CHAPTER I

A REVIEW OF

THE DISCHARGE MECHANISMS AND THE PROBE THEORIES.
SECTION A.

A REVIEW OF THE MECHANISMS FOR
LOW FREQUENCY ELECTRICAL DISCHARGES.

Hypotheses of the A.C. Discharge:

While the mechanism of the electrical discharge with metal electrodes under d.c. excitation and the relative importance of the various processes in the gas and at the electrodes are fairly well established, the low frequency silent electric discharge and the phenomena associated with it are little understood, though various attempts have been made to explain the mechanism of this type of discharge. It may be mentioned here that the mechanism of the low frequency a.c. discharge using metal electrodes is assumed by most workers to be the same as that for d.c. discharge. It has been shown by Craggs and Meek that the onset potentials for the a.c. discharge are the same as those for d.c. discharge. Similar results are reported by Watson though in some cases differences have also been reported. According to Loeb, the 60 cycle a.c. sparking potentials should not differ from the steady potential values unless corona precedes breakdown. Such gaps, after breakdown, have a tendency to go over to an arc, unless the current is limited by a resistance, internal due to the gas column or external in the circuit. Studies in these cases are generally restricted to the pre-breakdown measurements and measurement of the breakdown potentials only, the study of the current after breakdown being seldom made.
Hypotheses of the low-frequency silent electric discharge:

The mechanism for the d.c. discharge using metal electrodes has been tacitly assumed for the low frequency silent electric discharge using one or both electrodes of glass also, by a number of workers, to explain the influence of irradiation now called the Joshi effect. While it is known that the Joshi effect is observed readily over an extended range under the low frequency silent electric discharge using glass electrodes only, and is observed with difficulty under very restricted conditions using metal electrodes, no difference in the two types of discharge is suggested by these workers in the mechanisms proposed by them, viz., a change in the volume recombination due to the increased radius of the excited particles, a change in the mean free path and the number of collisions leading to a change in the mobility, a change in "some kind of recombination of ions as a result of collisions at the walls induced by the incident light", a change in the average velocity of the exciting electrons brought about by irradiation, or a change in potential gradient in the region of the anode due to the creation, on irradiation, of a stray ion sheath near the cathode. Joshi's theory of the new light effect, based on the postulates of (i) the formation of an adsorption-like boundary layer consisting of ions, electrons and excited particles, (ii) the liberation of photoelectrons from the above layer by but visible light, which, if uninterfered with, lead to the positive effect and (iii) the formation of negative ions due to the capture of these photoelectrons, leading to the negative effect, also did not originally differentiate between the l.f. silent electric
discharge and the d.c. discharge using metal electrodes, though subsequently it was suggested that the formation of the adsorption-like boundary layer would be more favoured on glass electrodes. However, no mechanism for the production of the pulses observed on the current time oscillogram, or the change in their amplitude and/or number, which constitutes the Joshi effect was suggested by these authors, though Joshi observed the sensibly instantaneous and reversible diminution in the amplitude of these pulses as early as 1944. It should be mentioned here that a hypothesis for the silent electric discharge, different from that for the d.c. discharge, based on the formation of a single bounded polarized wall complex due to the electron donating property of glass and its dissociation under light leading to the Joshi effect, has been suggested by Ahmed and Murti. However these authors also did not envisage any mechanism for pulse production or its preferential suppression.

The Hypothesis of Klemenc, Hintemberger and Hoffer:

The hypotheses for the low frequency silent electric discharge, suggesting some mechanism for the production of the pulses on the current-time oscillogram may now be considered. These hypotheses have been reviewed recently by Jatar, especially from the stand point of the Joshi effect. From an oscillographic study of the ozonizer discharge, Klemenc, Hintemberger and Hoffer showed that the high frequencies \((10^5 - 10^6 \text{c/s})\) referred to by Warburg were only unidirectional pulses. As an extension of the original picture of Warburg (vide infra [12]), these authors suggested the following mechanism.
When the potential during the a.c. cycle becomes large enough, ionization of the gas produces ions and electrons which move under the action of the applied field to the respective electrodes and deposit on them as surface charges. These surface charges give rise to a field opposite in direction to the one externally applied so that the resultant field diminishes. When the opposing field due to the surface charges is large enough the discharge stops. Now during the course of the a.c. cycle, the externally applied potential becomes zero and changes sign. At this instant the surface charges are free to get neutralized under the action of their own field. Being formed on the insulating glass surface, the neutralization takes place in discrete small sparks which constitute the observed h.f. pulses.

The Hypothesis of Deb and Ghosh:

Deb and Ghosh have extended the above mechanism further. In addition to the main sinusoidal trace due to the frequency input to the system, these authors refer to three different components: (i) groups of current pulses, in which individual pulses are separately observable at or near the peaks of the current wave, are called the l.f. pulses; (ii) groups in which the pulses are densely packed and run into one another, observable on and around the l.f. pulses, are called the h.f. pulses; and (iii) there is a set of highly damped oscillations. While the origin of the h.f. pulses is assumed to be the same as that proposed by Klemenc et al, the production of l.f. pulses is explained as follows: As above, the ions and electrons produced under discharge give rise to an opposing field which stops the
discharge. However, during the increasing part of the potential cycle, the breakdown voltage is again reached, inspite of the opposing field of the charges, causing further ionization. This increases the number of ions and electrons so that the discharge stops again. This starting and stopping of the discharge gives rise to l.f. pulses. It may be observed that the electrons due to their higher mobility reach and deposit themselves on the electrode forming a surface charge, while the positive ions mostly remain in space due to their smaller mobility and form a space charge. As a modification of the mechanism of Klemenc et al, these authors emphasize the predominant role of the electronic surface charge in controlling the ozonizer discharge.

In addition to some important points which are left unspecified, this hypothesis rests on certain assumptions which do not appear probable and leads to conclusions which are contrary to experimental results. For insulating electrodes, the secondary electron emission is known to be negligible. When the applied field is large enough, a stray electron may give an initial Townsend avalanche but its succession is not likely to be maintained. No mechanism for this has been specified. The alternative that the ionization produced in one single avalanche may give enough surface and space charges is not likely. An electron produces approximately \(2.5 \times 10^7\) ion pairs in atmospheric air at the conventional sparking potential. The estimates of Kip and Trichel for burst pulses in high pressure corona are also of the same order while the recent estimate of Harries and von Engel gives only \(10^4\) ion pairs per electron avalanche in chlorine at 5 mm Hg, while \(10^{11}\) ion
pairs are necessary to stop the discharge. No suggestion for such a copious supply of initiating electrons (Ca $10^7$) has been made. It is assumed that this copious supply of electrons is available from the surface charge of electrons deposited, it is not clear why these do not give rise to l.f. pulses when the applied field passes its peak value and begins to decline, as suggested by Harries and von Engel.\textsuperscript{25} Moreover, once the neutralization sparks have materialized, the surface charge of electrons would be neutralized and no supply of electrons for the subsequent l.f. pulses would be available.

Deb and Ghosh further assume that when the applied potential changes sign the surface and space charges neutralize in isolated sparks giving rise to h.f. pulses. Such a neutralization is possible only if the field due to the charges is high enough to cause breakdown. Moreover, such neutralization sparks are expected to give rise to oscillations and not pulses. While the authors assume that damped oscillations (depending on the circuit constants L, C and R) are produced by the recombination of polarized space charge, no reason is given why then recombination of surface charge gives rise to pulses and not oscillations. It is further evident that the h.f. pulses and the l.f. pulses referred to by these authors should appear at different positions of the current wave. However, the h.f. pulses mentioned by them appear on and above the l.f. pulses.

