + \left(\pi/L_0\right)^2} = \dfrac{N^2(3\lambda\rho)}{4E_0^2\left[\left(2{\cdot}405/a\right)^2 + \pi^2/\left(L - 2\bar{K}E_0/\omega\right)^2\right]} = \dfrac{N^2(3\lambda\rho)}{4E_0^2/\Lambda^2}$

by putting the values of $\bar{K}$ and D from Kihara's theory (1952).

From Kihara's theory (1952)

$$\nu_0/D_0 = \left(3.\sigma.N^2.\lambda/c_i\right) \exp\left\{-mc_i^2/2K(T_e)_0\right\} \qquad \ldots(5.15)$$

$$\nu_1/D_1 = \left(3.\sigma.N^2.\lambda/c_i\right) \exp\left\{-mc_i^2/2K(T_e)_1\right\} \quad \ldots (5.16)$$

Where σ, λ, β and c_i are molecular constants introduced by Kihara, N denotes the number of the molecules per unit volume and T_e is the electron temperature. Putting the values ν_0/D_0 and ν_1/D_1 in the equation (5.14) and remembering that

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

and $$mc_i^2.N.(3.\lambda.\beta)^{1/2}/2eE_1 = B_0P/E_1$$

where E =r.m.s. breakdown voltage = (peak r.f. voltage) / $2^{\frac{1}{2}}$ ...Kihara (1952) we get

$$-B_0P(E_0 - E_1)/E_0E_1 = \log\left(1 + \beta E_{d.c.}^2\right) \quad \ldots (5.17)$$

where E_1 is the breakdown voltage without taking into consideration of d.c. ionisation, and B_0 is the constant introduced by Townsend. The constant β can be calculated for different gases from the values of molecular constants given by Kihara; and as the value of E_0 is known that of E_1 can can be calculated for various values of $E_{d.c.}$

To take account of the effect of d.c. ionisation let us assume that if ν_2 is the ionisation coefficient for the radiofrequency field only and $\nu_{d.c.}$ is the d.c. ionisation coefficient,

$$\nu_1 = \nu_2 + \nu_{d.c.} \quad \ldots (5.18)$$

To calculate $\nu_{d.c.}$ both the primary and secondary ionisations have to be taken into consideration; when the primary ionisation is considered,

$$i = i_0 . \exp(\alpha_1 L) \qquad \ldots(5.19)$$

when both the primary and secondary effects are considered

$$i = i_0 . \exp\left[\frac{\alpha_2 L}{1 - \gamma . \exp(\alpha_2 L)}\right] \qquad \ldots(5.20)$$

where "α" and "γ" are Townsend's first and second ionisation coefficients respectively.

If α_1 has to account for both the α and γ effects then

$$\exp(\alpha_1 L) = \frac{\exp(\alpha_2 L)}{1 - \gamma \exp(\alpha_2 L)}$$

or

$$\alpha_1 = \alpha_2 - \frac{\log\left[1 - \gamma \exp(\alpha_2 L)\right]}{L} \qquad \ldots(5.21)$$

$$\therefore \nu_{d.c.} = \alpha \bar{K} E_{d.c.} - \frac{\bar{K} E_{d.c.} \log\left[1 - \gamma . \exp(\alpha L)\right]}{L} \qquad \ldots(5.22)$$

but since ν_1 and ν_2 correspond to breakdown for radiofrequency discharge

$$\nu_1 / D_1 = 1/\Lambda^2 \quad \text{and} \quad \nu_2 / D_2 = 1/\Lambda^2$$

and we get from equation (5.18)

$$D_1/\Lambda^2 = D_2/\Lambda^2 + \alpha \bar{K} E_{d.c.} - \frac{\left[\bar{K} E_{d.c.} \log\left\{1 - \gamma . \exp(\alpha L)\right\}\right]}{L}$$

Putting the values of D_1 and D_2 from Kihara's theory

$$\frac{E_1 \bar{K}}{N (3.\lambda.\rho)^{1/2}} = \frac{E_2 \bar{K}}{N.(3.\lambda.\rho)^{1/2}} + \alpha \bar{K} \Lambda^2 E_{d.c.} - \frac{\bar{K} E_{d.c.} \Lambda^2 \log\left\{1 - \gamma . \exp(\alpha L)\right\}}{L}$$

$$\therefore E_2 = E_1 - N (3.\lambda.\rho)^{1/2} . \Lambda^2 . \alpha . E_{d.c.} + \frac{N.(3.\lambda.\rho)^{1/2} \Lambda^2 E_{d.c.} \log\left\{1 - \gamma . \exp(\alpha L)\right\}}{L}$$

$$\ldots(5.23)$$

where E_2 is the radiofrequency breakdown voltage when both the radiofrequency and d.c. fields are present.

The numerical values of the third term have been calculated in case of air and H_2 though there is insufficient data for γ in the literature. However the values calculated are so small in comparison to first and second terms on the right hand side that its contribution can be neglected. Then

$$E_2 = E_1 - N . (3.\lambda.\rho)^{1/2} . \Lambda^2 . (\alpha/p) (E_{d.c.}/p) . p^2 \qquad \ldots(5.24)$$

Consequently equation (5.24) can be utilised for calculating E_2. To calculate E_1 the value of β has been obtained for each gas from the numerical constants introduced by Kihara.

TABLE - II.

Gas	Pressure m.m. Hg.	E_o Volts/cm.	$(\lambda p).10^{32}$	$1/\lambda^2$	β	B_o Volt per cm. mm Hg	$N.(3.\lambda.p)^{1/2}.\lambda^2$
Air	1.5	106.7	14.55	16.565	1.658×10^{-3}	365	2.121
Air	1.0	90.0	14.55	16.854	1.007×10^{-3}	365	1.414
Hydrogen	2.0	56.8	4.455	16.885	3.073×10^{-3}	130	1.538
Hydrogen	3.0	68.3	4.455	16.378	5.00×10^{-3}	130	2.379
Oxygen	2.0	86.6	8.189	159.5	2.564×10^{-4}	138	0.221
Carbondioxide	1.5	93.3	21.78	61.38	8.66×10^{-4}	250	0.6742

The values of E_1 can thus be calculated from equation (5.17) and this gradually increases with the increase of d.c. field. It is however to be noted that upto a value of ($E_{d.c.}/P$) of the order of 150 volts/cm. m.m. Hg. the rise of E_1 with $E_{d.c.}$ is almost linear but when $E_{d.c.}$ is increased still further, E_1 assumes extremely high values. This fact suggests that at high values of ($E_{d.c.}/P$) greater than 150 volt/cm. m.m. Hg. the drift velocity is no longer a linear function of E/P. After calculating the values of E_1 it is possible to calculate E_2 from the equation (5.24). The values of (α/P) for various values of E/P have been taken from the data given by Brown (1959) and the values of (E_2/E_o) have been plotted in the figs. 21, 22, 23, 24 (curves indicated by dotted lines). In case of air,

Carbondioxide and oxygen the equation has further been modified because attachment will influence the value of the breakdown voltage. The effect of attachment has been calculated in the same manner as has been done by Sen and Ghosh (1963) where it was shown that

$$E_2 = (E_2^A).b + L_o\,\omega(1-b)/\bar{K} \qquad \ldots(5.25)$$

where E_2 is the breakdown voltage calculated without considering attachment,

E_2^A = breakdown voltage when attachment is taken into consideration and

$$b = \left[\frac{\alpha/P - \eta/P}{\alpha/P}\right]^{1/2} \qquad \ldots(5.26)$$

where η/P is the attachment coefficient.

The values of η/P for air and oxygen for various ($E_{d.c.}/P$) values have also been taken from Brown (1959), due to lack of adequate data, the value could not be calculated inpase of carbondioxide. In the figs. 21 and 23 the ratio E_2^A/E_o have been plotted whereas in the figs. 22 and 24 the ratio E_2/E_o have been plotted.

By comparing theoretical and experimental data it is seen that there is quite good agreement in case of air both for pressure of 1.5 mm and 1 mm. The discrepancy observed may partly be ascribed to uncertainity in the values of the molecular constants. There is reasonable agreement in case of hydrogen for a pressure of 3 mm. However, for the pressure of 2 mm, though the agreement is good for lower pressure, wide divergence is noticed for $E_{d.c.} > 90$ volt/cm. In fact, the value of E_1 the breakdown voltage without considering d.c. ionisation becomes so large that wide divergence is noticed even if d.c. ionisation is considered. This fact suggests as has been mentioned (Sen and Bhattacharjee 1965) that perhaps the drift velocity does not remain a linear function of (E/P) and the loss of electron due to mobility is actually smaller than what is predicted by Warnerin and Brown's theory. In case of oxygen also

divergence becomes dominant at high d.c. fields even though attachment correction has been applied. Results would have improved slightly if attachment data were available in case of carbondioxide.

It can thus be concluded that for small d.c. voltage the theory proposed by Varnerin and Brown that loss of electrons increases due to mobility can explain the increase of breakdown voltage, but with the increase of d.c. voltage, ionisation due to d.c. field also has to be taken into consideration and this factor gradually increases with the applied d.c. field and becomes considerable at high d.c. voltage and thereby reduces the radiofrequency voltages necessary for breakdown. The observed discrepency can be ascribed partly to the uncertainity in the values of molecular constants introduced by Kihara in his theory of electrical discharge. In case of d.c. ionisation, the primary ionisation is much more predominant than the secondary effect which depends to a major extent upon the nature of the electrode and also upon the pressure of the gas in the discharge tube.

It should however be noted that the theory which has been advanced here is based upon the theory of electrical discharge by Kihara which assumes that electron velocity distribution function is Maxwellian. But in fact it actually does not hold good when radiofrequency voltage sufficient to cause breakdown is applied and departure from the Maxwellian distribution becomes more when d.c. ionisation effects which involve large transit of electrons are considered. Consequently the above theory suffers from the same limitations as are applicable to Kihara's theory. But it is noted that even with those limitations it can explain the experimental results at least upto a certain limit of d.c. voltage per cm.

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BREAKDOWN OF A RADIO-FREQUENCY DISCHARGE IN THE PRESENCE OF A SUPERIMPOSED d-c. FIELD

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ABSTRACT

Breakdown voltages have been determined in the case of some rare gases (He, Ne, A) and oxygen at a constant pressure (10 mm Hg) when excited simultaneously by a radio-frequency field (frequency 10 Mc/sec) and a variable d-c. field. It is found in all cases that the breakdown voltage is higher when both the fields are present than when the gases are excited by the radio-frequency field alone and the breakdown voltage gradually increases with the increase of the applied d-c. field. The variation of breakdown field with d-c. field is of the same nature in all of the gases studied. A theoretical expression for the breakdown voltage in the presence of both the r-f. and d-c. fields has been deduced from the theory of electrical discharge by Kihara (1952) together with the expression of equivalent length as deduced by Varnerin and Brown (1950). The theoretical expression cannot explain satisfactorily the experimental results, and the rate of rise of breakdown voltage in the d-c. field as obtained from theory is smaller than that obtained from experimental results. The discrepancy has been ascribed partly to the uncertainty in the values of the numerical constants introduced by Kihara and also to the increase of diffusion caused by the presence of positive ions—a factor which has not been taken into consideration in the present treatment.

INTRODUCTION

Varela (1947) observed that the breakdown potential in a discharge excited by a radio-frequency source increased when a d-c. potential less than the radio-frequency breakdown voltage was applied across the discharge tube. The discharge tube had aluminium electrodes in an atmosphere of 5 cm hydrogen and 20% argon. It was expected, however, that the presence of the d-c. field would hasten ionization with a given radio-frequency potential by virtue of higher peak electron velocities and that a residual potential following the discharge would hasten deionization; but the results were contrary to what was expected. Almost the same results were obtained earlier by Kirchner (1925, 1947) while he was studying the breakdown in gases by an r-f. field in the presence of a d-c. potential.

Varnerin and Brown (1950) calculated theoretically the distribution function of electrons in an ionized gas in the presence of both radio-frequency and d-c. fields. It is generally known that the gas in the cavity will break down when the losses of electrons to the walls of the cavity are replaced by ionization in the body of the gas. When an a-c. field is applied, electrons are lost by diffusion; when, in addition, a d-c. field is applied, electrons are lost both by diffusion and mobility. It has been shown by Varnerin and Brown that the new effective diffusion length L_{dc} of the vessel in the presence of the d-c. field is shorter than its undisturbed diffusion length L according to the equation

$$\frac{1}{L_{dc}^2} = \frac{1}{L^2} + \left\{\frac{\bar{K}E_{dc}}{2D}\right\}^2, \tag{1}$$

where $\bar{K}$ denotes the mobility of the electron and D the diffusion coefficient. They thus concluded that the only difference between the breakdown condition in the a-c.–d-c. case and the pure a-c. case is the substitution of a modified diffusion length L_{dc} for the characteristic diffusion length L.

That a greater breakdown field is necessary when the d-c. voltage is superimposed on the radio-frequency field was further shown by Brown (1956) in the case of air at 38 mm Hg, where a d-c. field of up to 200 volts/cm was applied.

No systematic study of the breakdown of gases under the simultaneous action of the a-c. and d-c. fields has so far been reported. It is expected that this study will throw more light on the mechanism of breakdown. The object of the present investigation is to determine the breakdown voltage in some rare gases (such as argon, neon, helium) and oxygen in a superimposed radio-frequency and d-c. field and to present a theory capable of explaining the observed results.

EXPERIMENTAL SETUP

Discharge tubes (Geissler tubes) filled with different gases, such as argon, helium, neon, and oxygen, as supplied by the manufacturers were used. Each of the discharge tubes is fitted with two aluminium electrodes. The method of determining the breakdown voltage under radio-frequency excitation has been described in an earlier paper by Sen and Ghosh (1963). The frequency of the exciting radio-frequency field is 10 Mc/sec. The method of applying the d-c. field obtained from dry batteries is shown in Fig. 1. The pressure of the enclosed gas has been taken to be 10 mm Hg as given by the manufacturers. The method consists in measuring the breakdown potential in the presence of the radio-frequency field only and then in repeating the measurement with the application of the d-c. field superimposed upon the radio-frequency field. The d-c. field is varied from 5 volts/cm to 70 volts/cm. The gases investigated are argon, helium, neon, and oxygen. Hydrogen could not be excited with the applied radio-frequency voltage. The lengths of the discharge tubes are as follows: helium—13.0 cm, neon—15 cm, argon—13.2 cm, oxygen—13 cm.

RESULTS AND DISCUSSION

The variation of the ratio E/E_0 (where E is the breakdown voltage per cm in the presence of both the radio-frequency and d-c. fields and E_0 is the breakdown voltage per cm in the presence of the radio-frequency field only) against E_{dc}, the applied d-c. voltage per cm, is shown in Figs. 2, 3, 4, 5. There is no detectable change in breakdown voltage other than that in the radio-frequency case for small d-c. voltages, which was less than 5 V/cm for all the gases studied; it is clear that with the application of the d-c. field, the radio-frequency breakdown voltage increases and the nature of the variation of E/E_0 with E_{dc} is practically the same for all the gases studied. The nature of the variation is the same as that observed by previous workers.

The physical significance of these results is at once apparent. In a radio-frequency field, breakdown occurs when the loss of electrons by diffusion and mobility is compensated by the generation of electrons by ionization. The application of the d-c. field further increases the loss due to diffusion and mobility

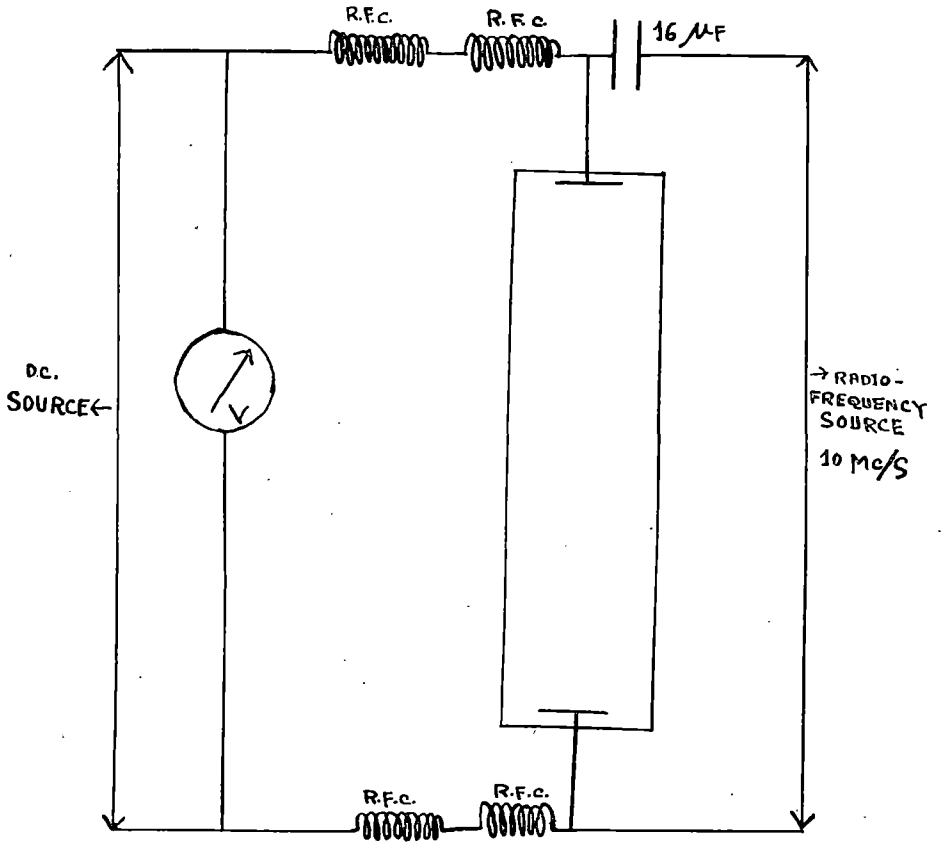

FIG. 1. Arrangement for applying d-c. voltage to the discharge tube.

and hence a larger electric field must be applied to produce more ionization to compensate for this increased loss. In the analysis which follows, we have employed the equations deduced by Kihara (1952) with the new diffusion length L_{dc} introduced by Varnerin and Brown (1950).

