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 gas 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 exci~~ta~~ting 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

$$\frac{E}{\omega^2}\,\frac{e}{m}\cdot(1-\cos\omega t) \leqq \lambda_e$$

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 starting 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 release~~d~~ 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 (1948) 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 reasonator 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, 1959, 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 electronic mean free path and the amplitude of oscillation, the breakdown condition is obtained from consideration of the continuity equations for electrons as

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

when "n" is the electron density, ν is the net production rate of electrons per electron and denotes the differences 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

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

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

$$\zeta = \nu / DE^2 \qquad ...(1.3)$$

where D = diffusion coefficient.

Values of ζ 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

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

α is the Townsend's first ionisation coefficient.

In a series of theoretical papers on h.f. discharge, Margenau~~s~~ 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 i~~n~~s 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 moleculer 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

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

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 a model giving cross-section of excitation as $Q(C_0, C) = fC^3/C_0^2$ 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 f is a molecular model constant with the dimension of area divided by velocity. According to this model the total cross-section $Q(C_0, C_0) = fC_0$ is proportional to the speed of colliding electrons. For high frequency field, the electron temperature is obtained as

$$KT_e = \left(1+\frac{\omega^2}{N^2\lambda^2}\right)^{-1/2}\cdot\frac{1}{(3\lambda\rho)^{1/2}}\cdot\frac{eE_0}{N\sqrt{2}}$$

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

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

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

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

$$\exp(B_0 P/2E) = A_1 PL\left(1 - \frac{E/B_0P}{C_2L/\Lambda}\right) \qquad \ldots(1.6)$$

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 Σ 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.Kovarick (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 ~~was~~ 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 asymptotic 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 x 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 x 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, $CF_3\ SF_3$. 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 Healay (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 theoretical 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 $\nu_m = 3{\cdot}5 \times 10^9 . p$ obtained from mobility measurements of Nielsen of Bradbury (1937) and the relation for the a.c. mobility, to get the value of E_e given by

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

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

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

They carried out experiments in air for two frequencies namely 48 Mc/sec and 30 Mc/sec. and the range of pressure varying from ~~0 mm~~ a few μHg 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 Verponesi (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~~er~~s 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 8.1 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, an~~d~~ 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 uncertainitics in the values of moleculer 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

$$E_0 = (E_0^a).b + \frac{L\omega(1-b)}{2\bar{K}} \qquad \ldots(1.12)$$

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 $\bar{K}$ = 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.

Bagnall 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 $150 < E/p_e < 250 \ \mathrm{V\,cm^{-1}\,torr^{-1}}$, ν has a constant value equal to $8.3 \times 10^9 \, p \ \mathrm{sec^{-1}}$ 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 disappeers.

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 fundemental 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

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

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

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

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

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

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

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 Backmark and Bengston (1941) led to a theoretical analysis by Danieelsson (1943). Assuming the zero electron emission energy Hennsberg, Orthuber and Steudel (1936) calculated the value of ϕ to be lying between 0° and 32.5°. Danielsson (1943) assumed $K = \propto$ i.e. $U_0 = 0$ 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 varify the different possibilities of source of occurence 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 $2.r = 3.d$, the dimension of the tube; d=length between electrodes, r=radius of electrodes.) 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 Guttons, 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 imposeible 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

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

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

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

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

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

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

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

$$f.d = \frac{(K-1)\,\Phi_n}{K \cos\phi}\left(e\,u/8m\right)^{1/2}$$ 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. Multipac~~k~~ting 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 affected 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. ~~Pus~~ 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

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

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

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

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 $I = I_0 \left(dt_0/dt \right)$ relates the current I_0 emitted at $x = 0$ in a time interval dt_0 to the current I arriving at a position x over a time interval dt. If $\left| dt_0/dt \right|_{\omega(t-t_0)=\pi} > 1$ electrons are emitted in an interval dt_0 around the proper starting phase ωt_0. If $\left| dt_0/dt \right|_{\omega(t-t_0)=\pi} < 1$ 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 $-90^\circ \leqslant \phi \leqslant -40^\circ$. 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 equlibrium 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 carries 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 abundences, 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 moleculer species radiates a characteristic set of frequencies which are governed by the Planck relation

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

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

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

where

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

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 x_{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.

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

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.

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

where D_ν is a photon diffusion coefficient defined as $c/3k$ where "C" is the velocity of light and k 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

$$N_j > f/h\nu$$

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 is 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 moleculer 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 inportant 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 invariebly 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. Rösler 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 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 moleculer 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. Spectral 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. Craggs 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

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

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 sideswise 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 them 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.

Duffendack 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

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

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

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

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 behaviour, 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

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

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

$$f_{ji} \cdot h \cdot \nu_{ji} \cdot \sigma_j \cdot \frac{i_0}{e} \cdot N_0 \cdot e^{-\sigma N_0 x}$$

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

$$f_{ji} \cdot h\, \nu_{ji} \cdot \frac{\sigma_j}{\sigma} \cdot \frac{I_0}{e} \left(1 - e^{-\sigma N_0 x}\right)$$

where "f" measures transition probabilities.

While the theoritical dependence conforms well with the experimental result, the total elatation cross section σ required by Duffendack and Koppius 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, 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. 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

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

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 spectacular 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 " $\dot{i}$ " flows in a homogenous electric field E which case occurs 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 electrically it 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 neighbourhod 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 doesnot 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 moleculer 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 moleculer 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 around 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 form 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 moleculer light and moleculer 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 moleculer lig~~t~~ht 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 const~~,~~ant is independent of pressure. It is evidently due to a decrease in the concentration of some participant in the process which forms molecule~~r~~s. I~~n~~t seems unlikely that this can represent the fall in the concentration of metastable atoms. The rate of decrease found here is resonable 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 Schreider (1949) proposed a similar discharge mechanism for quantitative spectrographic analysis of gas mixtures.

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

$$p \sim 10^{-3} \text{ m.m.Hg} \quad ; \quad i = 1{\cdot}5 \text{ to } 4 \text{ Amp.}$$

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. Rokhlin 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 is 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

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

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

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

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, ~~for~~ 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 then 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 theor~~i~~etically 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 i~~n~~s discussed in terms of simple ionisation recombination and excitation processes and used to e~~x~~stablish 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 monochromater 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)

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

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.

Jahn (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

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

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

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

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 oersteds and pressure of argon approximately 1×10^{-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 - Ne 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 conditions 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's 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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