The mechanism for the production of the l.f. pulses proposed by these authors has been elaborated by Harries and von Engel\textsuperscript{25} and is discussed later (p.183).
The Hypothesis of Khastgir and co-workers:

Khastgir and co-workers have also assumed essentially the same mechanism of neutralization of electronic surface and ionic space charges for the production of pulses which they call 'the discharge pulses'. The other set of comparatively short pulses observed in the oscillograms are ascribed by them to the electron avalanches formed by the Townsend collision process and are termed the 'Townsend pulses'.

In subsequent communications these authors suggest that the formation of the positive ion space charge is not due to the low velocity of the positive ions as compared with that of the electrons but is essentially due to the streamer mechanism of Loeb and Meek, as applied to the a.c. silent electric discharge, 'even when the quantitative criterion for the streamer formation does not prevail'. When the applied field is large enough, Townsend's cumulative ionization gives rise to a conical column of electrons and ions. The former deposits on the inner glass wall of the anode as a surface charge. The positive ions near the momentary anode are attracted by this negative (electronic surface) charge and form a stationary layer thus forming the electrical double layer. By the time the tip of the advancing streamer reaches the (cathode) glass wall, a gap is produced between the layer of positive ions and the upper surface of the streamer and hence a discharge is not possible. However, the electrons from the cathode can cross this gap and increase the density of the surface charge. At the threshold value of the applied field the density of this surface charge is large enough to repel these incoming electrons which make the gap highly
conducting. The current pulse which flashes across from electrode to electrode and bridges up the highly conducting gap is called the 'Townsend pulse' whereas the discharge or discharges across the electrical double layer, in the manner suggested by Klemenc et al and subsequently by Deb and Ghosh, will give rise to the 'discharge pulses'.

The mechanism for the production of the discharge pulses proposed by these authors is essentially similar to that proposed by Deb and Ghosh for h.f. pulses and has already been discussed above. For the Townsend pulses as also for the formation of the double layer, these authors extend the streamer mechanism of Loeb and Meek, involving photoionization in the gas phase, to the silent electric discharge. It is of interest to mention here that even for d.c. discharges using metal electrodes, where a copious supply of electrons from the cathode is available, photoionization in the gas phase leading to the streamer mechanism is possible only under very restricted conditions especially (i) for mixtures of gases when the excitation potential of one gas is larger than the ionization potential of another e.g., in air, (ii) for large values of pd (pd > 150 mm Hg cm) so that enough gas is available for the absorption of the photons, (iii) under discharge conditions with dissimilar electrodes where the cathode mechanisms may not be active e.g. in positive point-to-plane corona, and (iv) when the gaps are over volted. From the data available, the streamer mechanism does not appear to be probable (i) even in non-heterogeneous gases particularly hydrogen, (ii) even for such low values of pd as employed by these authors for iodine (pd < 5mm Hg cm).
(iii) under sleeve excitation where both electrodes are identical and (iv) even for $V \leq V_m$ as assumed by these authors for the positive Joshi effect.

The Hypothesis of Ramaiah and co-workers:

From an oscillographic study of the silent electric discharge and the Joshi effect, Ramaiah and co-workers postulate three different types of pulses: (a) Long pulses, (b) short pulses, and (c) Longer pulses observed only for very large fields. While no mechanism for the longer pulses of type (c) is given, it is suggested that the secondary electrons to initiate the longer pulses of type (a) are liberated from the cathode by mechanisms operative at the cathode, preferably by the positive ion bombardment, whereas those for the shorter pulses of type (b) are produced in the gas phase by photoionization of the gas. The general mechanism of the silent electric discharge is assumed to be essentially similar to that of the d.c. glow discharge.

Photoionization in the gas phase, assumed by these authors to be the chief mechanism for the production of the shorter pulses has been discussed above. In pure gases, the ionizing photons for photoionization could be produced by excitation of an inner shell or by ionization and excitation. As Weissler has pointed out, these processes do not take place in hydrogen. Moreover, the photoionization of the pre-excited gas particles assumed by these authors for the positive Joshi effect does not appear probable especially (1) in such low pressure gases as iodine vapour where the positive Joshi effect
is more copious, (ii) even at potentials below \( V_m \) when the positive effect is readily observed and (iii) with irradiation even in the red (6000 - 7000 \( \AA \)).

The Hypothesis of \( \text{Jatar}^{27} \)

A hypothesis for the low frequency silent electric discharge has also been proposed from these laboratories. The hypothesis assumes that (a) an adsorbed layer of the gas is formed on the walls of the discharge tube, including the electrodes. This layer under discharge anchors electrons and ions which are not neutralized completely due to the dielectric nature of electrode. (b) The emission of electrons from the electrode and the electrode layer is inherently limited due to the dielectric nature of the electrode. This emission may be due to one or more of the secondary processes at the cathode and/or an external source of irradiation. Assuming a mechanism essentially similar to that for metal electrodes, it is suggested that when the potential applied to the tube reaches the threshold value, discharge may be initiated by a stray electron in the gas. The electrons and ions thus created deposit on the respective electrodes. These, being deposited on a dielectric like glass, are not neutralized. This surface charge of electrons deposited during a half cycle constitutes the main source of electron supply for the next half cycle. When the potential during the next half cycle now reaches the threshold value, an electron from the cathode initiates a Townsend avalanche. The other electrons situated in the vicinity of the initiating electron and forming a "patch" feed into the initial Townsend avalanche thus enhancing ionization and giving rise to a pulse. Before the
space charge due to the positive ions could develop to a value so as to choke off the discharge, the limited supply of electrons from the patch is exhausted and the current begins to diminish. Thus the fast rising part of the current pulse is due to the collection of electrons created in the discharge of a patch while the later declining part of the pulse is due to the collection of positive ions. It may be mentioned here that while the deposition of the electrons on the surface is not expected to be in patches, it is suggested that all those electrons which are liberated from a limited area on the electrode by the action of photons so that they feed into one single pulse, constitute a patch, whereas the electrons for the discharge corresponding to the second pulse are liberated by the action of positive ions. The above explanation of the pulse is admittedly analogous to that suggested by Loeb for the pulses investigated in detail by his collaborators, with this difference that while in the latter case, the quenching of the discharge is ascribed to positive ion space charge in burst pulses, or to the negative ions in Trichel pulses or to the lowering of the field* due to the circuital resistance in

* It may be mentioned here that even in the case of the non-selfquenching counters, the positive ion sheath actually quenches the discharge, the role of the serial high resistance being merely to prevent leakage of charge and thus keep the wire potential below the threshold value while the positive ions are collected on the cathodes.
non-self-quenching counters, the quenching in the former is ascribed to the supply of electrons from the cathode being exhausted.

Though the hypothesis, meant originally for insulator electrodes, has been modified to explain the results using metal electrodes, it cannot admittedly be extended to explain the results under d.c. excitation. Moreover, under conditions where a single electron may give rise to a pulse especially at higher pressures and potentials, the hypothesis needs a modification in the concept of a patch as outlined above.

The Hypothesis of Warburg:

The other detailed hypotheses of the silent electric discharge may now be considered. The low frequency silent electric discharge using a Siemelins type glass ozonizer was first investigated in detail by Warburg. By using different modes of current measurement, he found that a low frequency alternating potential applied to an ionizer creates higher frequencies (10^5-10^6 cps), which according to him, do not contribute appreciably to the ion current nor cause any appreciable chemical reaction. These higher frequencies were later shown by Klemenc et al. from oscillographic studies, to be unidirectional pulses. It is of interest to mention here that an estimate of the frequency of these pulses observed on the oscillograph has been made from the intercept of the pulses on the time base using higher time base frequencies by Jatar. His results indicate that the intercept lies in the range
Fig 1

(a) Potential distribution in an ozonizer during one alternation of charge and discharge
(b) Cross-section of ozonizer
3-40 x 10^-5 seconds corresponding to frequencies in the range 2.5 to 30 kilocycles. The results of Harries and von Engel 24 and Khastgir and Setty are essentially similar. Radiofrequencies in the megacycle range referred to by Warburg and the still higher plasma oscillations of Tonks and Langmuir are not observed on the oscillograph though the former have been investigated by Khastgir and co-workers using straight and superhet receivers and also by others.