If L_0 denotes the equivalent length with the radio-frequency field alone, then according to Kihara (1952).

$$\frac{1}{L_0^2} = \frac{1}{\pi^2}\cdot\frac{\nu_0}{D_0}, \tag{2}$$

where ν_0 is the ionization coefficient and D_0 is the diffusion coefficient. When both the r-f. and d-c. fields are present, the breakdown condition is given by

$$\frac{1}{L_{dc}^2} = \frac{1}{\pi^2}\cdot\frac{\nu}{D}, \tag{3}$$

where

$$\frac{1}{L_{dc}^2} = \frac{1}{L_0^2} + \left\{\frac{\bar{K}E_{dc}}{2D}\right\}^2;$$

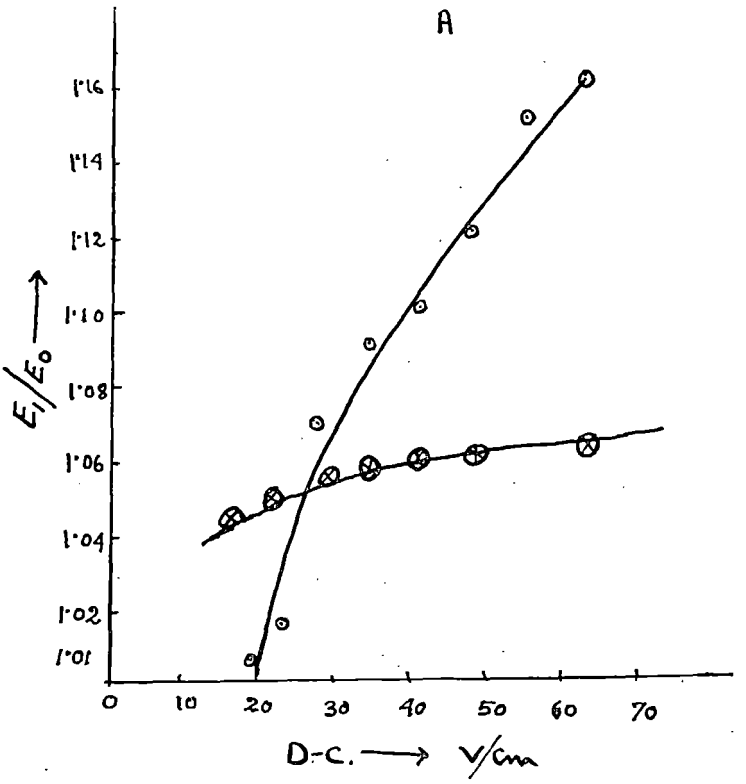

FIG. 2. Variation of E/E_0 with E_{dc} in argon (theoretical and experimental). ⊙—experimental, ⊗—from equation (6).

then

$$\frac{1}{L_0^2} + \left\{\frac{\bar{K}E_{dc}}{2D}\right\}^2 = \frac{1}{\pi^2}\cdot\frac{\nu}{D},$$

where ν and D represent the quantities for the new breakdown field. According to Kihara (1952),

$$\frac{\nu_0}{D_0} = \frac{3\sigma N^2\lambda}{C_1}\exp\left[-\frac{mC_1^2}{2K(T_e)_0}\right],$$

$$\frac{\nu}{D} = \frac{3\sigma N^2\lambda}{C_1}\exp\left[-\frac{mC_1^2}{2K(T_e)}\right],$$

where λ, σ, and C_1 are the molecular constants introduced by Kihara and N is the number of molecules per cc at the pressure of the gas, K is the Boltzmann constant, m the mass of the electron, and (T_e) is the electron temperature, which will be different for the two breakdown voltages. Consequently, from equations (2) and (3) we get

$$\frac{1/L_0^2}{1/L_0^2 + (\bar{K}E_{dc}/2D)^2} = \exp\frac{mC_1^2}{2K}\left[\frac{1}{T_e} - \frac{1}{(T_e)_0}\right]. \tag{4}$$

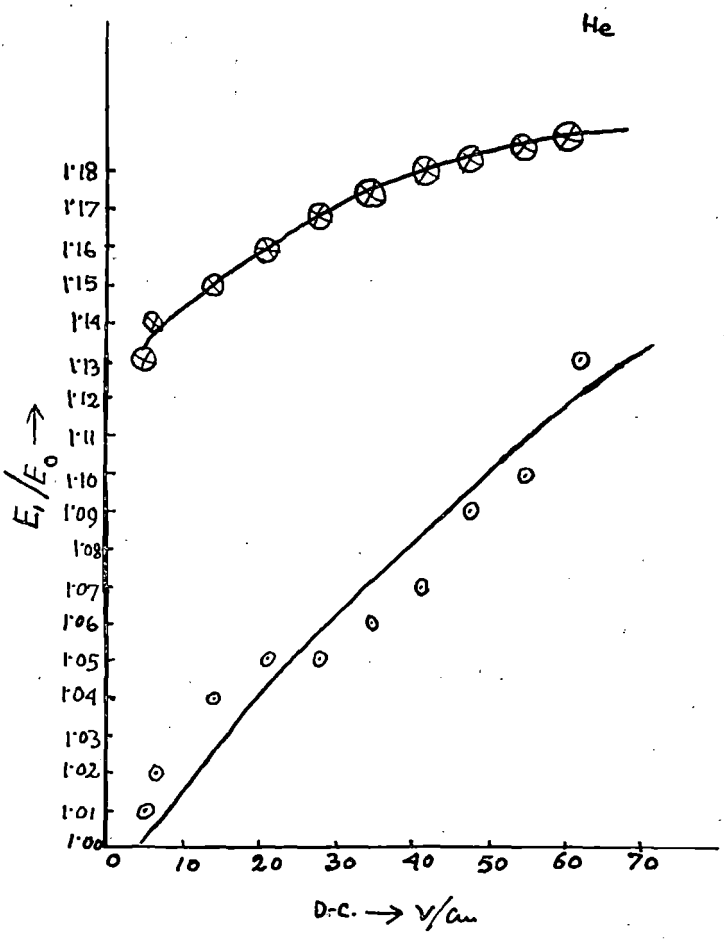

FIG. 3. Variation of E/E_0 with E_{dc} in helium (theoretical and experimental). ⊙—experimental, ⊗—from equation (6).

Assuming that $T_e = (T_e)_0$, we get

$$\log\left[1+\left(\frac{\bar{K}E_{dc}L_0}{2D}\right)^2\right] = -\frac{mC_1^2}{2K}\frac{(T_e)_0-(T_e)}{(T_e)_0^2}.$$

But according to Kihara (1952),

$$\frac{\bar{K}}{2D} = \frac{e}{K(T_e)_0}$$

and

$$K(T_e)_0 = \frac{eE_0}{N(6\lambda\rho)^{\frac{1}{2}}}$$

and similarly

$$KT_e = \frac{eE_1}{N(6\lambda\rho)^{\frac{1}{2}}}.$$

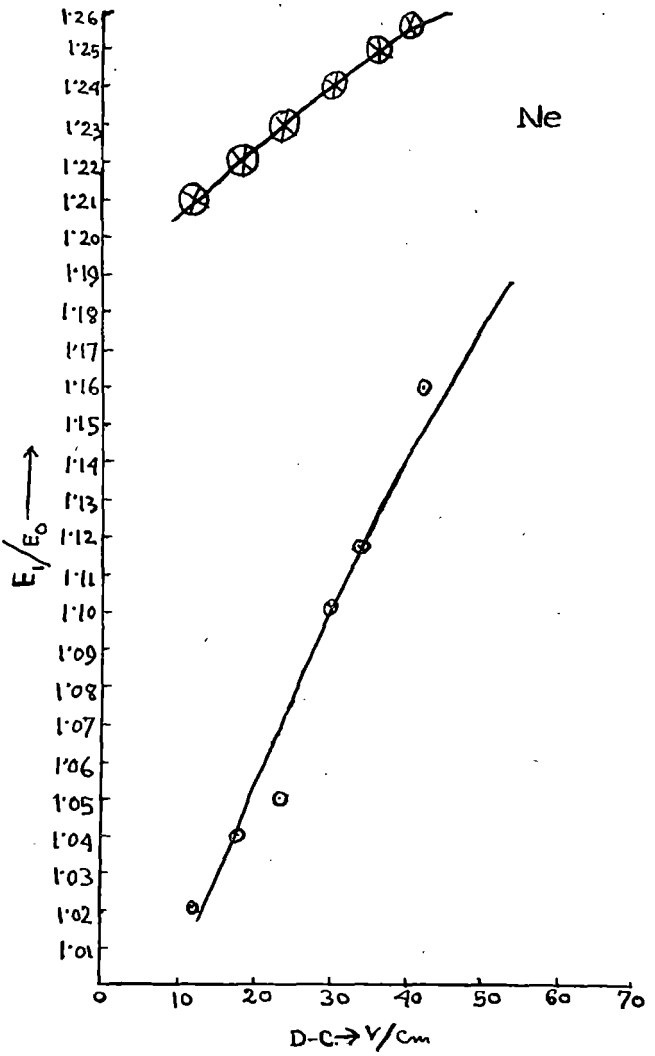

FIG. 4. Variation of E/E_0 with E_{dc} in neon (theoretical and experimental). ⊙—experimental, ⊗—from equation (6).

Putting these values into equation (5), we get

$$\log\left\{1+\left[\frac{eL_0E_{dc}}{2K(T_e)_0}\right]^2\right\}=N(6\lambda\rho)^{\frac{1}{2}}\left[\frac{E_t}{E_0}-1\right]. \tag{5}$$

According to Kihara, $L_0 = L' - (2\bar{K}/\omega)E_0$, where L' is the length of the discharge tube and ω is the angular frequency of the applied radio-frequency field. Hence

$$\log\left\{1+\left[\frac{e[L'-(2\bar{K}/\omega)E_0]E_{dc}}{2K(T_e)_0}\right]^2\right\}=N(6\lambda\rho)^{\frac{1}{2}}\left[\frac{E_t}{E_0}-1\right] \tag{6}$$

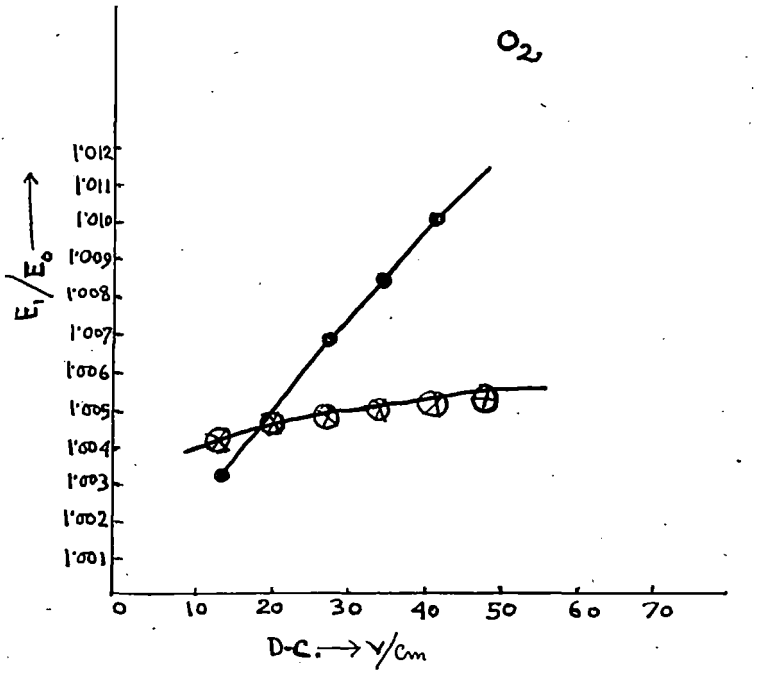

FIG. 5. Variation of E/E_0 with E_{dc} in oxygen (theoretical and experimental). ●—experimental, ⊗—from equation (6).

or
$$\frac{E_1}{E_0} = 1 + \frac{\log\{1 + [e(L' - (2\bar{K}/\omega)E_0)E_{dc}/2K(T_e)_0\}^2}{N(6\lambda\rho)^{\frac{1}{2}}}.$$

Since the radio-frequency breakdown voltage is known from experimental results, $(T_e)_0$ can be calculated from the relation (Kihara 1952)

$$K(T_e)_0 = \frac{eE_0}{N(6\lambda\rho)^{\frac{1}{2}}}.$$

The values of the mobility coefficient $\bar{K}$ for the value E_0/P have been obtained from the results reported by Brown (1959). The right-hand side of equation (6) has been calculated in this way, and the results are plotted side by side with the experimental values. In order to calculate the right-hand side of equation (6), the following values have been calculated from the data of molecular constants given by Kihara (1952).

The right-hand side of equation (6) can thus be calculated for different values of E_{dc}. The results are plotted side by side with the experimental curves. The quantitative agreement is not satisfactory except for argon and oxygen and also for values of E_{dc} near about 20 volts/cm. There is no agreement at all for helium and neon. The quantitative disagreement can be attributed partly to constants introduced by Kihara. The nature of the theoretical curve resembles the experimental curve to a certain extent, but the rate of rise as predicted from theoretical deduction is smaller than that obtained experimentally. It should be noted,

TABLE I

Gas	$\lambda \times 10^8$, cm³/sec	$\rho \times 10^{24}$, cm sec	$N(6\lambda\rho)^{\frac{1}{2}}$	E_0, volts/cm	$K(T_e)_0 \times 10^{12}$	L'_β, cm	$\bar{K} \times 10^{-6}$	$\frac{e[L-(2\bar{K}/\omega)E_0]}{2K(T_e)_0}$
Argon	7.8	1.35	282.1	16.28	0.0953	13.2	0.0368	114.1
Helium	4.4	0.20	81.58	14.61	0.2902	13.0	0.0821	36.17
Neon	$(\lambda\rho) \times 10^{32}$ 0.3710		52.96	17.3	0.517	15.0	0.1329	22.86
Oxygen	$(\lambda\rho) \times 10^{32}$ 8.356		726.6	23.0	0.0512	13.0	0.1304	203.8

$N = 3.55 \times 10^{17}$, $P = 10$ mm Hg, $f = 10$ Mc/sec, $\omega = 6.28 \times 10^7$ radians.

however, that in the above deduction we have not considered two effects: (*a*) increased loss due to diffusion because of the presence of positive ions and (*b*) the possible ionization contributed by the d-c. field itself. The contribution by the second factor to the theoretical computation of breakdown voltage would, however, decrease the actual value, because if there is any ionization caused by the d-c. field, it would tend to lower the value expected. Whereas this factor may lower the values of (E_1/E_0) somewhat in the case of helium and neon, it will reduce still further the values of (E_1/E_0) in the case of argon and oxygen, where the theoretical values are actually lower than the experimental values. Furthermore, in the case of oxygen the contribution due to the attachment of electrons has not been taken into consideration, and this actually modifies the expression for breakdown voltage. The increased loss due to diffusion in the presence of positive ions may be responsible for the higher values obtained experimentally, and in this calculation we have not taken this effect into consideration.

The theoretical and experimental results point, however, to the fact that in a discharge excited by the simultaneous action of radio-frequency and d-c. voltage, the loss of electrons is due both to diffusion and to mobility, and by employing the deductions of Kihara with the expression for the equivalent length as deduced by Varnerin and Brown, it has been possible to deduce results which can be compared with the experimentally observed values. The discrepancy can be ascribed to the uncertainty in the values of the numerical constants introduced by Kihara and to the fact that the presence of positive ions increases the diffusion—a factor which has not been taken into consideration here.

ACKNOWLEDGMENTS

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RADIO-FREQUENCY BREAKDOWN IN A SUPERIMPOSED D-C. FIELD

S. N. Sen and B. Bhattacharjee

RADIO-FREQUENCY BREAKDOWN IN A SUPERIMPOSED D-C. FIELD

S. N. SEN AND B. BHATTACHARJEE

Following the work done by the authors (Sen and Bhattacharjee 1965), the breakdown potentials of air, hydrogen, and oxygen excited by a radio-frequency field of frequency 10.3 Mc/sec in the presence of a superimposed d-c. field varying from 0 to 240 V/cm have been determined for various values of the d-c. field. The object of undertaking this work is to see how the radio-frequency breakdown voltage changes when the applied d-c. field is large in contrast to the small d-c. fields used in the previous investigations. The discharge tube is a cylindrical glass tube fitted with two electrodes, and the distance between the two electrodes is 3 cm and the diameter 1.25 cm. The method is the same

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as adopted in the previous paper. The variation of E_1/E_0, where E_1 is the radio-frequency breakdown voltage in the presence of a d-c. field and E_0 is the radio-frequency breakdown voltage in the absence of a d-c. field, has been plotted against d-c. voltage per cm. Measurements were taken for various values of pressure for the three gases but only three representative curves for the three gases have been plotted, each for a pressure of 2 mm Hg, in Fig. 1. The results show that the breakdown voltage in the presence of a d-c. field increases for small values of d-c. field, attains a maximum at a certain value

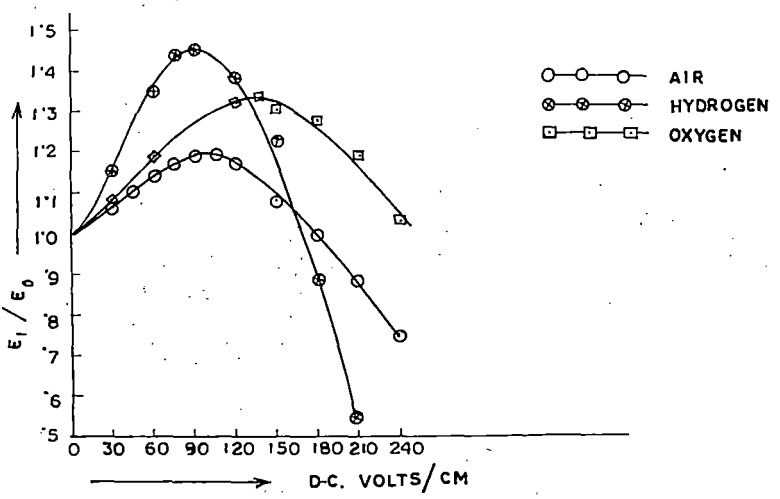

FIG. 1. Variation of radio-frequency voltage with superimposed d-c. field.

of d-c. field which is different for different gases, and then falls as the d-c. field is further increased. The variation is quite general, as has been observed in other gases also.

It is quite clear that whereas the increase of radio-frequency breakdown voltage can be explained by the theory put forward by Varnerin and Brown (1950) as due to increased loss due to mobility in the presence of a d-c. field, the occurrence of maxima and the consequent fall in the breakdown voltage show that other mechanisms are also operating. For small d-c. fields, the incorporation of Varnanin and Brown's increased diffusion length into Kihara's theory could at least give qualitative agreement with experimental results, as has been shown for rare gases by the present authors (Sen and Bhattacharjee 1965).

To explain the present results therefore the following mechanism is suggested. (*a*) For small values of d-c. field the contribution due to d-c. ionization has been neglected but when the d-c. field becomes of the order of that employed in the present investigation, there is a definite contribution to ionization due to the d-c. field in addition to ionization produced by the radio-frequency field, and this factor increases as the magnitude of the field increases. (*b*) Provided that the loss mechanism due to diffusion and mobility remains

unchanged, it is obvious that breakdown will take place when the combined loss due to diffusion and mobility is compensated by the combined ionization due to radio-frequency and d-c. field. Smaller values of the radio-frequency field will be necessary to cause breakdown because the d-c. field is also contributing to ionization. This can explain the fall in the radio-frequency breakdown voltage when the d-c. field is increased. With the increase of the d-c. field, the radio-frequency voltage necessary to cause breakdown will decrease gradually because d-c. ionization will be more dominant. (*c*) For breakdown at any d-c. voltage the rate of ionization due to the r-f. field plus the rate of ionization due to the d-c. field must equal the rate of loss due to mobility for the d-c. field plus the rate of loss due to diffusion. And the maximum in the curve will occur when the total rate of loss due to diffusion and mobility minus the rate of ionization due to the d-c. field becomes a maximum.