According to Warburg, a discharge tube may be regarded as a system of three capacities C1, C2 and C3 in series; C1 and C3 are associated with the glass walls and C2 = Cg with the gas so that the total capacity C is given by \( \frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} \).

When the gas breaks down as a dielectric, Cg may be regarded as shunted by an ohmic resistance Rg, when Rg represents the inverse of the conductivity produced in the gas due to ionization by collision under the field due to V. The capacity due to the walls may be denoted by Cw, where \( \frac{1}{C} = \frac{1}{C_w} + \frac{1}{C_1} + \frac{1}{C_3} \). The potential distribution inside a discharge tube under some simplifying assumptions, given by Warburg, is shown in fig.1(a), where a, b, c and d refer to the surfaces of the glass walls.

Assuming d at zero potential throughout, if a is brought to a potential E, then a charge CE will accumulate on the electrode a if the glass behaves as a perfect insulator and C is the total electrical capacity of the system. For simplicity now, time has to be allowed for displacement currents in the dielectrics and the ion currents in the gas. The initial situation on the
application of a potential $E$ is shown in curve I. If the potential difference across bc is large enough, the gas is ionized and a current flows in the gas phase bc such that c is positively charged and b is equally negatively charged a also accumulates more charge. This process will come to an end when the potential difference across the gas space will be reduced to a certain minimum value ($M$). This new potential situation is shown in curve II. Now a is brought to zero potential. If the gas were conducting, the charge CE would leave the system so that the potential distribution will be that shown in curve III. The potential difference $V_b - V_c$ is now of opposite sign and larger in absolute value. Hence an ion current will flow in the gas till the potential is reduced to the minimum value ($M$), where further conduction will cease, even though a, b and c retain certain charges and the potential situation is shown in curve IV.

From the mathematical relations, it has further been concluded that the integral values of the ion conduction currents do not depend on the voltage ($V_b - V_c$) at which conduction commences but are a function only of the minimum value ($M$) at which they cease.

It is significant to note here that in extending this early hypothesis of Warburg, some of the important points and concepts were lost sight of by later workers. Of these, mention may be made of the following: (1) In the original picture, a square wave of potential was assumed while the subsequent workers extended it to the a.c. sine wave, without fully considering the changes that would be necessary due to the gradual decrease of the applied potential from the peak to the
zero value. In analogy with the original picture of Warburg, it was assumed that when the potential applied on the gas phase exceeded the breakdown value, a discharge would take place and the charges produced under the discharge would give rise to an opposing field to stop the discharge. It was further tacitly and erroneously assumed that the charges would stay in situ after the peak value of the applied field is passed till the applied field reaches zero value, when they would neutralize under their own field. Before the applied field reaches the zero value, it would pass through values such that the effective field in the gas (which is the algebraic sum of the applied field and the opposing field of the charges produced under the discharge) would cause the movement of the positive ion space charge towards the electronic surface charge but will be low enough so that ionization and a discharge cannot take place. Even if it is assumed that the electronic surface charge is bound to the electrode surface due to the affinity of the gas layers, there is nothing to prevent the movement of positive ions from reaching the electronic surface charge at the electrode (wall) where recombination would be facilitated. (2) While the original picture of Warburg correctly incorporated the concept of a maintenance potential (M), up to which the discharge once initiated would continue, subsequent workers, losing sight of this important concept, assumed that the discharge would continue till the field on the gas reached zero value or in other words the opposing field due to the surface charges became equal to the applied field. It should be emphasized here that even with a square wave of potential applied to the discharge tube, the breakdown, as suggested by Warburg when both a and d are at zero
potential (change from curve III to curve IV fig. 1(a)), would occur only when the original value of \(V_b - V_c\) (shown in curve I, fig. 1(a)) exceeds \(I (V_b - V_c) I + (M) I\) or when the potential applied to the gas exceeds the sum of the breakdown and the maintenance potential. To illustrate, it was found by Warburg that for one ozonizer, the maintenance potential \((M) = 1650\) volts and the breakdown potential applied to the gas \(V_b - V_c = 3880\) volts, their total being 5530 volts. Now for any value of the applied potential \(V\) to the gas such that \(5530 > V > 3880\) volts, a discharge would start in the gas and would continue till the effective field was that corresponding to 1650 volts so that the field due to the charges would be less than that corresponding to 3880 volts. Now when the potential applied to the gas falls to zero, the field in the gas would be less than that corresponding to 3880 volts or what is necessary to cause breakdown.

Mention should also be made here of the conclusion that the integral value of the ion conduction current depends only on the maintenance potential \((M)\), while it is true that once the breakdown value has been reached, the discharge would continue till the maintenance value, irrespective of the breakdown value, it should be emphasized that the total current would depend not only on the maintenance value but also on the applied potential or more correctly on the overvoltage by which the applied potential exceeds the maintenance value. A similar relation, that the current depends on the overvoltage \(V = V_m\) where \(V\) is the applied potential and \(V_m\) the threshold potential, has been suggested by Joshi. The variation of the discharge current with the applied potential in hydrogen has been investigated.
recently by Jatar from the standpoint of the space charge relations. These studies indicate that the modified Townsend Werner equation, \( i \propto V(V - V_m) \), derived originally by Townsend and independently by Werner in a study of Geiger counter action, holds for the intermediate pressure range. For a wire-in-glass cylinder type semi-ozonizer, the variation of current with the applied potential was found to be linear corresponding to the Kip's Ohm's law region. Werner's equation for the dependence of \( i \) on the potential applied has also been assumed by Talekar.

The Hypothesis of Harries and von Engel:

The mechanism proposed by Harries and von Engel for the production of the pulses is similar in certain respects to that proposed by Deb and Ghosh for the production of the l.f. pulses. These authors state that when the field in the gap is sufficiently strong, the electrons and positive ions created in the gap by Townsend's cumulative ionization in an avalanche of an initiating electron, reach the opposite walls. The ions, metastables and photons liberate secondary electrons from the cathode giving rise to a series of avalanches. The opposite charges collected on the walls lead to a lowering of the field across the discharge space. The field is also lowered because of the voltage drop across the impedances in the circuit. This lowering of the field decreases the rate of ionization and the current which approach zero value. To account for the proper phase angle between the pulses and the applied potential, it is further assumed that each pulse is associated with a discharge covering a small elementary area. In addition, each pulse is accompanied by a change of wall charge which may be partial only
Fig. 2: Time variation of the fields during an a.c. cycle for low applied potentials:
(Proposed by Harries and von Engel)

A Applied field:
   (50 V/cm - Harries & von Engel)
   (90 V/cm - Jatar.)

B Breakdown field
   (100 V/cm).

G Field in the gas:

M Maintenance field:
   (80 V/cm)

W Wall charge field:
   (Max. 50 - Harries et al
    Max. 10 - Jatar)
and need not necessarily result in a change of polarity. The corresponding potential distribution in the tube and its time variation as envisaged by these authors is shown in fig. 2, both for potentials near the threshold potential, \( V_m \), as also for higher potential.

To explain the single pulse at \( V_m \), they state that 'the field in the gas, which is equal to the sum of the external field and the wall charge field exceeds the breakdown value only once.' Also, the wall charge field 'is equal to the peak applied field.' However, as suggested by Jatar, the wall charge field, assumed by these authors, need not have such a large value. It would be more appropriate to assume that the wall charge field decreases the field in the gas, not to zero value as assumed by these authors, but only the maintenance field, which may be slightly less than the breakdown field and up to which the discharge once initiated is able to maintain itself as the field is lowered. The corresponding changes in the potential distribution and its time variation as suggested in the modification proposed by Jatar are shown in fig. 3.