A generalized quantitative theory regarding the breakdown voltage in the presence of a superimposed d-c. field is being worked out, and a paper describing the results will be sent for publication soon.

In conclusion, it may be noted that data are available in the existing literature for the drift velocity of electrons for small E/P values where it is shown that for most of the gases, the drift velocity is linearly proportional to E/P, but it is doubtful whether the drift velocity is a simple linear function of E/P when E/P is of the order used in the present experiment. Consequently experiments are in progress in this laboratory for the measurement of the drift velocity of electrons when E/P varies from 15 to 200 V/cm mm of Hg. and the results obtained will be utilized in deducing the theory of r-f. breakdown in the presence of a d-c. field.

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Breakdown of a Radiofrequency Discharge in a Superimposed D.C. Field

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Breakdown voltages have been measured in case of air, hydrogen, oxygen and carbon dioxide at a pressure of a few millimeters of mercury when excited simultaneously by a radiofrequency field (frequency 10.3 Mc/sec) and a variable d.c. field which varies from 0 to 240 volt/cm. It is found that the breakown voltage increases when the d.c. field is small, and when the field is further increased it shows a maximum and then gradually falls for all the gases studied, the maximum occuring at a d.c. voltage which is different for different gases. It has been shown that, when the d.c. field is small, the dominant factor is the loss of electrons by diffusion as well as by mobility which causes the breakdown voltage to increase, but when the d.c. field is increased, contribution due to d.c. ionization has also to be taken into consideration. This d.c. ionization causes a decrease in the radiofrequency voltage necessary for breakdown. A mathematical expression has been deduced which explains satisfactorily the observed experimental results. In the expression deduced the effect of secondary ionization as well as that of electron attachment have been taken into consideration.

§ 1. Introduction.

In a previous paper (Sen and Bhattacharjee[1]) the breakdown voltages for some rare gases (He, Ne, A) and oxygen at a constant pressure (10mm Hg) were determined when excited simultaneously by a radiofrequency field (frequency 10 Mc/sec) and a variable d.c. field. It was found that the breakdown voltage is higher when both the fields are present than when the gas is excited by a radiofrequency field alone and the breakdown voltage gradually increases with the increase of d.c. field. A theoretical expression for the breakdown voltage in the presence of d.c. and radiofrequency field was deduced from the theory of electrical discharge by Kihara[2] utilizing the expression for equivalent length deduced by Varnerin and Brown.[3] In the expression thus deduced the contribution to ionization made by the d.c. field was not taken into consideration because the field applied was small compared to the breakdown radiofrequency field. It was evident however from the experimental results obtained in the previous paper that the rate of rise of breakdown field with the applied d.c. field gradually becomes smaller as the value of the d.c. field is increased. From this it was evident that the contribution to ionization by the d.c. field was gradually becoming dominant with higher d.c. fields and naturally if the d.c. field be sufficiently increased then the contribution to ionization by the d.c. field will be considerable and the radiofrequency voltage to cause breakdown will gradually decrease. The theoretical expression deduced in the previous paper could not explain satisfactorily the experimental results, it was pointed out that the discrepancy might be due (a) to uncertainty in the values of the molecular constants introduced by Kihara and (b) the effect of d.c. ionization was not taken into consideration. Vernerin and Brown[3] in finding the effect of d.c. field only considered the effects of increased diffusion and mobility but at high values of d.c. field the contribution due to ionization should also be taken into consideration. To find the effect of d.c. ionization, d.c. fields higher than those used in the previous investigation have to be applied. The purpose of the present investigation is to determine experimentally the values of breakdown voltage in the simultaneous presence of radiofrequency voltage and a d.c. voltage where the values of d. c. voltages are much greater than the radiofrequency voltages applied, and to present a consistent theory capable of explaining the experimental results. A research note covering the preliminary investigation has been published. (Sen and Bhattacharjee.[4])

§ 2. Experimental Arrangement

The method of measuring the breakdown voltage in the presence of radiofrequency and d.c. field is the same as in the previous paper (Sen and Bhattacharjee.[1]) The discharge tubes are of length 3 cm and diameter 1.25 cm and fitted with two platinum electrodes. The gases studied in the investigation are air, hydrogen, oxygen and carbon dioxide. Air, oxygen and carbon dioxide have been chosen in order to study the effect of electron attachment and the pressure is of the order of a few millimeters which has been measured with the help of a mercury manometer. The frequency of the radiofrequency voltage is 10.3 Mc/sec which has been accurately measured with a communication receiver; and the applied d.c. voltage, which has been provided with a series of dry batteries, has been varied from a few volts per cm to 240 volts per cm. Hydrogen and oxygen have been prepard by the electrolysis of a very dilute solution of barium Hydroxide in water and then allowing the gas to pass through traps of phosphorus pentoxide; Carbon dioxide has been prepared by the action of dilute sulphuric acid on a pure sample of sodium carbonate. The gas has been passed through a trap of distilled water to absorb traces of acid and finally dried by phosphorus pentoxide and collected in an evacuated chamber.

§ 3. Results and Discussion

The variation of radiofrequency breakdown voltage with the applied d. c. field has been plotted in Figs. 1,2,3 and 4 in case of air, hydrogen, oxygen and carbon dioxide respectively. The ordinate represents the ratio E_2/E_0 where E_2 is the radiofrequency breakdown voltage when both the radiofrequency and d.c. fields are present and E_0 is the breakdown voltage when only the radiofrequency voltage is present. It is seen from the nature of the curves that the breakdown voltage gradually increases with the increase of the d.c. field, then attains a maximum at a certain d.c. field which is different for different gases, and then falls as the d.c. field is further increased. A well defined maximum is obtained in each case and the variation of breakdown voltage with the d.c. field is quite general as it has been observed for all the four gases studied. It is thus quite apparent that whereas the theory of Varnerin and Brown[3] can explain the increase of breakdown voltage when the d. c. field is small as due to increased loss due to mobility in the presence of d.c. field, the occurance of maxima and the consequent fall in voltage shows that other mechanisms are also operating.

To explain the observed results it is therefore suggested that, whereas for small d.c. fields d.c. ionization can be neglected, the effect of d.c. ionization has to be taken into consideration when the d.c. voltage is of the order employed in the present investigation. The effect of d.c. voltage is also to increase the mobility and thereby cause an increased loss of electrons. In the calculation which follows we shall first consider the ionization due to d.c. field to be absent and only the loss due to mobility to be effective. We shall then find out how this breakdown field changes when the d.c. ionization is taken into consideration. In the presence of rediofrequency field the breakdown condition is given by,

$$\frac{\nu_0}{D_0}=\left(\frac{2{\cdot}405}{a}\right)^2+\frac{\pi^2}{L_0^2}=\frac{1}{\Lambda^2}$$

where $$L_0=\left(L-\frac{2\bar{K}E_0}{\omega}\right) \qquad (1)$$

Here ν_0 is the ionization coefficient and D_0 is the diffusion coefficient. E_0 the breakdown field in absence of d.c. field, L the length of the discharge tube, a is the radius of the tube, and $\bar{K}$ the mobility and ω the angular frequency of the applied field. When the d.c. field is also present, it has been shown by Varnerin and Brown[3] that the breakdown condition is given by

$$\frac{\nu_1}{D_1}=\left(\frac{2{\cdot}405}{a}\right)^2+\frac{\pi^2}{L_0^2}+\left(\frac{\bar{K}E_{DC}}{2D}\right)^2 \qquad (2)$$

From eqs. (1) and (2)

$$\frac{\frac{\nu_0}{D_0}}{\frac{\nu_1}{D_1}}=\frac{1}{1+\beta E_{DC}^2} \qquad (3)$$

where $$\beta=\frac{(\bar{K}/2D)^2}{\left(\frac{2{\cdot}405}{a}\right)^2+\frac{\pi^2}{L_0^2}}=\frac{N^2(3\lambda\rho)}{4E_0^2\left[\left(\frac{2{\cdot}405}{a}\right)^2+\frac{\pi^2}{\left(L-\frac{2\bar{K}E_0}{\omega}\right)^2}\right]}=\frac{N^2(3\lambda\rho)}{4E_0^2\frac{1}{\Lambda^2}}$$

From Kihara's paper[2]

$$\frac{\nu_0}{D_0}=\frac{3\sigma N^2\lambda}{c_i}\exp\left\{\frac{-mc_i^2}{2k(T_e)_0}\right\}$$

$$\frac{\nu_1}{D_1}=\frac{3\sigma N^2\lambda}{c_i}\exp\left\{\frac{-mc_i^2}{2k(T_e)_1}\right\}$$

where σ, λ, ρ and C_i are molecular constants introduced by Kihara, N denotes the number of molecules per unit volume and T_e is the electron temperature. Putting the values of ν_0/D_0 and ν_1/D_1 in the equation (3) and remembering (Kihara[2])

$$KT_e=\frac{eE}{N(3\lambda\rho)^{1/2}} \text{ and } \frac{mc_i^2N(3\lambda\rho)^{1/2}}{2eE_1}=\frac{B_0P}{E_1}$$

we get,

$$\frac{-B_0P(E_0-E_1)}{E_0E_1}=\log[1+\beta E_{DC}^2]\,, \tag{4}$$

where E_1 is the breakdown voltage without d.c. ionization, and B_0 is the constant introduced by Townsend. The constant β can be calculated for different gases from the values of molecular constants given by Kihara; and as the value of E_0 is known that of E_1 can be calculated for various values of E_{DC}.

To take account of the effect of d.c. ionization let us assume that, if ν_2 is the ionization coefficient for the radiofrequency field only and ν_{DC} is the d.c. ionization coefficient,

$$\nu_1=\nu_2+\nu_{DC} \tag{5}$$

To calculate ν_{DC} both the primary and secondary ionization have to be taken into consideration; when the primary ionization is considered,

$$i=i_0\exp\alpha_1L$$

when both the primary and secondary effects are considered,

$$i=i_0\exp\alpha_2L/1-\gamma\exp\alpha_2L\,.$$

If α_1 has to account for both the α and γ effects

then
$$\exp\alpha_1L=\frac{\exp\alpha_2L}{1-\gamma\exp\alpha_2L}\,.$$

$$\text{or } \alpha_1=\alpha_2-\frac{\log(1-\gamma\exp\alpha_2L)}{L}\,.$$

$$\therefore\quad \nu_{DC}=\alpha\bar{K}E_{DC}-\frac{\bar{K}E_{DC}\log(1-\gamma\exp\alpha L)\,.}{L}$$

but since ν_1 and ν_2 correspond to breakdown for radiofrequency discharge

$$\frac{\nu_1}{D_1}=\frac{1}{A^2} \text{ and } \frac{\nu_2}{D_2}=\frac{1}{A^2}$$

and we get from equation (5)

$$\frac{D_1}{A^2}=\frac{D_2}{A^2}+\alpha\bar{K}E_{DC}-\frac{\bar{K}E_{DC}\log(1-\gamma\exp\alpha L)\,.}{L}$$

Putting the values of D_1 and D_2 from Kihara's theory

$$\frac{E_1\bar{K}}{N(3\lambda\rho)^{1/2}}=\frac{E_2\bar{K}}{N(3\lambda\rho)^{1/2}}+\alpha\bar{K}A^2E_{DC}-\frac{\bar{K}E_{DC}A^2\log(1-\gamma\exp\alpha L)\,.}{L}$$

$$\text{or } E_2=E_1-N(3\lambda\rho)^{1/2}A^2\alpha E_{DC}+\frac{N(3\lambda\rho)^{1/2}A^2E_{DC}\log(1-\gamma\exp\alpha L)\,.}{L}$$

Table I.

Gas	Pressure mmHg	E_0 volt/cm	$(\lambda\rho)\times10^{32}$	$1/A^2$	β	B_0 volt/cm mmHg	$N(3\lambda\rho)^{1/2}A^2$.
Air	1.5	106.7	14.55	16.565	1.658×10^{-3}	365	2.121
〃	1.0	90.0	〃	16.854	1.007×10^{-3}	〃	1.414
Hydrogen	2.0	56.8	4.455	16.885	3.073×10^{-3}	130	1.538
〃	3.0	68.3	〃	16.378	5.00×10^{-3}	〃	2.379
Oxygen	2.0	86.6	8.189	159.5	2.564×10^{-4}	138	.221
Carbon dioxide.	1.5	93.3	21.78	61.38	8.66×10^{-4}	250	.6742

Where E_2 is the radiofrequency breakdown voltage when both the radiofrequency and d.c. fields are present.

The numerical values of the third term have been calculated in case of air and H_2 though there is insufficient data for γ in the literature. However the values calculated are so small in comparison to first and second terms on the right-hand side that its contribution can be neglected. Then

$$E_2=E_1-N(3\lambda\rho)^{1/2}A^2\left(\frac{\alpha}{P}\right)\left(\frac{E_{DC}}{P}\right)P^2 . \qquad (6)$$

Consequently equation (6) can be utilised for calculating E_2. To calculate E_1, the value of β has been obtained for each gas from the numerical constants introduced by Kihara.

The values of E_1 can thus be calculated from equation (4), and this gradually increases with the increase of d.c. field. It is however to be noted that up to a value of (E_{DC}/P) of the order of 150 volt/cm mmHg the rise of E_1 with E_{DC} is almost linear but when E_{DC} is increased still further, E_1 assumes extremely high values. This fact suggests that at high values of (E_{DC}/P) greater than 150 volt/cm mmHg the drift velocity is no longer a linear function of (E/P). There is no available experimental data in literature; hence experiments are in progress in this laboratory to measure mobility of electrons in various gases when (E/P) is of the same order of magnitude as has been used in this experiment. After calculating the values of E_1, it is possible to calculated E_2 from the equation (6). The values of (α/P) for various values of (E/P) have been taken from the data given by Brown[5] and the values of (E_2/E_0) have been plotted in the Figs. 1 to 4 (curves indicated by dotted lines). In case of air, carbon dioxide and oxygen the equation has further been modified because attachment will influence the value of the breakdown voltage. The effect of attachment has been calculated in the same manner as has been done by Sen and Ghosh,[6] where it was shown that

$$E_2=E_2{}^Ab+\frac{L_0\omega(1-b)}{\bar{K}}$$

where E_2 is the breakdown voltage calculated without considering attachment

$E_2{}^A$=breakdown voltage when attachment is taken into consideration

and $b=\left[\dfrac{\alpha/P-h/P}{\alpha/P}\right]^{1/2}$

where h/P is the attachment coefficient.

The values of h/P for air and oxygen for various (E_{DC}/P) values have also been taken from Brown[5]; due to lack of adequate data, the value could not be calculated in case of carbon dioxide. In the Figs. 1 and 3, the ratio $E_2{}^A/E_0$ have been plotted whereas in the Figs. 2 and 4, the ratio E_2/E_0 have been plotted.

By comparing theoretical and experimental data it is seen that there is quite good agreement in case of air both for pressure of 1.5mm and 1 mm. The discripency observed may partly be ascribed to uncertainty in the values of the molecular cohstants. There is reasonable agreement in case of hydrogen for a pressure of 3mm However, for the pressure of 2mm, though the agreement is good for lower pressure, wide divergence is noticed for $E_{DC}>90$ volt/cm. In fact,

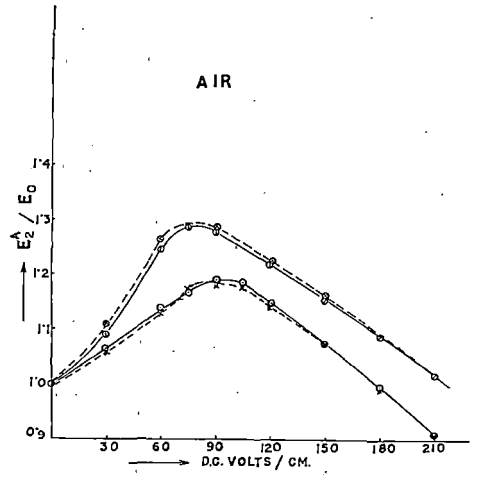

Fig. 1. Variation of E_2^A/E_0 with E_{DC} in air (theoretical and experimental)

○—○—○ Experimental
×—×—× Theoretical — P=1.5 mmHg
①—①—① Experimental
⊗—⊗—⊗ Theoretical — P=1.0 m.m.

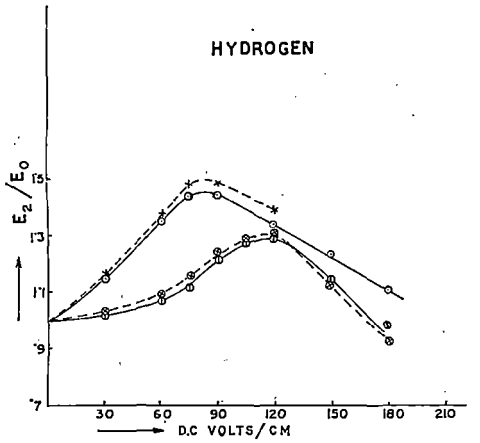

Fig. 2. Variation of E_2/E_0 with E_{DC} in hydrogen (theoretical and experimental)

○—○—○ Experimental
×—×—× Theoretical — P=2 mmHg
①—①—① Experimental
⊗—⊗—⊗ Theoretical — P=3 m.m.

the value of E_1 the breakdown voltage without considering d.c. ionization becomes so large that wide divergence is noticed even if d.c. ionization is considered. This fact suggests as has been mentioned before that perhaps the drift velocity does not remain a linear funear function of (E/P) and the loss of electrons due to mobility is actually smaller than what is predicted by Varnerin and Brown's theory. In case of oxygen also divergence becomes dominant at high d.c. fields even though attachment correction has been

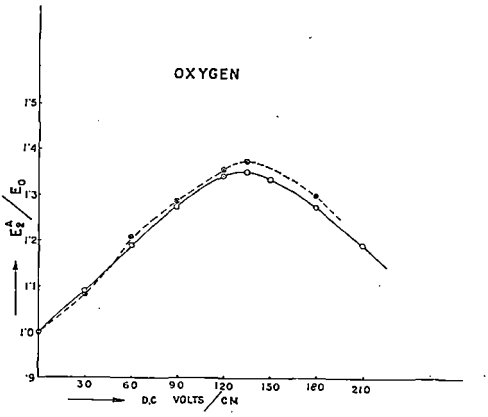

Fig. 3. Variation of E_2^A/E_0 with E_{DC} in oxygen (theoretical and experimental)

○—○—○ Experimental
⊗—⊗—⊗ Theoretical — P=2 mmHg

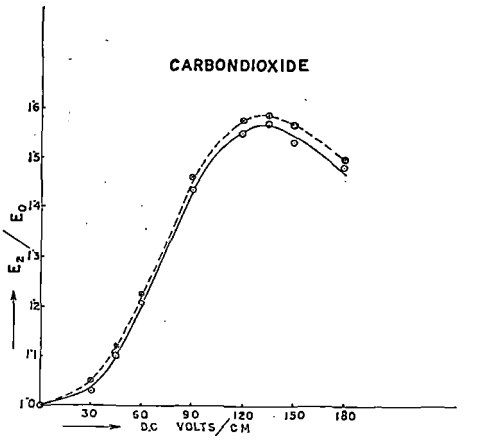

Fig. 4. Variation of E_2/E_0 with E_{DC} in CO_2 (theoretical and experimental)

○—○—○ Experimental
⊗—⊗—⊗ Theoretical — P=1.5 mmHg

applied. Results would have improved slightly if attachment data were available in case of carbon dioxide.

It can thus be concluded that for small d.c. voltage the theory proposed by Varnerin and Brown that loss of electrons increases due to mobility can explain the increase of breakdown voltage, but, with the increase of d.c. voltage, ionization due to d.c. field also has to be taken into consideration, and this factor gradually increases with the applied d.c. field and becomes considerable at high d.c. voltage and thereby reduces the radiofrequency voltages necessary for breakdown. The observed discripency can be ascribed partly to the uncertainty in the values of molecular constants introduced by

Kihara in his theory of electrical discharge. In case of d.c. ionization, the primary ionization is much more predominant than the secondary effect which depends to a major extent upon the nature of the electrode and also upon the pressure of the gas in the discharge tube.

It should however be noted that the theory which has been advanced here is based upon the theory of electrical discharge by Kihara which assumes that electron velocity distribution function is Maxwellian. But in fact it actually does not hold good when radiofrequency voltage sufficient to cause breakdown is applied and departure from the Maxwellian distribution becomes more when d.c. ionization effects which involve large transit of electrons are considered. Consequently the above theory suffers from the same limitations as are applicable to Kihara's theory.

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CHAPTER - VI.

LOW PRESSURE BREAKDOWN IN GASES IN A UNIFORM HIGH FREQUENCY ELECTRIC FIELD (a) WITHOUT MAGNETIC FIELD (b) WITH A STEADY TRANSVERSE MAGNETIC FIELD.

INTRODUCTION.

The mechanism of breakdown of a gas at pressures less than a few microns of mercury has been under investigation for some time to bring to light its salient features. For breakdown measurements some of the workers used the external electrodes and measured the peak starting potential and others used internal electrodes. Early investigations of breakdown field strengths in gases at low pressures and high frequency from 1 to 100 Mc/sec were carried out by Gutton and Gutton (1924, 1928), Gutton (1930) and Kirschner (1925, 1930). Their main observation was that the breakdown field strength decreases with decreasing frequency to values as low as 10 v/cm until a cutoff frequency is reached where breakdown becomes a matter of chance even at a very high electric field strength. A latter investigation by Backmark and Bengston (1941) led to a theoretical analysis of the mechanism by Danielsson (1943) where he proposed that the breakdown is caused by the increase of electrons by the resonance of secondary electrons with the electric field. A few electrons present initially by natural causes were accelerated to one end electrode where they produced secondary electrons by impact. These secondaries were emitted in a reverse electric field which carried them to the opposite electrode in approximately half a cycle to produce another group of secondaries. If secondary emission yield is greater than unity, electrons are multiplied to a very large quantity in a very short duration and this results in the breakdown of the gas. This mechanism is called breakdown by secondary electron resonance. Gill and Von Engel (1948) made observations in the frequency range of 12 to 75 Mc/sec and observed using external electrodes that the peak starting field strength for high frequency uniform electric field at a pressure of few microns for gases

like He, Hg, H_2 and air is independent of the nature of the gas and depends slightly on its pressure. They developed a theory postulated on the secondary electron resonance mechanism which was somewhat different in its mathematical formulation from that of Danielsson (1943), but it predicts a cutoff law relating cut-off frequency and electrode seperation. Hatch and Williams (1953, 1954) measured using internal electrodes the breakdown field strength in air and hydrogen at pressures of the order of 1 micron of Hg and exciting frequencies varying from 25 to 90 Mc/sec. By suddenly applying a high voltage and then lowering it slowly an upper breakdown curve has been observed which was then combined to the normal lower breakdown curve. Out-side this closed curve, no discharge could be started. They extended their work (1958) by developing a theory assuming higher order modes besides the conventional half cycle one. The phenomena has been explained assuming the process of bunching the electrons in the multipacting discharge otherwise known as secondary electron resonance discharge by Miller and Williams (1962), Paschke (1961) and Hatch (1961). Though a consistent theory of the phenomena of secondary electron resonance has been developed by Gill and Von Engel (1948) it is worth while to investigate some of the consequences of the theory with regard to variation of the starting voltage using external electrodes and the cut-off frequency with the length of the discharge tube.

The effect of superimposing an external field upon this type of discharge was investigated by Kossel and Krebs (1954) though no quantitative explanation of the observed results was provided. It has been found that superimposing a d.c. electric field parallel to high frequency electric field, starting can be made more difficult. A small static magnetic field perpendicular to the high frequency electric field causes a general increase of starting potential and a lowering of the cut-off frequency without changing the nature of $(E - \lambda)$ curve, where E is the starting potential and λ is the wavelength of the applied r.f. field. At large magnetic field, starting potential becomes

independent of frequency and for very low pressure (10^{-5}mm. Hg.) the discharge can be put out either by increasing the electric field or decreasing the magnetic field. Deb and Goswami (1964) made a theoretical approach to the phenomena when a steady magnetic field is placed perpendicular to high frequency electric field.

No systematic observation of the breakdown of gases controlled by secondary electron emission in a high frequency electric field in presence of an external d.c. magnetic field has so far been undertaken. The object of the present investigation is thus to study the effect of a transverse d.c. magnetic field on this type of breakdown with regard to starting field and the cut-off frequency. The theory of the previous workers has to be modified due to effects produced by the introduction of the magnetic field and it is presumed that these investigations may throw some light on the mechanism of such discharges.

E X P E R I M E N T A L A R R A N G E M E N T.

The breakdown potential of the gas has been determined in the same way as has been done by Gill and Von Engel (1948). The source of radiofrequency electric field is a tuned plate tuned grid oscillator covering the frequency range of 4 Mc/ sec. to 30 Mc/sec in three stages. The out put of the oscillator which can be varied from 0 to 500 volts has been measured by a vacuum tube voltmeter; measurements of the breakdown voltage at the highest frequency is limited by the radiofrequency voltage output of the oscillator. The cylindrical discharge tubes made of pyrex glass are properly cleaned and evacuated to 10^{-5} mm. of Hg. by an oil diffusion pump. The external electrodes which are perpendicular to the axis of the discharge tubes are connected to the radiofrequency source. Measurements have been taken in three discharge tubes of length 5 cm, 7cm and 15 cm (diameter of

each tube is 3.5 cm.) to study the effect of the length of the discharge tube on the value of breakdown potential as well as on the cut-off frequency. Besides pure and dry air, hydrogen prepared by the electrolysis of barium hydroxide solution and dried by phosphorouspentoxide have been used as the dielectric media. No special attempt for the purification of the gases has been made as traces of impurity and nature of the gas media have practically no effect upon this type of discharge. All the measurements have been made at a pressure of 1.5 micron of mercury which has been measured by an Edward penning pirani vacuum gauge. The steady magnetic field has been provided by an electromagnet having flat pole pieces of face area 7.5 cm x 4.5 cm placed at right angles to the length of the tube. The experiment with transverse steady magnetic field has been performed with the tube of 5 cm. length only so that the tube remains well inside the magnetic pole pieces to ensure uniform magnetic field which has been measured by a calibrated fluxmeter. Except the external electrodes and the discharge tube the system has been properly grounded. As the voltage is gradually increased a faint glow appears at the breakdown point and simultaneously there is slight drop in the output voltage at the vacuum tube voltmeter. This drop in voltage is less and less marked as the cut-off frequency is approached.

RESULTS AND DISCUSSION.

PART (a) LOW PRESSURE BREAKDOWN IN A UNIFORM HIGH FREQUENCY ELECTRIC FIELD.

To start with, starting potentials have been measured in air and hydrogen in a discharge tube of length 15 cm to verify the argument that secondary electron resonance is independent of the nature of the gas. The solid curve in fig.25 represents the results in case of air and the circles on it are the observations with hydrogen. The identical nature of the two breakdown curves

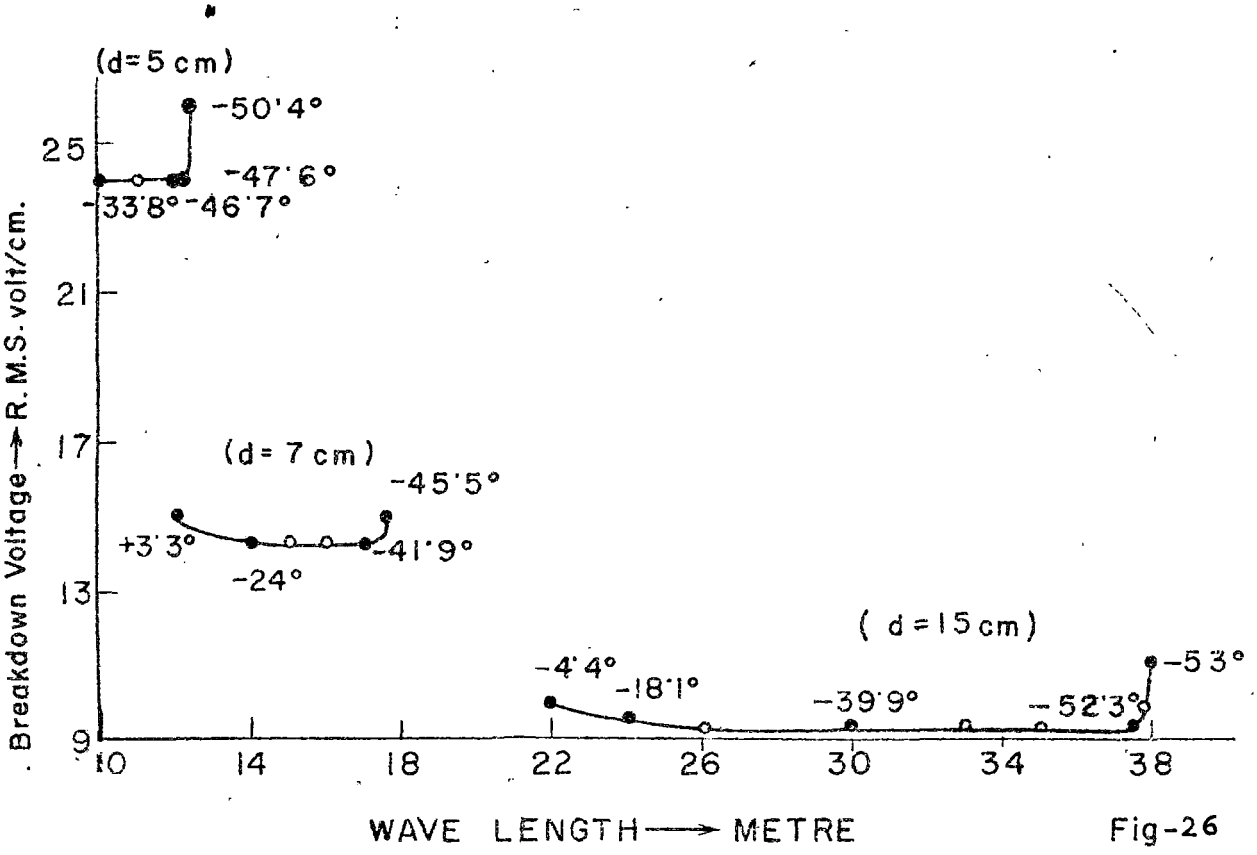
(d=5 cm)
-50·4°
-47·6°
-33·8°
-46·7°
(d=7 cm)
-45·5°
+3·3°
-41·9°
-24°
(d=15 cm)
-4·4°
-18·1°
-39·9°
-52·3°
-53°
Breakdown Voltage → R.M.S. volt/cm.
25
21
17
13
9
10
14
18
22
26
30
34
38
WAVE LENGTH → METRE

Fig-26

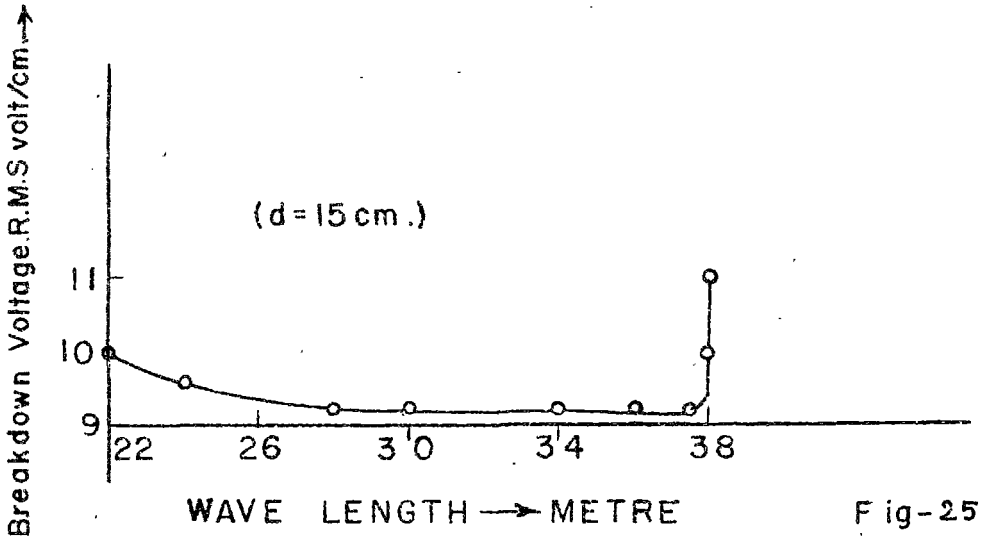
(d=15 cm.)
Breakdown Voltage R.M.S volt/cm →
11
10
9
22
26
3·0
3·4
38
WAVE LENGTH → METRE

Fig-25

indicates that the type of breakdown observed in the present experimental setup is independent of the nature of the gas and is controlled by secondary electron resonance. Starting potentials have been measured in three discharge tubes of length 5cm, 7 cm and 15 cm and the results have been plotted in fig.26. It is observed that the breakdown voltage is higher in tubes of shorter lengths and the cut-off wave length increases with the length of the discharge tube. Measurements towards the shorter wave length region could not be taken due to the limitation in the output power of the radiofrequency oscillator. It is evident that the curves are identical with those obtained by previous workers with the sharp cut-off towards the higher wavelength side.

The qualitative description of secondary electron resonance breakdown mechanism has been presented by Danielsson (1943), Gill and Von Engel (1948), Hatch and William (1953, 1954) and others almost in an identical way. At the start of a half cycle transit period, it is assumed that the electrons leave the emitting surface with energies of the order of 5 ev. At the end of the transit period most of these electrons arrive at the opposite end wall with energies of the order of 50 to 500 ev. The cyclic repetation of this process is referred to as resonance in this type of discharge. To proceed with a mathematical formulation of the process involved in the mechanism, some fundamental assumptions are necessary, though the extent to which many of these assumptions compensate in an undetermined manner the other processes occuring is not very clear. In order that this mechanism be operative it is necessary to assume that the electronic mean free path and wavelength of the applied high frequency field are both large compared to the electrode separation and both these assumptions are valid in the present experimental setup. For mathematical simplicity it is convenient to assume that all electrons have half cycle transit times, though according to Hatch and Williams (1954) this assumption is not an accurate representation of secondary emission

characteristics but is very useful in getting a simple formulation of the problem and leads to good correlation between theory and observation. Further the secondary electron emission velocities are normal to the end surfaces and the electric field between the electrodes is uniform in space. Space charge effects are negligible and it is assumed that the electron arrival energies exceed the ionisation potential of the gas, and that a few electrons are produced randomly between the electrodes by natural processes.

Based on these assumptions Gill and Von Engel (1948) deduced that the breakdown field E is given by

$$E = \frac{\omega^2 d - \pi v_0 \omega}{\frac{e}{m}\left[\pi \cos\phi + 2\sin\phi\right]} \qquad \ldots(6.1)$$

where ω is the angular frequency of the applied radiofrequency field and ϕ is the phase angle of the emitted secondary electron with respect to the electric field, d the length of the discharge tube and v_0 the initial velocity of the electron. The velocity of the electron when it strikes the opposite end is given by

$$v = v_0 + \frac{2eE}{m\omega}\cos\phi \qquad \ldots(6.2)$$

if it is assumed, as has been done by Gill and Von Engel (1948), that $\frac{v}{v_0} = K$, a constant then

$$v = \frac{K}{K-1} \cdot \frac{2eE\cos\phi}{m\omega} \qquad \ldots(6.3a)$$

$$d = \frac{eE}{m\omega^2}\left[\pi \cdot \frac{K+1}{K-1}\cdot\cos\phi + 2\sin\phi\right] \qquad \ldots(6.3b)$$

$$E = \frac{\omega^2 d}{(e/m)\,\Phi} \qquad \ldots(6.3c)$$

where $$\Phi = \frac{K+1}{K-1} \cdot \pi \cos\phi + 2\sin\phi \cdot \qquad \ldots(6.4)$$

Gill and Von Engel analysed their data using equations (6.3) and (6.4) and taking Φ as a parameter. Following Hatch and Williams (1954) the electron arrival energy can be expressed as

$$\mathcal{E} = \frac{1}{2} m v^2 \quad \text{where } \mathcal{E} \text{ is expressed in ev.}$$

combining this with equations (6.3a) and (6.3c) we get for the frequency

$$f = \frac{(K-1)\,\Phi}{K\pi d \cos\phi} \cdot \left(\mathcal{E}/8m\right)^{1/2} \qquad \ldots(6.5)$$

From equation (6.5) it can be seen that for fixed values of " ω " and " d ", E becomes minimum for the maximum value of Φ. Maximising Φ with respect to ϕ gives the condition

$$\phi = \tan^{-1}\left(\frac{K-1}{K+2} \cdot \frac{2}{\pi}\right) \qquad \ldots(6.6)$$

Using equation (6.3), (6.4), (6.5), (6.6) and taking the value of K = 3, Hatch and Williams fitted their observation and obtained the value of ϕ as $-56° \leq \phi \leq 18°$. They obtained the linear portion of the curve where electric field remains almost constant by assuming a fixed particular electron arrival energy $\mathcal{E}$, which in their case was 60 e.v. By way of comparison, Danielsson (1943) assumed $K = \infty$ i.e. $v_0 = 0$ with $0 \leq \phi \leq 90°$ and found $\mathcal{E} = 80$ e.v. Gill and Von Engel (1948) found, by fitting their equations to data for external electrodes at a seperation of 3 cm, that for K = 4, $\mathcal{E} = 90$ e.v. and cut-off occured at an escape limiting value of $\phi = -58°$. Their values of K of the order of 3 to 4 and electron arrival

energies of the order of 60 to 90 e.v. are compatiable with known secondary electron emission energies and yield.