Since the authors assume that the field in the gas is equal to the sum of the external field and the wall charge field, it is to be concluded that \( V_m \) the peak applied voltage to cause breakdown for the low frequency silent electric discharge, should be less than \( V_s \), the peak applied voltage to cause breakdown for the low frequency discharge using metal electrodes the same distance apart, a conclusion contrary to results.

From the size and shape of the pulse these
Fig. 3: Time variation of the fields during an a.c. cycle for high applied potentials:
(Proposed by Harries and von Engel, and modified by Jatar.):

A Applied field: (600 V/cm)
B Breakdown field: (100 V/cm)
G Field in the gas:
M Maintenance field: (60 V/cm)
W Wall charge field:
( Max. 600 - Harries et al )
( Max. 540 - Jatar )

Number of pulses: 12 - Harries & von Engel.
27 - Jatar.

Change of wall charge field per pulse:
100 - Harries & von Engel.
40 - Jatar.
Fig. 3

Time variation of the fields during one cycle per high applied potentialate (repeated by many and manipulated by Jahn)
authors calculate that the total number of electrons transferred per pulse would be of the order of $10^{11}$ whereas the total number of electrons created in a single electron avalanche is only of the order of $10^4$. Hence they conclude that 'a very large number (10^7) of avalanches seem necessary to transfer the pulse charge.' Such a large secondary emission from an insulator like glass does not appear probable. Moreover, for the highest fields applied, the momentary cathode is supposed to be covered with a very large number of positive ions to give the wall charge field of a magnitude comparable with that of the applied field. Such positive charges on adsorbed layers are known to alter the secondary emission appreciably. It is to be expected therefore that as the deposition of positive ions increases, the secondary emission would go on changing, so that the pulse amplitude would also go on changing, a conclusion contrary to the observed results.

It is significant to note here that on the above hypothesis, where the pulse is supposed to originate as a result of the starting and stopping of the discharge due to the opposing field of the wall and/or surface charges produced in the pulse, the effective field in the gas never exceeds the breakdown value and varies between the breakdown and the maintenance value irrespective of the applied field.

From the foregoing it is to be concluded that though different hypotheses have been proposed for the silent electric discharge, none of them is in complete accord with the observed results. Further work towards the elucidation of the various processes taking place seems necessary before the correct
picture of the discharge could be presented.
SECTION B.

A REVIEW OF PROBE THEORIES.

Insulated Probe:

Extensive studies of space potential and other 48 properties have been made in electrolytes and also in gas discharges by the use of probes. Similar studies are also 49 being made extensively in case of crystals. In electrolytes and crystals, the probe measurement may be regarded as a potentiometric measurement of the potential; the zero or minimum current indicating the space potential. Essentially similar considerations have been applied to measurements in gas discharges also. Earlier workers in gas discharges inserted a insulated probe in the discharge space and measured the potential corresponding to the zero current, and that potential was taken to be the space-potential. However, their results 51 were shown to be inaccurate by Langmuir due to difference in mobilities of electrons and ions.

Langmuir's Probe:

Langmuir's method essentially consists of in joining the probe with one of the electrodes, usually the anode, through a potential source and varying the potential of the probe with respect to the reference electrode so as to get a full characteristic of the probe. The simple current-potential curve obtained by Langmuir and other workers has been explained by Langmuir as follows:—
When the probe is highly negative with respect to the surrounding space, the probe is surrounded by a sheath of positive ions and the current to the probe is ionic only and space charge limited (Part BA in fig. 4). As the probe is made less negative, the electrons, because of their larger mobility can overcome the potential barrier and reach the probe. This commences at 'A' in fig. 4. As the probe potential is further increased, a point, 0, is reached at which the numbers of ions and electrons reaching the probe are equal and no current is registered in the probe circuit. This occurs when the probe is slightly negative with respect to space such that the excess energy and mobility of the electrons over the ions are counterbalanced by the opposing potential. The walls of the discharge tube or any conductor kept floating in the discharge space attain this potential, leading to equal collection of ions and electrons by ambipolar diffusion, and hence it is called the wall potential. As the probe is made further positive, the probe attains the space potential corresponding to the point 'C', at which the positive ions are just unable to reach the probe. For potentials beyond this, the current to the probe is space charge limited and electronic only. The point C, corresponding to a change in the slope of the probe current-potential characteristic thus indicates the space potential.

Assuming:

\[ A = \text{Area of the probe.} \]
\[ F = \text{Area of the space charge sheath surrounding the probe.} \]
\[ j^+ = \frac{i^+}{F} = \text{the positive ion current density at the probe.} \]
\[ j^- = \frac{i^-}{A} = \text{the electron current density at the probe.} \]
\[ e = \text{electronic charge.} \]
\( M^+ = \text{Mass of the positive carriers.} \)
\( m^- = \text{Mass of the negative carriers (electronic).} \)
\( V = \text{the potential difference between the probe and the plasma.} \)
\( d^+ = \text{thickness of the space charge sheath.} \)
\( N^+ = \text{density of the positive carriers.} \)
\( N^- = \text{density of the negative carriers.} \)
\( \bar{C}^+ = \text{rms velocity of the positive carriers.} \)
\( \bar{C}^- = \text{rms velocity of the negative carriers.} \)
\( T^+ = \text{temperature of the positive carriers.} \)
\( T^- = \text{temperature of the negative carriers.} \)
\( k = \text{Boltzmann's constant.} \)

The current density in the region BA for the plane probe is given by:

\[ j^+ = \frac{1}{9\pi} \sqrt{\frac{2e}{m^+}} \frac{V^{3/2}}{d^2} = \frac{eN^+\bar{C}^+}{Z_1} \]  \( \text{(1)} \)

For the region AC, the electron current density is given by:

\[ j^- = \frac{i^-}{A} = eN^- \sqrt{\frac{kT^-}{2\pi m^-}} \exp \left( -\frac{V_e}{kT^-} \right) \]

so that \( \log j^- = \log \left( eN^- \sqrt{\frac{kT^-}{2\pi m^-}} \right) - \frac{V_e}{kT^-} \) \( \text{(2)} \)

so that \( \log j^- \) plotted against \( V \) yields a straight line, of which the slope is given by \( \frac{V_e}{kT^-} \) \( \text{(2')} \)

Beyond C, the rate of increase of current will be slower than the previous rate as the electron current is now space charge limited and changes as \( V^{3/2} / d^2 \), instead of exponentially.
The above ideal picture is based on the following assumptions:

(i) The distribution of energy is Maxwellian.

(ii) The probe does not disturb the plasma i.e., the resistance in the probe circuit is very large so that the probe current is very small as compared to the tube current.

(iii) The accommodation coefficient of the probe is unity and there is no secondary emission from the probe and no ionization in sheath.

(iv) The mean free path is larger but not very much larger than the dimensions of the probe.

(v) The sheath is small compared with the probe.

(vi) The plasma oscillations are absent. (vide infra p. 191 ff)

With the above assumptions, the various properties of discharges are investigated as follows:

(a) The space potential $V_\phi$: - It is seen that the log $j_-$ vs $V_p$ curve will undergo an abrupt change in slope at $V = 0$ and $V_p = E$. While the change observed is not ideally sharp as theory might suggest, a fair approximation to the transition point, and thus the evaluation of $V = 0$ can be had by drawing two straight lines through the two more nearly linear segments of the curve and choosing the intersection.