Following Hatch and Williams let us assume K = 3 then $\Phi = 2(\pi \cos\phi + \sin\phi)$ consequently equations (6.3c) and (6.4) can now be fitted to the experimental curve (fig. 26). Some points are chosen in each curve and the calculated values of corresponding ϕ are marked there(e).The values of ϕ so obtained are not much different from the values obtained by previous workers in all the three tube lengths of 15 cm, 7 cm and 5 cm respectively.

The cut-off occurs because at lower frequencies the electron must leave the wall in more negative phases in order that they take half a cycle to travel the length of the tube. For negative values of ϕ , the field, until it reverses, will oppose the motion of electrons in Z direction along the axis, say. Their initial velocity takes them a little distance against this force, and then they turn back, accelerating towards Z = 0, until the reversal of the field decelerates them and turns them finally in the proper direction. The largest permissible value of ($-\phi$) is that which just returns the electrons to the wall and hence the second turning point is $\frac{dZ}{dt} = 0$ at $Z = 0$. In more negative values of ϕ , the second turning point is theoretically at negative values of Z which means that the electrons are driven back to the wall at a very low speed and stick there, so that no multiplication can take place.

The cut-off frequency f_{co} can be obtained using equation (6.5) and assuming that the arrival energy of electron is critical i.e. secondary emission coefficient $\delta = 1$ and using the upper breakdown phase angle boundary value ϕ_{co} we get

$$f_{co} = \frac{(K-1)\left[\frac{K+1}{K-1}\pi \cos\phi_{co} + 2\sin\phi_{co}\right]}{K\pi d \cdot \cos\phi_{co}} \cdot \left(\frac{E_{crit}}{8m}\right)^{1/2} \quad \text{---(6}$$

For constant K, ϕ_{co} and $\mathcal{E}_{crit}$ the above relation becomes

$$f_{co} \times d = \text{constant} \qquad \ldots(6.8)$$

where the constant of the relation (6.8) is obtained by fitting the experimental curve. Gill and Von Engel obtained the value of this constant from general similarity theorem to be 79. Hatch and Williams tried to fit the relation (6.8) to their work and those of Guttons (1924, 1930) and Gill and Von Engel. Results of Guttons fitted very well to the curve, but that of Gill and Von Engel and Hatch and Williams showed divergence from the predicted law. For length of the tube greater than 2 cm, the divergence increases with increase of length of the tube and shows a tendency of increase of the value of the constant. This is due to sidewall effect as shown by Chandrakar and Von Engel (1965) and Francis (1960) and Hatch and Williams (1954). From our observations, we have also calculated the values of ϕ_{co} using equation (6.4) and from equation (6.7) the values of $\mathcal{E}_{crit}$ for each length of the tube were also calculated. These quantities are shown in table I.

T A B L E - I.

Length of discharge tube (d) cm.	Diameter of the Discharge tube cm.	Frequency at cut off f_{co} Mc/s.	$(f_{co} \times d)$	Breakdown voltage at cutoff point (E_{co}) volt/cm.	Phase angle at cut off (ϕ_{co}) degree	Arrival energy at cut off $\mathcal{E}_{crit}$ e.v.
15	3.5	8	120	9.3	-52.3°	102.5
7	3.5	17	119	14.3	-44.3°	73.5
5	3.5	24	120	24	-48.8°	88

From the table it can be seen that the values of Φ_{co} are not much different from the observations of the previous authors. The values of $\mathcal{E}_{crit}$ are also slightly different than the experimental value of energy of 80 e.v. for secondary emission coefficient $\delta = 1$. Fitting equation (6.8) to experimental results the value of the constant is found to be ≈ 120 for all the three lengths of the tube. This value, though much higher than the value predicted by Gill and Von Engel is yet not much uncommon as can be seen from the works of Hatch and Williams where for tube length of 4 cm, the result shows the value of the constant as 120. In our experiment the lengths are much higher than the length of the tubes taken by Hatch and Williams, but comparable with some of the observation tube lengths taken by Gutton and Gutton (1930)[(1924)] and Gill and Von Engel. In fig. (27) the cut-off law given by equation (6.8) is represented for the values of the constant 79 and 120 by solid curve and dotted line respectively and also the points of the different observations made previously along with our observations. It is found that for larger length of the tube, equation (6.8) fits in a better way with the observations if we take the value of the constant to be 120, whereas for smaller length, the value 79 is more reasonable. The reason for the increase of experimental $(f_{co} \times d)_{value}$ from the value of the constant 79 was ascribed by Hatch and Williams (1954) Francis (1960), Chandrakar & Von Engel (1965) and Gill & Von Engel (1948) to the fact that at the larger seperations the loss of electron to the side wall increases and most likely this loss will be more effective for smaller diameter of the tube. Chandrakar and Von Engel (1965) recently tested this assumption in their low pressure ring discharge experiment. At larger separation, the distortion of electric field may also be responsible for preventing some of the electrons from taking part in full half cycle of the transit and hence the loss may increase.

The breakdown voltage at cutoff V_{co} may be written by eliminating ω between (6.3c) and 96.5) and using the relation

$$\mathcal{E}_{crit} = m v^2/2$$

as

$$V_{co} = E_{co} \cdot d = \left(\frac{K-1}{K}\right)^2 \frac{\mathcal{E}_{crit}\left[\frac{K+1}{K-1}\pi \cos\phi_{co} + 2\sin\phi_{co}\right]}{2e\cos^2\phi_{co}} \qquad \ldots(6.9)$$

The relation (6.9) shows that it is independent of the wall seperation and applied frequency. This fact may help in studying the effect of electrode geometry on the mechanism. Hatch and Williams assumed ϕ_{co} and K as constant when relation (6.9) becomes.

$$V_{co} = C \cdot \mathcal{E}_{crit} \qquad \ldots(6.10)$$

where 'C' is a constant the value of which is obtained by fitting with experimental data. In table II the values of V_{co} obtained experimentally, $\mathcal{E}_{crit}$ obtained from table (I) are given for the three lengths of the tube

T A B L E - II.

Length of the tube (d) cm.	Breakdown voltage at cut-off E_{co} Volts/cm.	Energy of arrival at cutoff ($\mathcal{E}_{crit.}$) e.v.	C Volts/ev.
15	9.3	102.5	1.36
7	14.3	73.5	1.36
5	24	88	1.36

The table clearly shows that the value of 'C' is a constant as predicted by relation (6.10) and when $\mathcal{E}_{crit}$ is expressed in e.v. and V_{co} in volt, the value of 'C' is 1.36.

It can thus be stated that the theory of Gill and Von Engel fits in with fair amount of success to our different observations. The yield of values of different unknown parameters involved in the theory for the process of fitting shows a fair amount of consistency among themselves for different lengths of the tube and when compared to the values obtained by previous workers.

PART (b) LOW PRESSURE BREAKDOWN BY A UNIFORM HIGH FREQUENCY ELECTRIC FIELD WITH A UNIFORM TRANSVERSE D.C. MAGNETIC FIELD.

The equation of motion of a secondary electron in presence of a transverse steady magnetic field and under the action of the oscillatory field

$$\vec{E}_x = E \sin(\omega t + \phi)$$

is given by

$$\frac{d\vec{v}}{dt} = -\frac{e}{m}\left[\vec{E} + \vec{v} \times \vec{H}\right]$$

and hence

$$\frac{dv_x}{dt} = -\omega_H v_y + \frac{eE}{m}\sin(\omega t + \phi) \qquad \text{...(6.11)}$$

$$\frac{dv_y}{dt} = \omega_H v_x$$

where $\omega_H = \frac{eH}{m}$ = cyclotron frequency.

From (6.11) $\frac{d^2 v_x}{dt^2} = -\omega_H^2 v_x + \frac{e\omega E}{m}\cdot\cos(\omega t + \phi)$

The solution of the complementary function $\frac{d^2 v_x}{dt^2} + \omega_H^2 v_x = 0$

is $v_x = A\cos(\omega_H t) + B\cdot\sin(\omega_H t)$

where A and B are two constants to be determined from the boundary conditions.

The particular integral

$$\frac{d^2 v_x}{dt^2} + \omega_H^2 v_x = \frac{e\omega E}{m}\cos(\omega t + \phi) \qquad \text{...(6.12)}$$

has the solution

$$v_x = A'\cos(\omega t + \phi)$$

where A' is another constant

Putting this value of v_x to equation (6.12)

$$-A'\omega^2\cos(\omega t + \phi) + \omega_H^2 A'\cos(\omega t + \phi) = \frac{e\omega E}{m}\cos(\omega t + \phi)$$

$$\therefore \quad A' = \frac{e\omega E}{m(\omega_H^2 - \omega^2)}$$

Hence the complete solution is

$$v_x = A\cos(\omega_H t) + B\sin(\omega_H t) + \frac{eE\omega\cos(\omega t+\phi)}{m(\omega_H^2-\omega^2)}$$

The boundary conditions are $v_x = v_0, \quad v_y = 0, \quad x = y = 0 \quad$ at $t = 0$.

Now

$$\frac{dv_y}{dt} = \omega_H v_x = A\omega_H\cos(\omega_H t) + B\omega_H\sin(\omega_H t) + \frac{eE\omega\omega_H\cos(\omega t+\phi)}{m(\omega_H^2-\omega^2)}$$

$$\therefore v_y = A\sin(\omega_H t) - B\cos(\omega_H t) + \frac{eE\omega_H\sin(\omega t+\phi)}{m(\omega_H^2-\omega^2)} + C$$

where C is a constant and Let $\beta = (\omega_H^2 - \omega^2)$. Putting the value of v_y in equation (6.11) we get C= 0

Hence

$$v_x = A\cos(\omega_H t) + B\sin(\omega_H t) + \frac{e\omega E}{m\beta}\cos(\omega t+\phi)$$

$$v_y = A\sin(\omega_H t) - B\cos(\omega_H t) + \frac{e\omega_H E}{m\beta}\sin(\omega t+\phi) \qquad \ldots(6.13)$$

Insertation of boundary conditions to equation (6.13) leads to the equation of velocity components and displacement components

$$v_x = \left[v_0 - \frac{eE\omega}{m\beta}\cos\phi\right]\cos(\omega_H t) + \frac{e\omega_H E}{m\beta}(\sin\phi)(\sin\omega_H t) + \frac{eE\omega}{m\beta}\cos(\omega t+\phi) \qquad \ldots(6.14)$$

$$v_y = \left[v_0 - \frac{eE\omega}{m\beta}\cos\phi\right]\sin(\omega_H t) - \frac{e\omega_H E}{m\beta}(\sin\phi)(\cos\omega_H t) + \frac{eE\omega_H}{m\beta}\sin(\omega t+\phi) \qquad \ldots(6.15)$$

$$x = \frac{1}{\omega_H}\left[v_0 - \frac{eE\omega}{m\beta}\cos\phi\right]\sin(\omega_H t) - \frac{eE\sin\phi}{m\beta}\cos(\omega_H t) + \frac{eE}{m\beta}\sin(\omega t+\phi) \qquad \ldots(6.16)$$

$$y = \frac{1}{\omega_H}\left[v_0 - \frac{eE\omega\cos\phi}{m\beta}\right]\left[1 - \cos\omega_H t\right] + \frac{eE\omega_H}{m\omega\beta}\left[\cos\phi - \cos(\omega t + \phi)\right] - \frac{eE\sin\phi}{m\beta}\sin(\omega_H t)$$

...(6.17)

As before, let us assume that the tansit time of electron across the tube length is $t = \pi/\omega$, the half of the period of oscillatory field. Putting this value of t in equations (6.14) and (6.15) and taking the resultant velocity

$$v^2 = v_0^2 + 2\left(1 + \cos\frac{\omega_H}{\omega}\pi\right)\left[-\frac{v_0\omega eE}{m\beta}\cos\phi + \left\{\frac{eE\omega\cos\phi}{m\beta}\right\}^2 + \left\{\frac{eE\omega_H\sin\phi}{m\beta}\right\}^2\right] - \frac{2v_0 eE\omega_H\sin\left(\frac{\omega_H}{\omega}\pi\right)\sin\phi}{m\beta}$$

...(6.18)

After Von Engel, let us assume that $v/v_0 = K$ and hence

$$v^2 - v_0^2 = v^2\left(1 - \frac{1}{K^2}\right) \quad \text{and} \quad v_0 = v/K$$

Hence

$$v^2\left(1 - \frac{1}{K^2}\right) = 2\left(1 + \cos\frac{\omega_H}{\omega}\pi\right)\left[-\frac{v\omega eE\cos\phi}{Km\beta} + \left\{\frac{eE\omega\cos\phi}{m\beta}\right\}^2 + \left\{\frac{eE\omega_H\sin\phi}{m\beta}\right\}^2\right] - \frac{2veE\omega_H\sin\left(\frac{\omega_H}{\omega}\pi\right)\sin\phi}{Km\beta}$$

... (6.19)

The electron is striking the other end with the velocity v_c given by equation (6.19) at an inclination angle θ to the axis of the cylinder. The angle θ is given by

$$\tan\theta = v_y/v_x$$

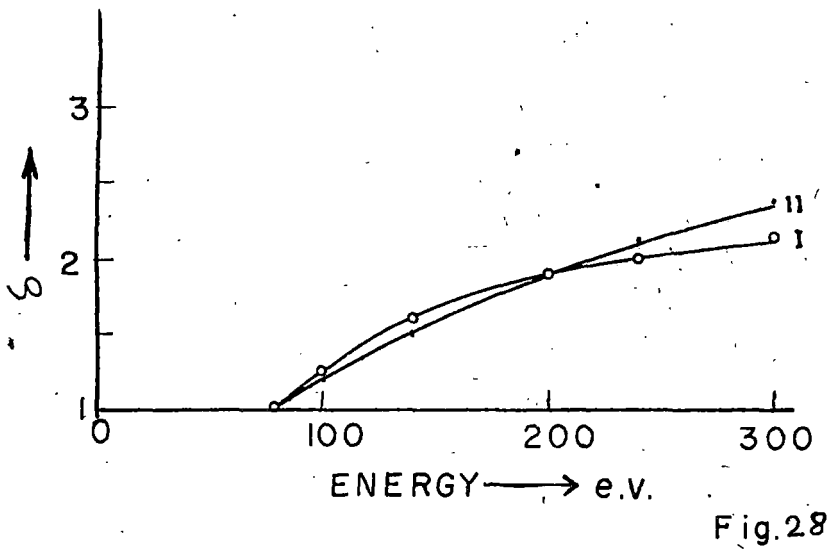
II: MUELLER (1945)
II: EMPIRICAL.
δ
3
2
1
0
100
200
300
II
I
ENERGY ⟶ e.v.

Fig.28

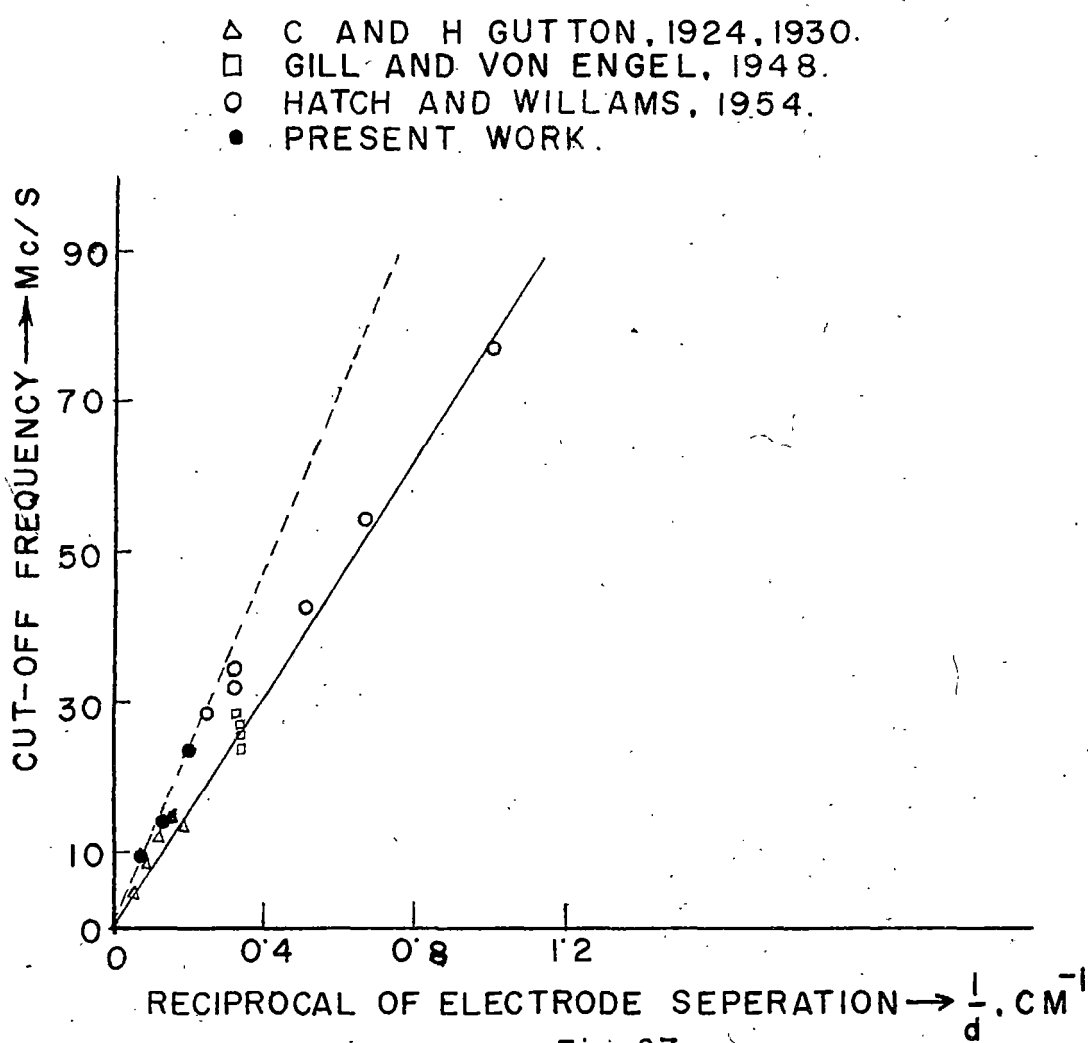
△ C AND H GUTTON, 1924, 1930.
□ GILL AND VON ENGEL, 1948.
○ HATCH AND WILLAMS, 1954.
● PRESENT WORK.
CUT-OFF FREQUENCY ⟶ Mc/S
90
70
50
30
10
0
0
0·4
0·8
1·2
RECIPROCAL OF ELECTRODE SEPERATION ⟶ 1/d, CM⁻¹

Fig-27

Bruining (1954) has shown that for certain metallic surfaces the relation between δ_θ and δ_0 is given by

$$\log \frac{\delta_\theta}{\delta_0} = C' (1 - \cos\theta)$$

where C' is a constant which is different for different surfaces and δ_θ is the maximum value of δ for an angle of incidence θ of primary electron of any energy and δ_0 = the maximum value of δ for normal incidence of primaries of the same energy. After Deb and Goswami (1964) we shall use this relation in case of glass, since no such relation between δ_θ and δ_0 is available for glass except a few experimental results of increase of δ_θ over δ_0. From the reported result of increase of by 50% over δ_0 for $\theta = 60°$ to $\theta = 0°$ in case of glass the value of the constant C' becomes approximately equal to unity, consequently

$$\delta_\theta/\delta_0 = \exp(1 - \cos\theta)$$

If n_θ and n_0 are the corresponding secondary yields of electrons for the same number of primaries, then

$$\frac{\delta_\theta}{\delta_0} = \frac{n_\theta}{n_0}$$

So it can be said that a particle with velocity smaller than the velocity of the normally incident particle is identical in its capacity to yield secondary electrons, when it hits the surface at a certain angle of inclination.