(b) The wall potential; $V_w$: - The value of the wall potential $V_w$ can at once be taken as $V_w = V_p - E$ from the point where $i_+ + i_- = i_p = 0$. The magnitude of the wall potential $V_w$ can also be computed on the basis of the theoretical considerations as

$$V_w = \frac{kT_+}{2e} \log \frac{T_-}{T_+} \frac{N_+}{N_-}$$

\[ (3) \]
(c) The electron temperature, $T_-$: Assuming the Maxwellian distribution and that $T_-$ and $N_-$ are independent of $V$,

$$\log j_- = B - \frac{V e}{kT_-} \quad \text{so that} \quad \frac{d \log j_-}{dV} = -\frac{e}{kT_-}$$

so that, since $e$ and $k$ are constant $T_-$ is calculated.

The other parameters such as $N_+, N_-$, the energy distribution factor etc. can also be evaluated.

While the changes in $T_-$ and $N_-$ with $V$ may not be appreciable for steady discharges with a high rate of ionization, serious disturbances would be caused in decaying plasmas or weakly ionized plasmas due to such changes and the method cannot be applied. Also the method is generally restricted to gas pressures in the range $10^{-5}$ to $1\text{mm Hg}$, and cannot be applied to higher pressures because the mean free path should be larger than the dimensions of the probe. However, some attempts have been made to analyse the high pressure plasma by extending the Langmuir theory. A similar case is that of discharges in magnetic fields where the movements of the electrons are governed by the Larmor radius. Though the problem there also becomes highly complicated, attempts have been made to elucidate the theory of the probe in these discharges.

**Probe in low frequency electric discharges:**

Under a.c. excitation where the potential applied to the tube and consequently the potential at every point inside the discharge space are constantly changing, steady conditions giving rise to a permanent sheath formation and space charge limitation of the current may not be possible. Moreover, the
discharge under low frequency excitation using glass electrodes essentially consists of discrete pulses which do not conform to the steady state conditions obtained under d.c. discharges. As pointed out by Loeb the situation can become very complex when the discharge itself is excited by potentials varying with time, when oscillations are present and when a.c. potentials are applied to the probe. When a.c. potentials are used to excite the discharge, two different cases may be considered. (1) When the frequency of the potential applied to the probe is appreciably larger than that used for exciting the discharge, it may be assumed that during one complete cycle of the probe potential, the tube potential would undergo little change so that the ionization, energy distribution and other properties would remain sensibly steady. Even in this case, cumulative effects may be present due to differences in individual cycles especially in the rate of recombination, so that interpretation of data may be extremely difficult. (2) If the frequency of the probe potential is low as compared to that of the exciting potential, average values of the wall potential, the space potential and energy distribution corresponding to different phases of the a.c. would be measured. The densities of charges would correspond to some cumulative equilibrium value.

The situation is further complicated by the presence of electronic and ionic oscillations, the oscillations generated by the probe operating in the plasma, and the different forms of striations and other regular and irregular types of oscillations of a lower frequency (1000 cycles to 10^5 c/s), reported by a number of workers.
Case (i) \[ E_2 \leq E_{(AC)} \]

Case (ii) \[ E_2 = E_{(AC)} \]

Case (iii) \[ E_2 > E_{(AC)} \]

(a) Experimental arrangement for a-c potentiometry

(b) Wave forms of probe and space potentials.

Space potential ~

Probe potential ~
Further for any d.c. potential applied to the probe, a steady difference in potential between the probe and the space could not be envisaged so that the probe could not be at the space potential throughout the a.c. cycle. An a.c. potential is therefore applied to the probe so that at least under certain conditions, if the phase difference between the two a.c. potentials viz., the one applied to the tube and the other applied to the probe, is zero, the probe would be at the space potential throughout the a.c. cycle. Before considering this case, it is of interest to consider a simple potentiometer using a.c. potentials.

If an experiment is carried out with the arrangement shown in fig. 5. Where A B is the potentiometer wire, \( E_1 \) is the main source of a.c. EMF, \( E_2 \) the variable source of a.c. EMF, \( G \) a suitable a.c. detector and \( C \) is the probe connected to AB at \( C \), it is seen that under case (i) when the probe potential is appreciably smaller than the applied potential (or in other words, \( E_2 \) is smaller than the potential difference across AC), the detector \( G \) registers a current which is proportional to the shaded area between the two potential wave-forms. As the probe potential (or \( E_2 \)) is gradually increased, the condition shown in case (ii) is reached when the probe potential (or \( E_2 \)) is equal to the potential difference between A and C and no current is registered in \( G \). As the probe potential (or \( E_2 \)) is further increased, case (iii) is reached when the current in \( G \) again increases. Fig. 6 shows an actual curve observed when \( E_1 \) was 40 volts rms and \( E_2 \) was changed gradually from zero. It should be emphasized that in the above it is tacitly assumed that there
Probe current-potential characteristic obtained in an experiment with an ordinary potentiometer with a.c. potentials.

\[ E_1 = 40 \text{ volts} \]

\[ E_2 \text{ variable a.c. current detector} \]
is no phase difference between the two a.c. potentials \( E_1 \) and \( E_2 \).
If \( E_1 \) and \( E_2 \) are out of phase completely, no minimum in current
would be observed, the case corresponding to the d.c. potentiometer
when the positives of \( E_1 \) and \( E_2 \) are not connected together. The
phase difference in \( E_1 \) and \( E_2 \) may be anything within two extremes
of phase difference viz., zero and \( \pi/2 \). It is easy to show that
a minimum in current will only be obtained when the phase
difference between \( E_1 \) and \( E_2 \) is not greater than \( \pi/2 \).

The problem of probe measurements in electrolytes
may now be considered. This differs from the previous case in
that here there are two types of current carriers, positive ions
and negative ions, whereas there was only one carrier, electrons,
in the previous case. For simplicity again it is assumed that the
two a.c. potentials, \( E_1 \) and \( E_2 \) are in phase and the mobility of
the two types of carriers is sensibly the same. It is of interest
here to measure the currents in both the halves of the a.c. cycle
separately. The experimental arrangement may be as shown in
fig. 7, where \( E_1 \) is the main source of a.c. EMF, \( E_2 \) is the variable
source of a.c. EMF, applied to the probe \( P \), the current detector
\( G_1 \) measures the current in the positive half i.e., when the probe
is negative with respect to space and hence collects positive
ions and the other detector \( G_2 \) measures the current in the second
half when the probe collects negative ions. The same three cases
as in the potentiometer experiment may now be considered.

Case (i) When the probe potential is smaller than
the space potential:- It is seen that in the positive half, \( ABC \),
the probe is negative with respect to space and collects positive
Waveforms of Probe and Space potential

(a) Experimental arrangement for a.c. probe in Electrolyte.
ions so that a current would be registered in the detector $G_1$. In the other half CDE, the probe, being positive with respect to space, collects negative ions and a current is registered in $G_2$. Thus both the detectors $G_1$ and $G_2$ will record some current which will be proportional to* the areas ABCB' and CDED' respectively.

Case (ii) When the probe potential equals the space potential:— Since there is no difference of potential between the probe and the space surrounding and since the mobilities of the two types of carriers is the same, the probe would not collect either positive ions or negative ions and no current would be registered either in $G_1$ or $G_2$.

Case (iii) When the probe potential is larger than the space potential:— In the positive half, ABC, the probe is positive with respect to space and collects negative ions so that a current is registered in $G_2$. In the other half CDE, the probe being negative with respect to space collects positive ions so that a current will be registered in $G_1$. Thus again both the detectors $G_1$ and $G_2$ will record some current which will be proportional to* the areas ABCB' and CDED' respectively.

The following points of importance may be noted:

(a) As the probe potential is gradually increased from zero, the

* It may be mentioned here that a necessarily proportional relation is not envisaged here. The current will only be a function of the area which indicates the difference in potential between the probe and the surrounding space. The relation may be exponential or of any other type e.g. that given by the Child Langmuir relations 42,43,44 or the Townsend Werner relation.
current as registered in both G₁ and G₂ gradually diminishes, reaches a minimum value and then increases again. This minima corresponds to the value of the space potential.

(b) The current in a particular detector, G₁ or G₂, does not depend on any half (ABC or CDE) of the potential cycle but depends on the type of carriers collected by the probe i.e., the direction of the potential difference between the probe and the surrounding space.

The case of the discharge plasma may now be considered. The factors which require special mention are:

(I) There is a vast difference in the mobilities of the different types of current carriers. For simplicity again only two types of current carriers viz., electronic (negative) and ionic (positive) are considered. The complications due to the formation of negative ions as also those due to the presence of more than one type of positive ions, if any, will be considered later.

(II) There is a constant production of new ions electrons and excited atoms and molecules due to collisions of the second kind. It is of interest to mention here that in a weak electrolyte also, ions are constantly being produced due to dissociation as they are being removed. However, the two processes of production, the one in the discharge plasma and the second in weak electrolytes, are fundamentally different.

(III) Particularly at low pressures, there is sheath formation round the probe leading to space charge limitation of the current. In the case of electrolytes also, a similar accumulation of
charges leading to certain polarization effects could be avoided by the use of a.c. potentials.

The following five typical cases under ideal simplified conditions, the potential cycles for which are shown in fig. 8, may now be considered.

Case (i):- When the probe potential is appreciably smaller than the space potential:- In the positive half cycle ABC, the probe is appreciably negative with respect to space and collects positive ions. Since the potential difference between the space and the probe is appreciable, the electrons are not able to diffuse against the potential gradient. The probe thus collects only positive ions and a current (which will be a function of the area ABCB') is registered in $G_1$. In the negative half cycle CDE, the probe collects electrons and a current is registered in $G_2$. Even in this case, especially when the potential difference between the probe and the space is small e.g., corresponding to the points A, C and E on the potential cycle, there will be some diffusion of electrons. To a first approximation, this may be accounted for by regarding the base line ACE shifted upwards by a small amount.

Case (ii): When the probe potential is slightly smaller than the space potential:- Now in the positive half cycle ABC, the probe collects positive ions due to the field between the space and the probe but since field is small, the electrons are capable of diffusing to the probe. Thus, while the probe potential is still smaller than the space potential, the probe collects both positive ions and electrons and for a
particular value of this difference, the probe may collect equal numbers of positive ions and electrons. Under this condition, no current would be registered in $G_1$. On the other hand, in the negative half cycle CDE, the probe collects only electrons, positive ions not being able to diffuse against this potential gradient so that some current is still registered in $G_2$.

**Case (III):** When the probe potential is equal to the space potential:— Since there is no potential difference between the probe and the space throughout the potential cycle, the different carriers would only diffuse to the probe. Because of their larger mobility and energy, the electrons would diffuse in larger numbers and thus throughout the potential cycle the probe would collect only electrons (while some positive ions may also diffuse the net effect would be the collection of electrons only) so that the galvanometer $G_2$ registers a current. It is of interest to mention here that $G_1$ will not register any current under these circumstances. A comparison of the current in $G_2$ in the present case with that in the previous case indicates that while in the latter (previous case) the electrons were collected only in one half, in the present case electrons are collected throughout the potential cycle. However, in the previous case, the collection is due to a field due to the difference of potential between the probe and the space whereas in the present case the collection of electrons is only by diffusion. It is not unlikely that the current in the present case, being only due to diffusion, may be smaller than that in the previous case.

**Case (iv):** When the probe potential is slightly larger than the space potential:— This case is exactly
similar to the case (ii) above. In the positive half cycle ABC, the probe is positive with respect to space and collects electrons so that a current is registered in G₁. In the negative half cycle CDE, the probe is negative so that it collects positive ions. But electrons also diffuse against the potential gradient so that in the negative half the total charge collected by the probe is zero and no current is registered in G₁ or G₂.

Case (v): When the probe potential is appreciably larger than the space potential:—This is analogous to case (i). In the positive half cycle ABC, the probe is positive and collects electrons, actuating G₁. In the negative half, the probe is negative and collects positive ions giving a current in G₂.

From the simple picture of the probe given above the following conclusions may be drawn: As the probe potential is gradually increased from zero, the current registered both in G₁ as well as in G₂ gradually diminishes, reaches a minimum value and then increases again. Due to a difference in the mobility of the two types of carriers, the minimum in G₁ should be obtained over an extended range of potential and further the value of the minimum current in G₁ should be lower than that in G₂. In this latter, the minima should be more sharp and the minimum current may not be zero.

Mention should here be made of the different complicating factors and limitations which modify the above simple picture. While these will be discussed in detail later, the chief amongst these are mentioned below:
(a) The above simple picture of an a.c. single probe is based on another tacit assumption which requires special mention. For simplicity, it is assumed that the current flowing to the probe in any half cycle will be proportional to or a function of the area given by the difference between the probe and the space potential cycles. This will be true if there is uniform ionization throughout and ionization due to collision does not take place as in the case of electrolytes. For gas discharges, where this is not so and ionization due to collision takes place, accumulation of charges in different regions modifies the potential at each point. In practice this function will be very complex for the following reasons. It is expected that during the earlier part of the potential cycle, e.g. AB before the \( \text{fig} \text{ q} \), instantaneous value of the applied potential reaches the threshold value, the gas will behave as a dielectric, no ionization will be present and only capacitive current will flow. This is called the non-ionizing part of the potential cycle. Beyond the threshold value i.e. beyond B, the gas will be ionized and a discharge current will flow, for a part of the potential cycle till either the peak value, point C, or the maintenance value, point D, is reached (vide infra p. 118 ff). This is referred to as the ionizing part of the potential cycle. Beyond this the discharge will stop again and only capacitive current will flow. The conditions in the second half cycle will also be the same. In addition to the complexity of the current flowing through the tube, changes in the potential at different points in space may also be effected due to ionization and accumulation of charges during the region BC or BD. Such changes will alter the simple sinusoidal potential variation for a point
in space, fig. 10, though that for the probe will not be altered. In such cases the average of the probe potential will be equal to the average (or rms) value of the space potential though it may not be so for the different part of the potential cycle. Since the average rms values are the same the current registered by a particular galvanometer may still be minimum (or zero). On the other hand, an instrument like the cathode ray oscillograph, which registered the time delineation of the current or the potential may indicate a difference corresponding to capacitive and the ionizing part of the potential cycle (p. 118f).

Fig. 9

Non-ionizing and ionizing parts of the potential cycle.
(a) In all probe studies it is assumed that the resistance of the probe is appreciably larger than the resistance of the gas column, so that the probe does not disturb the plasma which is investigated. The use of glass electrodes for exciting the discharge renders it difficult to achieve this condition because of the very high resistance of the glass, so that the plasma is appreciably disturbed and the probe current is comparable with the tube current. Moreover, the amount of ionization and the glow in the discharges using glass electrodes are appreciably smaller than those using metal electrodes. The picture is further complicated by the fact that, especially when the probe potential is appreciably different from the space potential, the probe itself participates in the discharge and gives auxiliary discharges.

(b) Since the frequency of the potential applied to the probe is exactly the same as that used to excite the discharge and the detectors used indicate the overall current over a half cycle, the probe measures only the rms values of the space potential and other parameters.

(d) Unlike the glow discharge under smooth d.c. potentials, the low frequency a.c. discharge always gives oscillations and pulses of frequencies higher than the input. Such oscillations are known to complicate probe studies, as mentioned earlier. However, since the probe in the present case measures only the rms values, the disturbance may not be appreciable.

(c) The above simple picture would be further modified if there is a difference in phase between the potential applied to the probe and that used to excite the discharge. While it is
possible to make the major inductance and the capacity in the two circuits sensibly equal, stray inductances and capacities render an exact balance very difficult. The problem is further complicated due to the presence of a number of oscillations and pulses and due to changes in the capacity due to ionization.