Muller's (1945) results on hard pyrex glass is given in the fig. (28) which shows the average number of electrons released from the glass surface

irrespective of the angle of emission as a function of the speed of the primaries. An empirical relation between energy of primary electrons in e.v. and δ, the yield can be represented by an equation

$$\delta = 1{\cdot}2\,(\mathcal{E}/100)^{2/3}$$

This relation is fitted to the experimental curve which shows that the fitting is valid between 80 e.v. to 300 e.v. of energy of primary. In secondary resonance breakdown, the primary energies lie well within this limit. Hence we can utilise this relation between δ and $\mathcal{E}$.

Let $\mathcal{E}_{eff}$ be the effective energy of the particle which will yield the same number of secondaries, when it hits the surface normally as particle of energy $\mathcal{E}_o$ will yield hitting at an angle θ, we have then $\mathcal{E}_{eff} > \mathcal{E}_o$; the ratio of yield from Mueller's results fitted equation can then be written as

$$\frac{\delta_\theta}{\delta_o} = \left(\frac{\mathcal{E}_\theta}{\mathcal{E}_o}\right)^{2/3} = \frac{n_\theta}{n_o} = \exp(1-\cos\theta)$$

If v_{eff} = velocity of the primary corresponding to energy $\mathcal{E}_\theta$

v = velocity of primary corresponding to $\mathcal{E}_o$

then

$$\left(\frac{v_{eff}}{v}\right)^{4/3} = \exp(1-\cos\theta)$$

$$\therefore\ v_{eff} = v\,\exp\left[\frac{3}{4}(1-\cos\theta)\right]$$

Consequently we can state that the effect of hitting the surface with velocity v at an angle θ is equivalent to hitting the surface with velocity v_{eff} at normal incidence where v and v_{eff} are related by the above equation. Hence

to account for the effect of hitting the surface obliquely, if we replace v by $v_{eff}\left\{\exp -\frac{3}{4}(1-\cos\theta)\right\}$ in equation (6.19). We get the relation,

$$v_{eff}^2\left(1-\frac{1}{K^2}\right) = 2\left(1+\cos\frac{\omega_H}{\omega}\pi\right)\left[-\frac{v_{eff}\,\omega\, e\, E\exp\left\{\frac{3}{4}(1-\cos\theta)\right\}}{Km\beta}\right.$$

$$\left.+\left\{\frac{eE\exp\left\{\frac{3}{4}(1-\cos\theta)\right\}\omega\cos\phi}{m\beta}\right\}^2+\left\{\frac{eE\exp\left\{\frac{3}{4}(1-\cos\theta)\right\}\omega_H\sin\phi}{m\beta}\right\}^2\right]$$

$$-\frac{2v_{eff}\,eE\exp\left\{\frac{3}{4}(1-\cos\theta)\right\}\omega_H\sin\phi\,\sin\left(\frac{\omega_H}{\omega}\pi\right)}{Km\beta} \qquad \ldots(6.20)$$

From equation (6.20) we find that introducing v_{eff} in place of v changes the value of E to $E\exp\left\{\frac{3}{4}(1-\cos\theta)\right\}$. In other word, the effect of hitting obliquely at the surface can well be represented by replacing E by $E\exp\left\{\frac{3}{4}(1-\cos\theta)\right\}$ in any relation deduced from the solution of equation (6.11).

Deb and Goswami (1964) indicated that the general solution of equation (6.20) in simplified from is unobtainable. For large magnetic field, however, a simplified assumption may be taken, as was done by Deb and Goswami (1964) that the second turning point appears approximately after the completion of one full cycle of the cyclotron frequency i.e. when $\omega_H/\omega = 2n\pi$ where n is an integer. The justification of this assumption may be sought in the fact that the fraction of the phase that is not considered in this approximation occupies little portion of the half cycle of transit i.e. the distance t between the end wall and position of electron, when it has executed a number of complete revolutions due to cyclotron rotation, is small in both positive and negative sides of the wall.

Applying this assumption to equation (6.20) we get

$$v_{eff}^2\left(1-\frac{1}{K^2}\right)=4\left[-\frac{v_{eff}\,\omega eE\exp\left\{\frac{3}{4}(1-\cos\theta)\right\}}{Km\beta}+\left\{\frac{eE\exp\left\{\frac{3}{4}(1-\cos\theta)\right\}\omega\cos\phi}{m\beta}\right\}^2\right.$$

$$\left.+\left\{\frac{eE\exp\left\{\frac{3}{4}(1-\cos\theta)\right\}\omega_H\sin\phi}{m\beta}\right\}^2\right] \qquad \ldots(6.20a)$$

and displacements at $t=\pi/\omega$ from equation (6.16) and (6.17)

$$x=-\frac{2eE\sin\phi}{m\beta} \qquad \ldots(6.20b)$$

$$y=\frac{2eE\,\omega_H\cos\phi}{m\omega\beta} \qquad \ldots(6.20c)$$

The square of the resultant displacement

$$D^2=x^2+y^2=\left(2eE/m\beta\right)^2\left[\frac{\omega_H^2\cos^2\phi}{\omega^2}+\sin^2\phi\right]$$

$$\therefore D=\frac{2eE}{m\beta}\left[\frac{\omega_H^2\cos^2\phi}{\omega^2}+\sin^2\phi\right]^{1/2} \qquad \ldots(6.21)$$

To calculate the resultant displacement when the electron strikes the opposite end, the value of the y- component of displacement at $t=\pi/\omega$ has been calculated from equation (6.20c) and the results are entered in the last column of the table III for different values of the magnetic field. The resultant displacement is $(x^2+y^2)^{\frac{1}{2}}$ at $t=\pi/\omega$. Using the y- displacement and taking $x=5$ cm. the resultant displacement for minimum and maximum values of the magnetic field, "D", lies between 5.297 cm and 5.702 cm. and the length of the tube is 5 cm. Consequently as a first approximation the resultant displacement can be taken to be equal to the length of the tube. Making this assumption and introducing the effect of

oblique hitting of the electron to the end surface we get from equation (6.21) as

$$\frac{d.m.(\omega_H^2-\omega^2).\omega}{2.e.E\ \Phi_H} = \exp\left[\frac{3}{4}(1-\cos\theta)\right]$$

where

$$\Phi_H = \left[\omega_H^2\cos^2\phi + \omega^2\sin^2\phi\right]^{1/2} \qquad \ldots(6.22)$$

as $\frac{3}{4}(1-\cos\theta) < 1$ the equation can be written

$$\frac{d.m.(\omega_H^2-\omega^2).\omega}{2eE\ \Phi_H} \approx 1 + \frac{3}{4}(1-\cos\theta) \qquad \ldots(6.23)$$

We have again

$$\tan\theta = -\frac{\omega_H}{\omega}\cot\phi$$

Therefore

$$\sec\theta = \frac{\Phi_H}{\omega\sin\phi}$$

or

$$\cos\theta = \frac{\omega\sin\phi}{\Phi_H}$$

Putting this value of $\cos\theta$ in equation (6.23)

$$\frac{d.m.(\omega_H^2-\omega^2)\omega}{2eE\ \Phi_H} = 1 + \frac{3}{4}\left(1-\frac{\omega\sin\phi}{\Phi_H}\right)$$

and carrying the simplification a few steps

$$\sin^2\phi(49\,\omega_H^2 - 40\,\omega^2) + 24\,\Lambda_H\,\omega\sin\phi + (16\Lambda_H^2 - 49\omega_H^2) = 0$$

where $\Lambda_H = \frac{m\,d\,(\omega_H^2-\omega^2)\omega}{2eE}$

$\ldots(6.24)$

Consequently, from equation (6.24), for different values of λ_H, ω_H and ω, the value of $\sin\phi$ is obtained. Since equation (6.24) is quadratic in $\sin\phi$ so the phase angle values are chosen depending upon the portion of the curve under consideration. In fig. (29) experimental curves for magnetic field values of 18 gauss, 21 gauss, 30 gauss and 45 gauss are given upto the highest range of frequency at which the measurements are limited by the r.f. voltage limitation of the present experimental setup. In each curve some points are chosen and the values of ϕ from equation (6.24) are obtained for each point.

The limitation of r.f. out put voltage restricted us in obtaining the almost linear portion to cut-off point only but not the other end of the curves. Hence throughout our discussion, we have confined our discussion and fittings to the linear portion of the curves where energy is almost constant as shown by Hatch and Williams (1954).

From equation (6.20a) taking the assumption $\left(\frac{\omega_H}{\omega}\right)\pi = 2n\pi$ $(n = 1, 2, 3 \text{ etc})$ we get

$$v^2\left(1-\frac{1}{K^2}\right) = 4\left[\frac{-v e E \omega \cos\phi}{K m \beta} + \left\{\frac{eE\omega\cos\phi}{m\beta}\right\}^2 + \left\{\frac{eE\omega_H \sin\phi}{m\beta}\right\}^2\right]$$

or
$$v^2 + v\left[\frac{4}{1-\frac{1}{K^2}} \cdot \frac{eE\omega\cos\phi}{Km\beta}\right] - \left(\frac{4}{1-\frac{1}{K^2}}\right)\left[\left(\frac{eE}{m\beta}\right)^2\left(\omega^2\cos^2\phi + \omega_H^2\sin^2\phi\right)\right] = 0$$

This equation is solved for v as other quantities are known. The energy of arrival $\mathcal{E}_0 = \frac{mv^2}{2}$ is then calculated and using the relation

$$\mathcal{E}_{eff}/\mathcal{E}_0 = \exp\left\{\frac{3}{2}(1-\cos\theta)\right\}$$

the values of $\mathcal{E}_{eff}$ for the cut-off points of each value of the magnetic field have been obtained. These values are shown in table III.

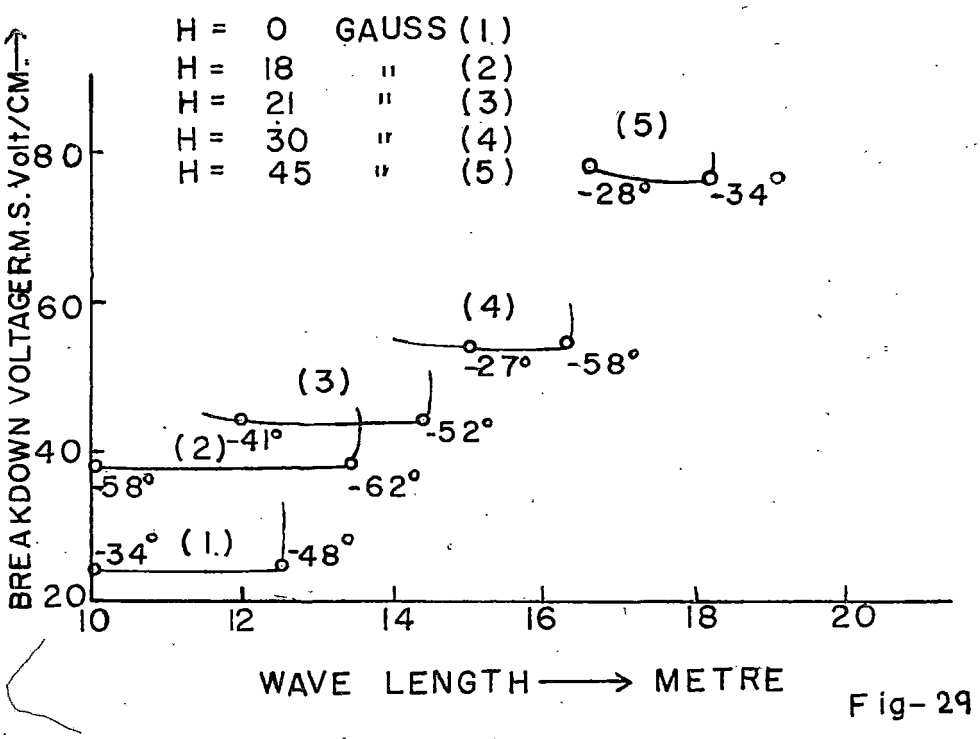
H = 0 GAUSS (1.)
H = 18 " (2)
H = 21 " (3)
H = 30 " (4)
H = 45 " (5)
BREAKDOWN VOLTAGE R.M.S. Volt/CM
80
60
40
20
10
12
14
16
18
20
WAVE LENGTH ⟶ METRE
(5)
-28°
-34°
(4)
-27°
-58°
(3)
-41°
-52°
(2)
-58°
-62°
-34°
(1.)
-48°

Fig-29

TABLE - III.

H Gauss	f_{co} Mc/s	E_{co} Volt/cm	$(-\phi_{co})$ degree	$v_{co}\times10^{-8}$ cm/sec	ε original e.v.	ε effective e.v.	ε critical from table-I	Larmor radius cm.	δ displacement from equ. (6.20e)
18	22	38	62	4.3	52	88.4	88	1.327	1.75
21	21	44	52	3.57	35.85	86.04		.9445	2.228
30	18.5	54	58	3.1	27.04	75.35		.5741	2.601
45	16.5	76	34	1.84	8.52	38.09		.2272	2.747

From the table III, it is seen that the values of $\varepsilon_{original}$ is much smaller than the critical value of ε for $\delta = 1$ and the value of ε_{crit} calculated from the cut-off point of the curve of H = 0. But the value of $\varepsilon_{effective}$ for H upto 30 gauss is near or equal to ε_{crit} for H = 0, though the value shows gradual decrease as H is increased. The deviation is not remarkable upto H = 30 gauss, but for H = 45 gauss, the value of $\varepsilon_{effective}$ is much smaller than the ε_{crit} . The reason of this deviation is due to different approximations made in calculating ϕ and v from comparison with the experimental results. It is evident from the results that these approximations do not much effect the results for small magnetic field, but for high magnetic field the different terms neglected in obtaining equation (6.21) and (6.20a) modified the values of ϕ and v to a large extent and consequently the deviation of the values of the different parameters. However, considering the limitations of our theory in explaining the mechanism of the discharge and the experimental results by

the process of fitting it can be said that the agreement is fairly good at least for moderate values of the magnetic field. This treatment also shows that the mechanism of secondary electron resonance is still operative in original sense as the case of the breakdown of the gas, when the magnetic field is also present. It is also expected that if the original solutions of equation of motion of electron could be obtained, much better fitting of the experimental results and consequently more resonable values of the parameters could be obtained.

The values of the Larmor radius and those of y- displacement at $t = \pi/\omega$ have been numerically calculated for different values of the magnetic field and entered in the ninth and tenth column of table III respectively. The y- displacement when the electrons reach the opposite end for each of the values of the magnetic field is smaller than the diameter of the discharge tube (3.5 cm.), the Larmor radius in each case is much smaller than the radius of the tube for energies of electrons high enough to cause breakdown and the majority of electrons which are actually responsible for the continuance of the secondary electron resonance breakdown find ample free space during their transit between the end walls and are not lost due to collision with the side walls.

It is further observed from table III that an empirical relation between H, f_{co} and E_{co} can be obtained from the experimental data. The quantity $(H \cdot f_{co}/E_{co})$, where H is expressed in gauss, f_{co} in Mc/sec and E_{co} in volts/cm., is almost a constant as shown in table IV.

T A B L E - IV.

H Gauss	f_{co} Mc/sec	E_{co} Volts/cm.	$(H f_{co}/E_{co})$ Expt.	$(-\phi_{co})$ in degree	θ_{co} in degrees	$(H f_{co}/E_{co})$ Calc.
18	22	38	10.42	62	51	5.698
21	21	44	10.02	52	66	6.7
30	18.5	54	10.27	58	77	6.119
45	16.5	76	9.77	34	85	10.1

To test whether the theoretical analysis made above can explain the empirical relation observed we obtain from equation (6.22)

$$\frac{m.d.\omega_H^2\left(1-\frac{\omega^2}{\omega_H^2}\right).\omega}{2eE\,\omega_H\cos\phi_{co}\left(1+\frac{\omega^2}{\omega_H^2}\tan^2\phi_{co}\right)^{1/2}} = \exp\left\{\frac{3}{4}\left(1-\cos\theta_{co}\right)\right\}$$

as for the magnetic field used in this experiment $\frac{\omega^2}{\omega_H^2} \ll 1$

and $\frac{\omega^2}{\omega_H^2}\tan^2\phi_{co} = \cot^2\theta_{co}$, we get

$$\frac{m.d.\omega_H\,\omega}{2eE\cos\phi_{co}\left(1+\cot^2\theta_{co}\right)^{1/2}} = \exp\left\{\frac{3}{4}\left(1-\cos\theta_{co}\right)\right\}$$

or $$\frac{m\,d\,\omega_H\,\omega}{2eE} = \frac{\cos\phi_{co}}{\sin\theta_{co}}\exp\left\{\frac{3}{4}\left(1-\cos\theta_{co}\right)\right\}$$

$$\therefore \frac{f_{co}\times H}{E_{co}} = 6{\cdot}37\,\frac{\cos\phi_{co}}{\sin\theta_{co}}\exp\left\{\frac{3}{4}\left(1-\cos\theta_{co}\right)\right\} \text{ for } d=5\text{ cm.}$$

...(6.25)

where f_{co} is in Mc/sec H in gauss and E_{co} in volts/cm are expressed. In table IV the values of Φ_{co} and θ_{co} for different magnetic fields are given. Empirically we find that the r.h.s. of equation (6.25) is a constant and equal to 10, so we may say that θ_{co}, Φ_{co} and f_{co} adjust themselves in such a way that at the point of cut-off given by equation (6.25), the value of r.h.s. of equation remains constant for any magnetic field. To test the validity of this conclusion, the individual values of r.h.s. of equation (6.25) are calculated for each magnetic field and results entered in the last column of table IV. The table shows that the value of the constant compares reasonably with fair amount of agreement in the order of magnitude between the empirically determined value and the theoretical value of the last column. The discrepancy may be attributed to the different approximations taken and their validity during the theoretical deductions. Consequently, it can be concluded with reasonable agreement the cut-off relation

$$\frac{f_{co} \times H}{E_{co}} = \text{constant}$$

is true for moderate values of the magnetic field at the point of cut-off.

CONCLUSION.