While the above factors are all applicable to the method adopted, the use of air, especially at a relatively higher pressure, as employed in the present work leads to further complications.

Probes in high frequency discharges:

A number of workers have used double probe method to investigate the different properties of the high frequency discharges. The Langmuir's probe requires a reference electrode immersed in the plasma with respect to which the potential of the probe is varied to get the full characteristic. However, in a high frequency discharge such an electrode can not be found. Keeping this difficulty in view, Banerji and Ganguli developed a double probe method to be used in high frequency discharges. It is a modification over the Langmuir method. But there are certain inconsistencies in their method which have not been explained by them. They pointed out that any of the electrodes employed for exciting the high frequency discharge cannot be used as a reference point because of its alternating potential. To get rid of this difficulty they inserted in the discharge tube another reference electrode, which was in the form of a hollow iron bobbin, large compared to the probe and placed out side the main discharge space.
Beck has critically analysed the work of Banerji and Ganguli. He calls the reference electrode as the antiprobe. According to him (i) the antiprobe should not disturb the discharge and (ii) the probe current should not change the potential of the antiprobe with respect to the plasma surrounding it. This latter condition is satisfied if the product of the area of the antiprobe and the concentration of the ions and electrons is large compared to the corresponding product for the probe. While this condition was not satisfied in the arrangement adopted by Banerji and Ganguli, who placed the antiprobe outside the main discharge, an attempt was made by Beck to satisfy the above condition by placing the antiprobe in the discharge space and increasing its area to be nearly 2600 times that of the probe. Even with this arrangement, the ratio of electronic to ionic current was found to be about 25:1 whereas theoretically it should lie between 600:1 and 400:1, a value nearly attained experimentally in d.c. discharges when the anode is used as a reference point. From a comparison of d.c. and h.f. discharges under identical conditions, it is concluded by Beck that the two types of discharges were essentially the same especially in respect of their characteristics and the electron temperature and the eventual space potential variations do not influence the measurements. Moreover, the mean electric force in the glow of an h.f. discharge is independent of the current and the frequency of excitation, the electrons behaving as they would under a corresponding d.c. field. An essentially similar suggestion was put forth by Townsend.

The method of Beck is useful in determining the electron energy and the potential distribution only, under
discharges with large ion and electron densities. The method has been employed recently to investigate the electron energies in h.f. discharges by Mehta.

Kojima and Takayama have developed independently a double probe method to study the high frequency discharges. In the arrangement adopted by these workers, the probes were always kept in a neutral position inside the discharge column such that the plane of the probes is at right angles to the direction of the applied h.f. field and no current is registered for zero probe potential if the density of ionization is the same at both the probes. With d.c. potentials applied to the probe, the current potential characteristic is symmetrical and shows saturation for sufficiently large positive and negative potentials.

If the density of ionization at the two probes is not the same, an EMF, \( V_c \), is developed due to the diffusion of electrons such that the probe in the less ionized part is positive. If the electric field necessary to prevent this diffusion of electrons be \( E \),

\[
b_- NE = D_- \frac{dN}{dx} \tag{5}
\]

where \( b_- \) is the mobility, \( N \) is the density and \( D_- \) is the diffusion coefficient. Integrating the above equation

\[
V_c = - \int_{1}^{2} E \, dx = \frac{D_-}{b_-} \log \frac{N_2}{N_1} \tag{6}
\]

Hence,

\[
V_c = - \frac{KT_-}{e} \log \frac{N_2}{N_1} \tag{7}
\]

from the Einstein's relation.

If the density of positive ions is equal to that
of the electrons in the plasma, \( \frac{N_2}{N_1} \) is measured by the ratio of the saturation currents and \( V_c \) is given by the potential at zero probe current so that \( T_- \) is calculated. When the diffusion of positive ions is also taken into account, the quation may be written as

\[
V_c = - \frac{P_+ - P_-}{b_+ + b_-} \log \frac{r_i^2}{r_i^1} \tag{8}
\]

A comparison of this method with that of Johnson and Malter revealed that while the values agreed with each other for weak discharges, for strong discharges the \( T_- \) values calculated by Kojima and Takayama method were appreciably larger than those by the Johnson and Malter method. While the double probe method has been used to measure the electron temperature only, an arrangement of four probes is employed to measure the electric field. It may be mentioned here that the above method will work only when the charge density at the two probes is not different.

Double probe in ionosphere:

Reifman and Dow have described dynamic probe measurements in the ionosphere. Their experimental method consists of applying a scanning voltage between two collectors on the rocket and transmitting the resulting volt-ampere characteristic to the ground. They have obtained characteristic very much similar to those of Langmuir. However, they calculate the ion density from the saturated region of the characteristic using a method which is based upon the linearity of the \( i_p^2 \) plot as a function of \( \delta V \). They have further tried to calculate the
electron energies. But from their observations they infer that the energy distribution is more nearly Davydov than Maxwellian and a temperature can not be assigned to the electrons. However, from the apparent similarity of the characteristics obtained by them, Johnson and Malter suggest that the energy distribution should be Maxwellian only.

Floating double probe in decaying plasma:

Johnson and Malter have proposed an excellent floating double probe method for studying the different parameters of the discharges. Their method was originally meant for studying the decaying plasma, but it is such a general method that it can be applied to study any type of ionized gases. Its applicability is universal as such it has won high appreciation from different workers, inspite of its combersomeness. An essentially similar basic idea was proposed by Beck for his studies of the double probe and the technique has been used recently for the study of electron energies under h.f. discharges by Mehta. Since the method of Johnson and Malter has been employed in the present studies, it is considered in details below.

The general experimental arrangement is shown in fig.11,(1), the potential difference $V_d$ across the two probes in the probe circuit is termed the differential voltage and the associated current, $i_d$, the circuit current. The electron temperature is determined from the study of the variation of $i_d$ with $V_d$. 
(I) Basic double probe circuit.

(II) Sample potential diagrams of the double probe method.

(a) $V_d = 0$

(b) $V_d = \text{small negative voltage}$

(c) $V_d = \text{farly large negative voltage}$
Under the simplifying assumptions that (i) the two probes are equal in area, (ii) there is no contact potential difference or no difference in plasma potential from point to point, and (iii) \( V_d \) has no effect upon the ion current to the system, the potential situation at different values of \( V_d \) may be shown by fig.12(1), and the current-potential characteristic in fig.12.

For \( V_d = 0 \) (fig.12), \( i_d = 0 \) and the condition corresponds to point 0 in fig.12. For small negative value of \( V_d \), probe 1 moves closer to plasma potential and probe 2 moves further away so that the extra electrons flowing to probe 1 make up the deficiency at probe 2. The system is located at some point b in fig.12. For a larger negative value of \( V_d \), corresponding to point y in fig.12 probe 1 collects a sufficient electron current to balance the entire positive ion current flowing to the system. Further increase in the negative values of \( V_d \) can cause no further change in the current distributions, and the system moves along the flat portion \( yx \) of fig.12.

In practice, due to changes in sheath thickness, the dotted portion \( yx' \) with a slight slope is obtained. For positive values of \( V_d \), the portion \( 0zw \) or \( 0zw' \) will be obtained due to symmetry.

Denoting the saturation probe currents to probes 1 and 2 by \( i_{p1} \) and \( i_{p2} \) respectively and the electron current to probe 2 by \( i_{e2} \),

\[
|i_{e2}| = |i_d| - |i_{p2}| \tag{9}
\]

as shown in fig.12.
Voltage-current characteristic of the double probe method.
The generalized potential diagram for the system is shown in fig. 13. Where the above assumptions (i) and (ii) are accounted for. Three methods have been suggested for the determination of the electron temperature.

1. Logarithmic Plot Method: Assuming Boltzman's relation, since the net current to the system must be zero,

\[ \log \left( \frac{\varepsilon_1 e_2}{e_0} - 1 \right) = \phi V_d + \log \sigma = \log \Gamma \quad \cdots \quad (10) \]

where

\[ \phi = \frac{e}{kT} = \frac{11600}{T} \quad \cdots \quad (11) \]

\[ \Gamma = \left( \frac{\varepsilon_1 e_2}{e_0} - 1 \right) \quad \cdots \quad (12) \]

and

\[ \sigma = \left( \frac{A_1 \bar{j}_{01}}{A_2 \bar{j}_{02}} \right) e^{\phi V_d} \quad \cdots \quad (13) \]

Thus the plot of \( \log \Gamma \) against \( V_d \) should yield a straight line whose slope is a measure of the electron temperature. This is essentially similar to the equation of the Langmuir single probe except that here \( \Gamma \) is used in place of the electron current. It should be noted that the slope of the log plot is unaffected by any of the factors included in \( \sigma \), i.e., probe areas, electron random current densities, difference in plasma potential between probes and contact potentials. Since the current drain in the double probe is hundreds of times smaller than that in the single probe, it is more likely that the random current densities would not change with the probe current, a condition necessary for the unambiguous determination of the electron temperature. A comparison of equation (10) with the corresponding equation for the single probe further reveals that the constant term in the present equation is independent of the plasma potential. It is to be concluded, therefore, that the double probe method is inherently more general, and can be used
General potential diagram for the double probe method:

- $j_{o1}$: Electron space current in the plasma adjacent to probe No. 1
- $j_{o2}$: Electron space current in the plasma adjacent to probe No. 2
- $V_1$: Probe to plasma potential, probe No. 1
- $V_2$: Probe to plasma potential, probe No. 2
- $V_c$: Potential gradient and contact potential, etc.
during or after the discharge and even when the plasma potential varies with time \(^\text{61}\).

2. The Equivalent Resistance Method: The log plot is laborious process and can be avoided under some simplifying assumptions. For \( V_d = 0 \), taking the equivalent conductivity \( \frac{d\varepsilon_2}{dV_d} \) and writing \( \frac{d\varepsilon_2}{dV_d} = \frac{d\varepsilon}{dV_d} \), one gets

\[
T_\gamma = 11600 \left( \frac{G - G^2}{(1 + \sigma)^2} \left[ \sum i_p \frac{dV_d}{d\varepsilon} \right] \right)_{V_d = 0}
\]

so that

\[
T_\gamma = 11600 \left( G - G^2 \right) \left[ \sum i_p \frac{dV_d}{d\varepsilon} \right]_{V_d = 0}
\]

\[
= 11600 \left( G - G^2 \right) R_0 \sum i_p
\]

where

\[
G = \left[ \frac{i_2}{i_p} \right]_{V_d = 0} = \frac{1}{1 + \sigma}
\]

and

\[
R_0 = \left[ \frac{dV_d}{d\varepsilon} \right]_{V_d = 0}
\]

Since \( G \) can be obtained directly from the current-potential characteristic, and \( R_0 \), "the equivalent resistance" can also be evaluated, this provides a rapid and convenient method of obtaining \( T_\gamma \).

While computing \( T_\gamma \) from the above relations, it is desirable to compute the value of the probe currents for \( V_d = 0 \), at which the slope of the current-potential characteristic is measured. If the values corresponding to points \( y \) and \( z \) of fig. 12 are employed, the value of \( T_\gamma \) comes out to be larger. It has been shown that theoretically one is justified in extrapolating the sloping saturated regions \( yx' \) and \( zw' \) to the region \( yz \) and
for all practical purposes, if the characteristic is reasonably symmetrical, the sloping regions may be extended 0.8 of the way and horizontally the rest of the way.

3. The Intercept Method: If for $V_d = 0$, one is operating in the region $yx'$ or $zw'$, the equivalent resistance method cannot be used. In this case, if two points, $a$, and $b$, are taken on the linear portion between $y$ and $z$, it can be shown that

$$T = \frac{1}{600} \left[ \frac{(V_{db} - V_{da})}{\log \left\{ \frac{\Xi_{e_2}}{\Xi_{a_2}} \frac{a - 1}{b - 1} \right\}} \right]$$

where the subscripts denote the values at the corresponding points. The values of $T$ calculated from this intercept method are in excellent agreement with those obtained by other methods if $a$ and $b$ are not very close to $y$ and $z$.

Some other parameters, such as the ion density and the fraction of electrons sampled, have been evaluated for the discharges investigated by them. Some of these are discussed later (Part chapter XLI).

Some of the possible sources of error in the double probe method may now be considered. In the evaluation of the saturated ion probe currents, two possible sources of error are present. In the first place, the points $y$ and $z$ are not well marked but are uncertain. However, Johnson and Malter point out that small changes in these cause little change in the result, since a change in the $\Xi_{e_2}$ also causes a change in $\Xi_{e_2}$ in the same direction so that

$$\left[ (\Xi_{e_2} / \Xi_{e_2}) - 1 \right]$$

remains sensibly constant.
Secondly in the region $yz$ itself, small changes in the sheath thickness would cause the ion currents of each probe to vary. However, even this source of error is of little significance, as pointed out by the authors, because of the corresponding change in $i_2$ with a change in $i_p$ as suggested above. Moreover, a change in $i_p$ causes an opposite change in $i_2$ so that $\xi_p$ remains approximately constant. The extrapolation of the flat sloping regions to the region $yz$ for $V_d = 0$ has already been mentioned earlier.

The above ideal picture assumes uniform electron densities and probe plasma potentials along the probe surface. However, it is emphasized that even large non-uniformities in these introduce only small corrections in the value of $\xi$. However, it may be mentioned here that, especially when the two probes are of equal areas, the percentage of electrons sampled by them is very low. While no cases of a non-Maxwellian distribution are reported, it is well to remember that to conclude from such a small sample that the distribution is completely Maxwellian, and the concept of an electron temperature is permissible, may prove a dangerous extrapolation.

Yamamoto and Okuda on Double Probe:

An interesting contribution to the several problems connected with the floating double probe method has been made by Yamamoto and Okuda. The authors have analysed the variation of ion current due to sheath expansion and have obtained the criterion for applicability of the usual double-probe method and also the general expression for the estimation of electron
temperature. From the relation between probe characteristic and
electron energy distribution, a floating triple probe method has
been proposed. This method is useful for measuring the energy
distribution in electrodeless or h.f. discharges. By special use
of the floating double or triple probe, the measurement of
potential distribution in such a quasi-plasma as an ion sheath,
can also be obtained.

It is of interest to mention here that the use of
a combination of two probes for exploring plasma properties is
nearly as old as that of single probe. Earlier workers used
two identical probes immersed in the positive column of a
discharge and measured the potential difference developed between
them. From this measurement the potential gradient of the
positive column in the gas discharges could be computed. In such
an arrangement neither probe takes up the potential of the plasma
around it, but if the probes are close together, their errors
cancel out and the difference of potential between them is equal
to that between the points in the plasma where they are inserted.
By combining this method with that of Langmuir one can obtain the
value of the space potential, \( V \) and the gradient \( \frac{dW}{dx} \) along with
other parameters of the discharge.

Among the various methods reviewed above that of
Johnson and Walter seems applicable to all types of discharges.
The method has been fully developed by the authors and is
suitable for the quantitative study of the ionized state of the
gas. In the present work where the study of the low frequency
a.c. discharge is undertaken, the method has been employed to
measure the electron temperature, the ion density and the floating potential. However, the method does not yield any information about the potential distribution inside the discharge tube, for which the single probe method discussed earlier is used. It is expected that combination of results obtained by the two methods would give the full data regarding the parameters of this type of discharge.