The phenomena of low pressure breakdown by secondary electron resonance oscillations has been explained in the light of the theory put forward by Gill and Von Engel and Hatch and Williams. The measurements without magnetic field lead to the conclusion that all the predictions of the theory of Gill and Von Engel (1948) can be extended for a wide range of the dimension of the discharge tube. The increase in the value of the constant ($f_{co} \times d$) at cut-off justifies to some extent the predicted reasoning of Hatch and Williams (1954) and supported recently by the work of Chandrakar and Von Engel (1965) as due to side wall effect specially when the length of the discharge tube is large. For increase of the length of the discharge tube the

constant increases which was also observed by previous workers for gaps shorter than those used in the present work. The quantity $V_{co}/\varepsilon_{crit}$ has been found to be a constant for all the three lengths of the discharge tube, a result which follows from the theoretical analysis.

The observations with magnetic field and the subsequent fitting of these observations to our theory yielded the values of the phase angle which are reasonable. Though our procedure has obtained a simplified form for the energy of arrival of the electrons, yet it gives results for the effective energy of arrival for moderate magnetic field with fair amount of accuracy.

The validity of the different assumptions made for the deduction of the simplified theory of breakdown with magnetic field are open to questions in the rigid theoretical sense. But in view of the fact that no conclusive theory showing the behaviour of the discharge for the continuous change of magnetic field can be deduced without making some simplifying assumptions and considering the usefulness of the theory in explaining the experimental results, it can be concluded that the assumptions can be regarded as valid in the range of the magnetic field studied in the present investigations.

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CHAPTER - VII.

EFFECT OF EXTERNAL MAGNETIC FIELD ON THE INTENSITY OF EMISSION LINES IN THE VISIBLE REGION OF THE SPECTRUM FROM RADIOFREQUENCY DISCHARGE COLUMN.

INTRODUCTION.

Different aspects of the radiation property of the gaseous discharge column excited by d.c. electric field were investigated by many workers for a long time and a fair amount of knowledge has been obtained on different mechanisms of the radiation emitting processes. One of the interesting features of the glow discharge which has not yet been completely understood is the different processes by which the intensity of the radiation from the column changes under different discharge conditions and in presence of external field.

Rossler and Schonherr (1938) identified both pressure and current dependent losses of the radiation of mercury line ($6^3P_1 - 6^1S_0$) and attributed them to collisions of the second kind with neutrals and electrons respectively. Many workers observed decrease in intensity at large density, specially in inert gases. Fowler and Duffendack (1949) found the dependence of the intensity of the spectral lines upon the tube current to be linear within experimental error. This relationship was observed for all types of transitions and over a current range of half m.A. to one hundred mA. All the density vs. intensity curves have essentially the same form, rate of decay and location of the maximum except the transition $2^3P - 3^3D$. The possibility of an unrecognised process other than direct excitation has been suggested from the results of observations of radiation from a low voltage arc in helium as a function of gas density, tube current and tube potential. Duffendack and Keppins (1939) observed increase of intensity of radiation for the family of transitions ending with 6^3P states in the negative glow which shows an exponential saturation with mercury concentration and varies linearly with tube current. Hedges and Michels (1928) observed maxima in the radiation

intensity with change of pressure from positive column of helium discharge. Altogether they studied thirteen lines in the visible region. Bakhlin (1939) observed maxima of some resonance lines of mercury vapour discharge by applying longitudinal magnetic field. Kulkarni (1944) studied discharges in some gases, including some rare gases in the apparatus used for observation of Zeeman effect and found the intensity of some of the spectrum lines show maxima at different magnetic field intensities which again was found to depend on wavelength and the presence of foreign gas. Some lines did not however show maxima even at the highest magnetic field intensity available in the setup. No detailed mathematical analysis was put forward.

But very little knowledge both experimental and theoretical, is available on the optical radiation property of high frequency discharge though Beck (1935) in a point to point comparison found steady glow discharge in mercury indistinguishable from 100 Mc/s discharge, and also the identical nature of their radiation property. In view of these observation it will be worthwhile to investigate the radiation property of high frequency discharge and it is proposed in the present investigation to study the effect of transverse d.c. magnetic field on the intensity of optical radiation. The investigation has shown some interesting results on the influence of external magnetic field on the intensity of line radiation. A theory from very elementary considerations has been proposed to explain the results on the change of total optical radiation intensity of the column.

EXPERIMENTAL ARRANGEMENT.

The discharge tubes are fitted with aluminium electrodes and filled with gases neon, argon and helium respectively which are spectroscopically pure and at a pressure of 10 m.m. mercury as supplied by the manufacturer. These tubes

are the same as were used in an earlier experiment while studying breakdown in combined radiofrequency and d.c. field. The high frequency field is supplied by a tuned plate tuned grid oscillator. The uniform magnetic field is applied by an electromagnet which is calibrated by a gaussmeter. The photovoltaic surface connected with a galvanometer measures the relative intensity of the total radiation from the column.

A constant deviation spectrometer with glass prism is used to obtain the spectrum of the discharge column in the visible region. A camera with sliding arrangement photographs the spectrum. The photographs of the spectra are later analysed by a microphotometer arrangement and the intensity profiles are obtained for each line. Care has been taken to see that exposure time for different sets of spectra of the same gas at different magnetic fields remain rigidly the same.

RESULTS AND DISCUSSION.

High frequency discharge falls in the catagory of thermal electron discharges. Analysis of the radiation from the thermal discharges must be made on the basis of electron concentration and its velocity distribution. It is reasonably accurate to consider that the electron temperature which governs the velocity distribution remains constant over large regions of the discharge. This is because the electron temperature is almost directly proportional to the electrostatic field in the gas and the electrostatic field is tangentially constant, at least, from its conservative property. In the absence of space charge, there can be no change in normal component either, thus establishing the conditions for constancy of electron temperature.

In the steady state of the glow discharge column at a fixed pressure, the electrons colliding with neutral atom may excite it or ionise it. Since

excitation potential is much lower than ionisation potential, so an electron on the average suffers a large number of inelastic exciting collisions with neutral atoms before it actually ionises an atom. In the steady state, the average population in an excitation level determines the intensity of the line. The process of populating a level by electron collision with neutral atom is dependent upon the rate of collison, excitation cross section and density of the colliding particles. Consequently, it is most likely that any external influence changing the rate of collision and density of colliding particles will effect the population density of different excitation levels and thereby cause a change in intensity.

The change of population in a given state of excitation due to collisional interaction between electron and atom is represented by the production function P which can be written for elatations of a type having the cross-section $\sigma_{j0}(u)$ per unit volume per unit time as : (Fowler 1956)

$$P_j = 4\pi (N_-) \int_{u_{min}}^{\infty} u^3 . \sigma_{j0} . \Phi . du \qquad \ldots(7.1)$$

where u = relative velocity of interacting electron and atom which is practically the velocity of electrons as atom's velocity is very small compared to electron.

N_- = electron density

P_j = production function for j^{th} state of excitation from ground state, the corresponding radiation frequency being ν_{j0}.

u_{min} = minimum velocity of electron for which $\sigma_{j0} = 0$

Φ = Maxwell - Boltzman distribution function.

Following Fowler (1956), for gases which do not attach electrons, the production function is directly proportional to the current density and if

radiation is the chief energy loss mechanism, the radiation must be propertional to the current just as in monoenergetic electron discharge. Consequently we can take production function to be proportional to total intensity of radiation. The production function for all types of excitation can be obtained by taking summation over j, provided we assume that all the transitions are between ground state and excited level. The total production function

$$P = \sum_j P_j = \sum_j 4\pi (N_-) \int_{u_{min}}^{\infty} u^3 . \sigma_{j_0} . \phi . du$$

Consequently, we can take the total intensity I of the complete radiation coming out of a discharge column as proportional to P. Therefore

$$I \propto \sum_j 4\pi (N_-) \int_{u_{min}}^{\infty} u^3 . \sigma_{j_0} . \phi . du \qquad \ldots(7.2)$$

Mott and Massey (1950) found that for optically allowed transitions, the cross -section is approximately given by

$$\sigma_{j_0} \approx \frac{3}{4\pi} . \frac{e^2 c^3}{h} . \frac{A_{j_0}}{u^2 \nu_{j_0}^3} . \log (2mu^2/h\nu_{j_0})$$

where A_{j_0} = Einstein's transition probability

C = velocity of light

h = planck's constant

We have assumed here that electrons are distributed following Maxwell - Boltzman distribution law and constitutes the electron gas at a temperature T_e which is called the electron temperature, a measure of energy of the electrons. Consequently, the pressure of the electron gas is given by

$$P_e = (N_-) K T_e$$

where K is Boltzman constant

Putting the value of ϕ and σ_{j_0} in equation (7.1) we get

$$P_j = 4\pi(N_-)\int_{u_{min}}^{\infty} u^3 \cdot (m/2\pi KT_e)^{3/2} \cdot \exp(-mu^2/2KT_e) \cdot \frac{3e^2c^3 A_{j0}}{4\pi h \nu_{j0}^3 u^2} \cdot \log(2mu^2/h\nu_{j0}) \cdot du.$$

$$P_j = 4\pi(N_-)\cdot(m/2\pi KT_e)^{3/2} \cdot \frac{3e^2c^3 A_{j0}}{4\pi h \nu_{j0}^3} \cdot \int_{u_{min}}^{\infty} u \cdot \exp(-mu^2/2KT_e) \cdot \log(2mu^2/h\nu_{j0}) \cdot du$$

Without going to evaluate exactly the right hand side of the above equation, if we consider only the terms involving T_e and P_e, then as a first approximation it can be said that

$$P_j \propto \frac{P_e}{T_e^{5/2}} \exp\left[-m u_{min}^2/2KT_e\right]$$

And since $P = \sum_j P_j$ so we get

$$P \propto \frac{P_e}{T_e^{5/2}} \exp\left[-m u_{min}^2/2KT_e\right]$$

...(7.3)

which is proportional to the intensity of total radiation from the column

When a transverse magnetic field is applied to the discharge column, the column is constricted. Due to this constriction of the column, the electron collision and hence the equivalent pressure of the electron column increases. The decrease of the mean free path results in the decrease in the average energy gained by an electron between two successive collisions with neutral atom. Consequently the electron temperature decreases (Von Engel 1955, Sen and Gupta 1967). So from the very simple consideration, the overall effect of the application of steady transverse magnetic field on the radiation property of the discharge column can be accounted for by the change of P_e and T_e with magnetic field only and assuming that other factors arising in equation (7.3) remain unaffected by the magnetic field.

Let us assume that in presence of magnetic field, the values of P_e and T_e are given by P_{eH} and T_{eH} . Elevin and Hayden (1958) provided a relation between P_{eH} and P_{eo} as

$$P_{eH} = P_{eo}\left[1 + C\left(H/P_{eo}\right)^2\right]^{1/2} \qquad \ldots(7.4)$$

The term $C = (e/m)(L/v_r)$ where L is the mean free path of electron at a pressure of 1 m.m. mercury and v_r is the random velocity of electron, and H is the magnetic field. The authors assumed C to be constant within the value of H/P_{eo} = 300 GAUSS/m.m. of Hg.

The relation between T_e and P_e as given by Von Engel (1955) is

$$x^{-1/2} \exp(x) = \beta(\ell PR)^2 \qquad \ldots(7.5)$$

where $x = eV_i/KT_e$ and $\ell = \left(a V_i^{1/2}/\bar{K}+P\right)$, P = Pressure and β is a numerical constant.

Here $\bar{K}^+$ = mobility coefficient of positive ion.

V_i = ionisation potential

a = initial slope of the efficiency of ionisation curve.

Following Sen and Gupta (1967) it is assumed that T_{eo}, P_{eo} and T_{eH}, P_{eH} are the temperature and pressure of the electron gas without and with external magnetic field respectively which satisfy the relation (7.5).

Hence

$$\frac{\exp\left(eV_i/KT_{eH}\right)}{\exp\left(eV_i/KT_{eo}\right)}\left(\frac{T_{eH}}{T_{eo}}\right)^{1/2} = \left(\frac{P_{eH}}{P_{eo}}\right)$$

Assuming $T_{eo} - T_{eH} = \Delta T_e$; where $\Delta T_e \ll T_{eo}$ (Sen and Gupta 1967) and simplifying we get

$$T_{eo} - T_{eH} = \frac{2T_{eo}^2 \log\left(P_{eH}/P_{eo}\right)}{T_{eo} + 2eV_i/K}$$

$$\therefore T_{eH} = T_{eo} - \left\{2T_{eo}^2 \log\left(P_{eH}/P_{eo}\right)\Big/ T_{eo} + 2eV_i/K\right\}$$

...(7.6)

If total production function in presence of magnetic field be P_H and corresponding intensity of total radiation I_H, then using relations (7.2), (7.3), (7.4), we get

$$\frac{P_H}{P_o} = \frac{I_H}{I_o} = \left(\frac{P_{eH}}{P_{eo}}\right)\left(\frac{T_{eo}}{T_{eH}}\right)^{5/2} \exp\left[-\frac{\mathcal{E}_m}{K}\left(\frac{1}{T_{eH}} - \frac{1}{T_{eo}}\right)\right]$$

where $\mathcal{E}_m = \frac{1}{2} m u_{min}^2$ = minimum excitation energy

$$I_H/I_o = \left(\frac{P_{eH}}{P_{eo}}\right)\left(\frac{T_{eo}}{T_{eH}}\right)^{5/2} \exp\left[-\frac{\mathcal{E}_m}{K} \cdot \frac{T_{eo} - T_{eH}}{T_{eo}^2}\right]$$

if we assume $T_{eH}\, T_{eo} \approx T_{eo}^2$

Putting the value of T_{eH} from equation (7.6)

$$I_H/I_o = \left(\frac{P_{eH}}{P_{eo}}\right)\left[\frac{1}{1-2T_{eo}\log\left(P_{eH}/P_{eo}\right)/T_{eo}+2eV_i/K}\right]^{5/2} \exp\left[-\frac{\mathcal{E}_m}{K}\cdot\frac{2\log\left(P_{eH}/P_{eo}\right)}{T_{eo}+2eV_i/K}\right]$$

Taking log of both sides we get

$$\log\left(\frac{I_H}{I_o}\right) = \log\left(\frac{P_{eH}}{P_{eo}}\right) + \frac{5}{2}\log\left[\frac{1}{1-\frac{2T_{eo}\log\left(P_{eH}/P_{eo}\right)}{T_{eo}+2eV_i/K}}\right] - \frac{\mathcal{E}_m}{K}\cdot\frac{2\log\left(P_{eH}/P_{eo}\right)}{T_{eo}+2eV_i/K}$$

since $\left\{2T_{eo}\log\left(P_{eH}/P_{eo}\right)/T_{eo}+2eV_i/K\right\} \ll 1$ the above equation reduces to

$$\log\left(\frac{I_H}{I_o}\right) = \log\left(\frac{P_{eH}}{P_{eo}}\right) + \frac{5}{2}\cdot\frac{2T_{eo}\log\left(P_{eH}/P_{eo}\right)}{T_{eo}+2eV_i/K} - \frac{2\mathcal{E}_m\log\left(P_{eH}/P_{eo}\right)}{T_{eo}+2eV_i/K}$$

$$= \left[1+\frac{5T_{eo}}{T_{eo}+2eV_i/K} - \frac{2\mathcal{E}_m}{K\left(T_{eo}+2eV_i/K\right)}\right]\log\left(\frac{P_{eH}}{P_{eo}}\right)$$

$$= \alpha\log\left(\frac{P_{eH}}{P_{eo}}\right)$$

where $\alpha = 1 + \frac{5T_{eo}}{T_{eo}+2eV_i/K} - \frac{2\mathcal{E}_m}{K\left(T_{eo}+2eV_i/K\right)}$ ...(7.7a)

Hence $I_H/I_o = \left(\frac{P_{eH}}{P_{eo}}\right)^{\alpha} = \left\{1+C\left(H/P_{eo}\right)^2\right\}^{\alpha/2}$ ...(7.7b)

The values of the different quantities of expression (7.7) is tabulated and shown in table I for the three gases.

TABLE - I.

Gas	$\left(\frac{2eV_i}{K}\right)$ $\times 10^{-5}$ °K	V_i volts	$\mathcal{E}_m$ e.v.	$Cx10^3$	$\left(\frac{T_{e_0}}{V_i}\right)$ $\times 10^{-2}$ °K/Volts.	Radius of the tube "R" cm.	$\rho \times 10^3$	α	Pressure P_{e_0} m.m. Hg.
Mean	5.035	21.5	16	1.93	9	.9	6	.4852	10
Helium	5.74	24.5	18	.23	10	.8	4	.5172	10
Argon	3.713	15.7	10.8	2	7.5	.8	40	.5092	10

The values of the constants of second and third columns are taken from Von Engel (1956), that of fourth column from the works of Druyvesteyn and Penning (1940) and of sixth and eigth columns from Von Engel (1955) from which the values of T_{e_0} are taken utilising the universal curve of T_{e_0}/V_i against ρPR where ρ is a constant, R the radius of the tube. The values of "C" are chosen by fitting the equation (7.7b) with the experimental curve, as there are no reliable values of "C" for rare gases. The ratio of the intensity of the total radiation from a column with and without magnetic field is obtained directly by taking the ratio of the galvanometer deflections at two values of the magnetic field keeping the maintainance voltage constant. These ratio I_H/I_o is plotted against magnetic field H in figs. 30, 31, 32. In all the three gases studied (Ni, He, A) it is observed that the ratio of the intensity of the total radiation increases with the increase of the magnetic field, but at very high magnetic field the curves show a saturation effect as is observed by the fall of the rate of rise of the quantity I_H/I_o. However, the present setup could not provide us with magnetic field of very high intensity to investigate whether the curves show a maximum and then decrease. Presently, work is being carried out with a new setup

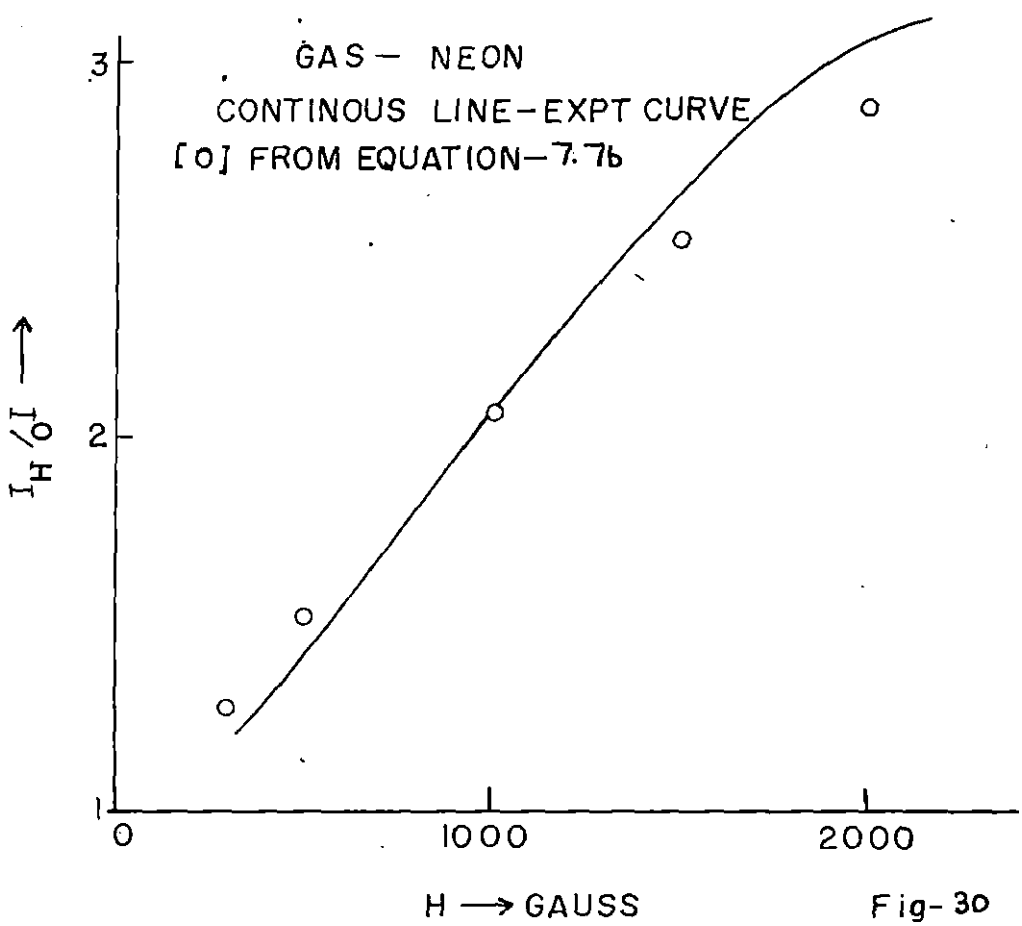

GAS — NEON
CONTINOUS LINE-EXPT CURVE
[o] FROM EQUATION-7.76
3
2
1
I_H/I_0 ⟶
0
1000
2000
H ⟶ GAUSS

Fig-30

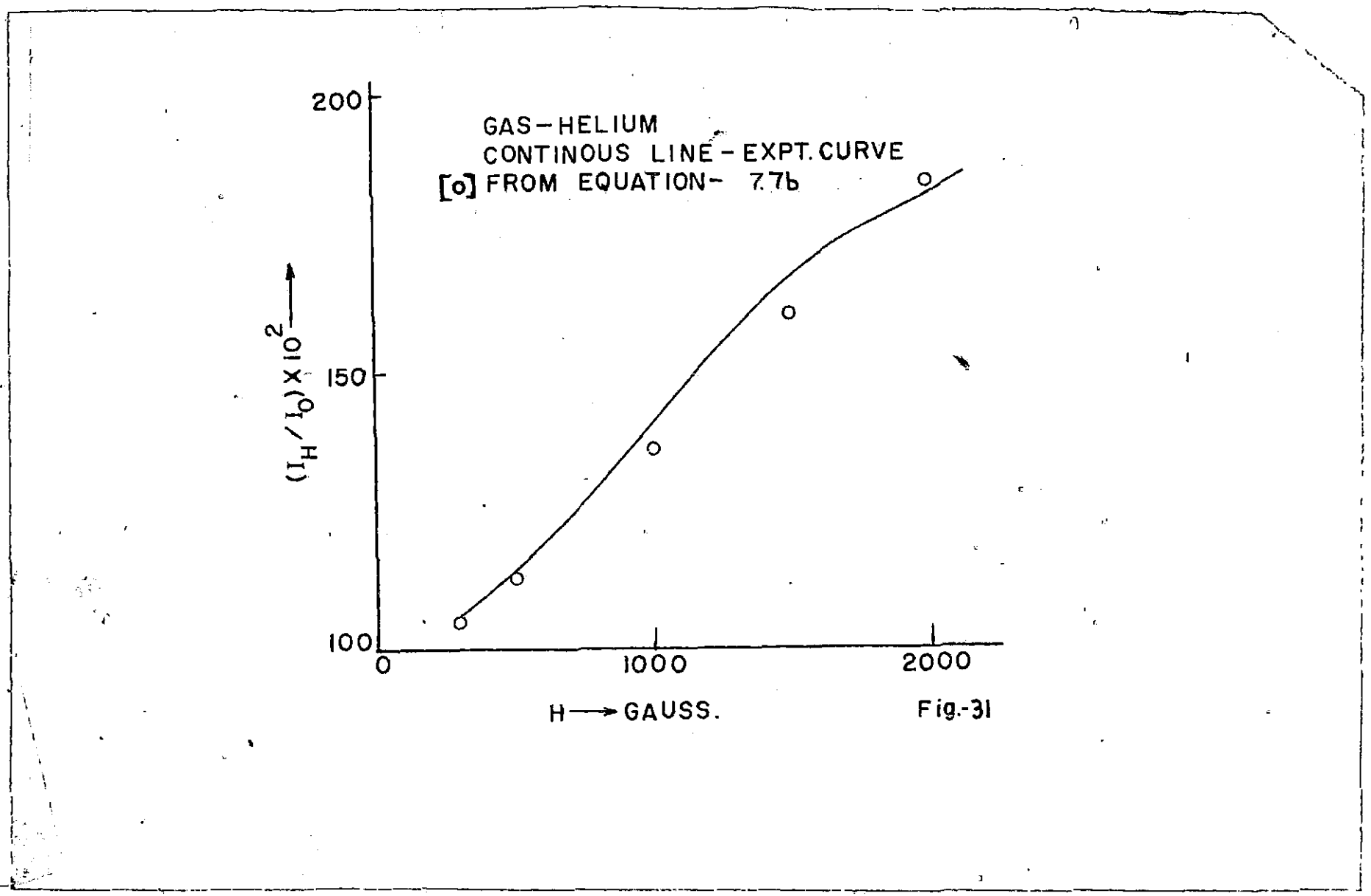

GAS – HELIUM
CONTINOUS LINE – EXPT. CURVE
[o] FROM EQUATION – 7.7b
200
150
100
0
1000
2000
$(I_H / I_0) \times 10^2$
H ⟶ GAUSS.

Fig.-31

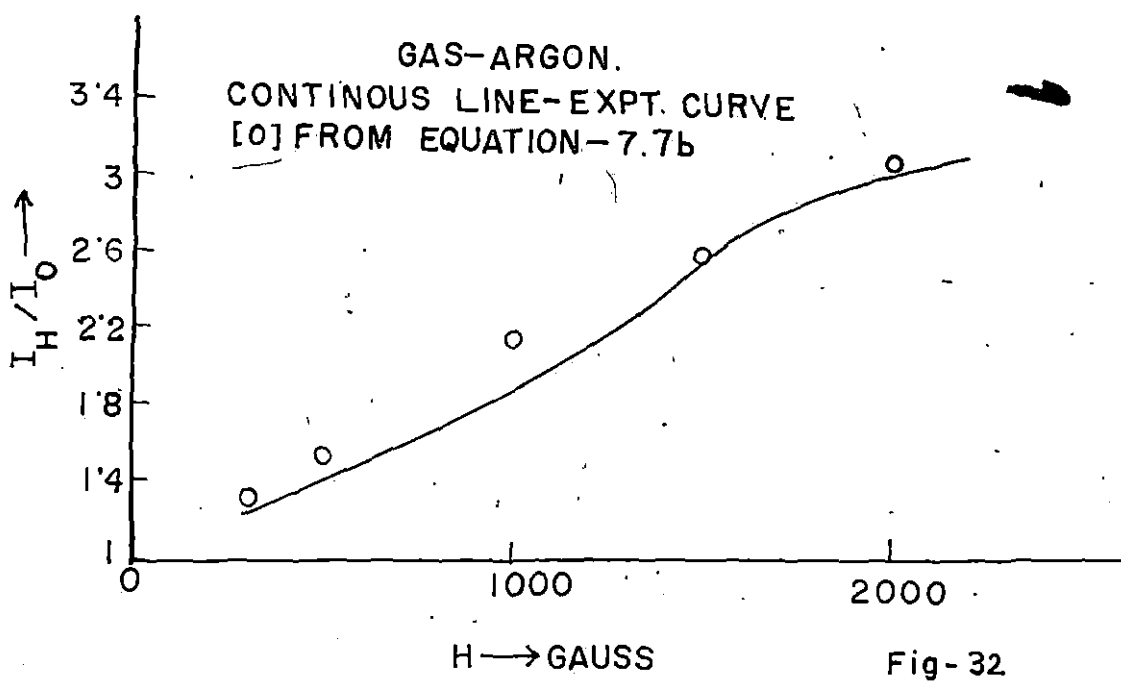

GAS–ARGON.
CONTINOUS LINE–EXPT. CURVE
[o] FROM EQUATION–7.7b
3·4
3
2·6
2·2
1·8
1·4
1
0
1000
2000
$I_H / I_0 \longrightarrow$
H ⟶ GAUSS

Fig-32

to investigate the case in a streng magnetic field.

The enhancement of the total radiation by the application of the magnetic field is always associated with the increase of the intensity of individual lines of the spectrum. The photographs of the spectra of some arbitrary regions of three gas discharge columns are shown in figs. 33, 34, 35 along with the information of the envierement at which the photographs were taken and the respective microphotometer tracing of the intensity profiles are also given. The intensity profile curves show that the different spectral lines increase at different rate when magnetic field is applied. The present microphotometer tracer beam could not penetrate through the darkest lines photographed i.e. lines of high intensity. The tracing of all the moderately intense lines that are photographed show a marked increase in the magnetic field but at different rate. However the increase of intensity of bright lines can be seen in the photographs itself. Consequently we can say that the increase of intensity of total radiation is always associated with the increase of intensity of the different lines of the spectra of the discharge column. It may be such that the total enhanced radiaton is equally distributed among the different excitation levels, and as the initial populations of the excitaion levels are different, the lines are increased in different ratio. Further analysis of the lines' radiation requires information about population and excitation mode of the individual lines without which it is not possible to arrive at some quantitative results.

Comparison of the theoretical points obtained from equation (7.6b) and the solid experimental curves in figs. 30, 31, 32 show a fair amount of agreement between theory and experiment throughout the range of observation for all gases when computed values of 'C' are used. Nonavailability of any reliable values of C led to the computation of the values of C which is open to criticism as a source of error. The value of C so obtained shows not much divergence from

GAS - HELIUM.

SOURCE - R.F. DISCHARGE TUBE.

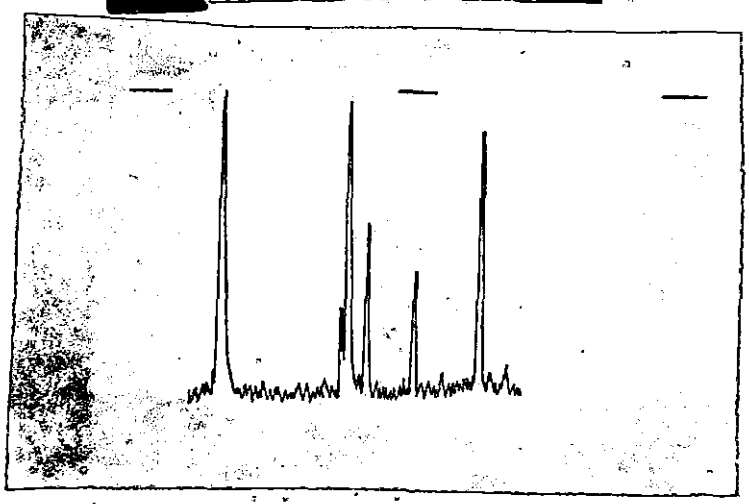
FREQUENCY OF EXCITATION = 4·1 Mc/s

MAINTAINANCE VOLTAGE = 160 Volts.(r.m.s.)

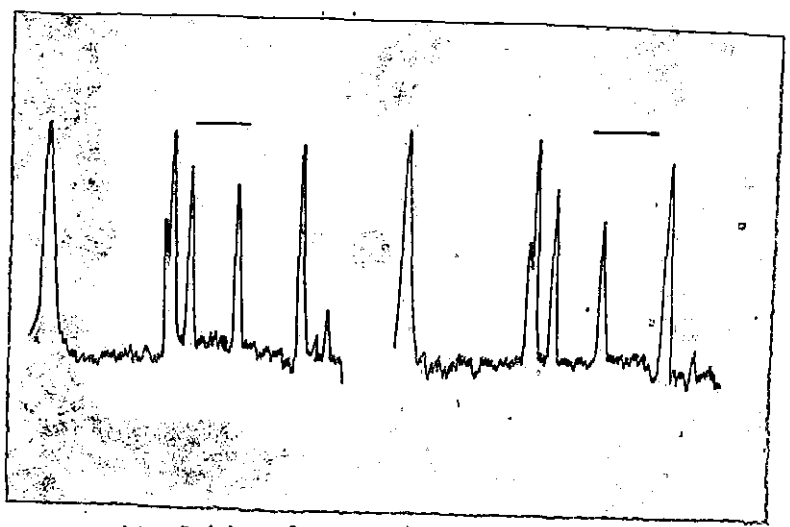
H = 0 GAUSS

H = 0·8 K. GAUSS

H = 2·1 K. GAUSS



H = 0 GAUSS



H = 2·1 K. GAUSS H = 0·8 K. GAUSS

⟹ DIRECTION OF MICROPHOTOMETER TRACER BEAM

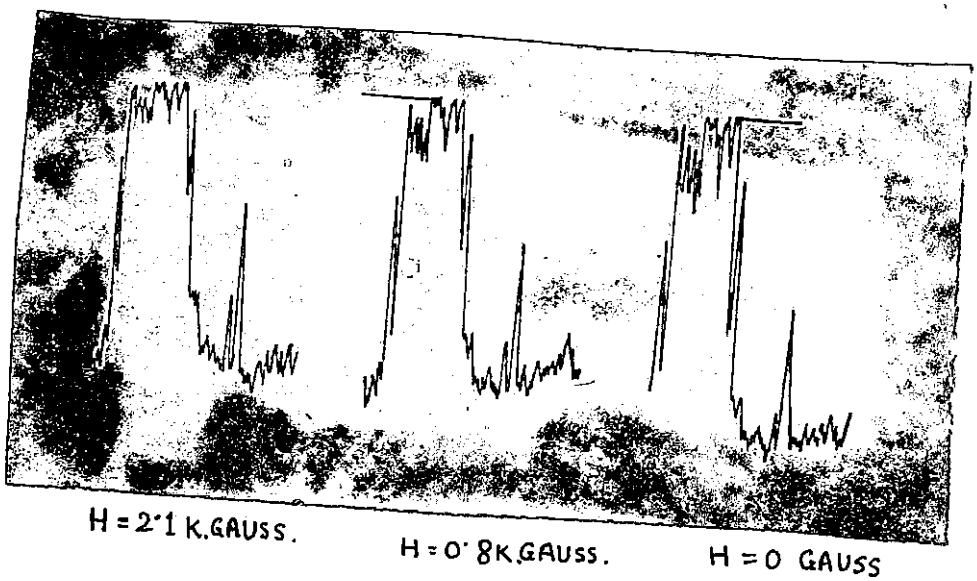
Fig. 33.

GAS - NEON

SOURCE - R.F. DISCHARGE TUBE.

FREQUENCY OF EXCITATION = 4·1 Mc/s.

MAINTAINANCE VOLTAGE = 180 Volts(r.m.s.)



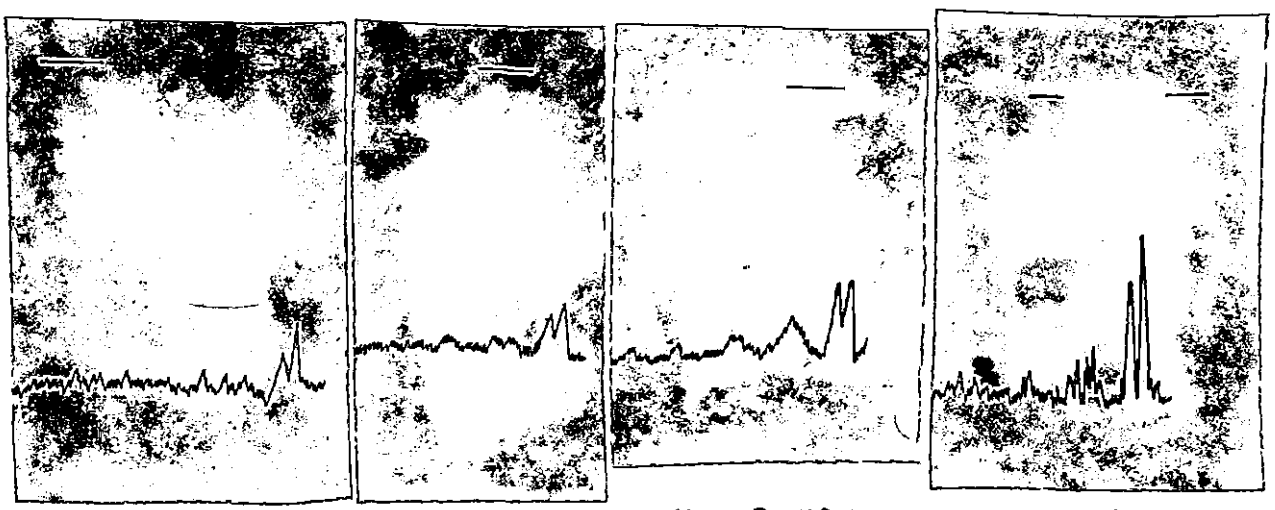
/

⟹ DIRECTION OF MICROPHOTOMETER TRACER BEAM

Fig 34.

GAS - ARGON

SOURCE - R.F. DISCHARGE TUBE.
FREQUENCY OF EXCITATION = 4·1 Mc/s.
MAINTAINANCE VOLTAGE = 140 Volts(r.m.s.)



⟶ DIRECTION OF MICROPHOTOMETER TRACER BEAM

Fig. 35.

the values used by the previous authors and also approximate values calculated from the definition of C . Moreover the assumption that C is independent of magnetic field is not valid as has been shown by Elevin and Haydon (1961), Sen and Gupta (1967) because C is a function of v_r , the random velocity which is itself a function of the magnetic field. The uncertainity in the measurements of v_r and also L , the mean free path at 1 m.m. Hg. fails to give any reliable value of C even at low magnetic field which is the main reason for the necessity of computation of its value. However, the present computed values of C lie very close to values given by Sen and Gupta (1967) for He, Ne and A, and the discrepancy between the respective values of C may be attributed to the experimental conditions which is different from that of the present work.

It may be mentioned here that in assessing the effect of magnetic field on the radiating column, only consideration is made about the influence of the magnetic field on two parameters P_{e_0} and T_{e_0} which is a known fact but possibility of having some effect on other parameters involved in the mechanism can not be ruled out.

The saturation tendency of I_H/I_0 at high magnetic field could not be explained by the present simple theory though it can explain the result upto $H/P_{e_0} = 200$ gauss/ m.m. Hg. The reason for the short-fall of the theory may be attributed to the doubtful validity of the expression for T_{e_H} at high magnetic field and acceptance of C as independent of H.

Considering the uncertainities in the computed values of C and validity of the different expressions for the variation of the parameters P_{e_0} and T_{e_0} in the range of work, the theoretical approach may be said to have a fair amount of success in explaining the present experimental results for neon, argon and helium.

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