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Lieutenant, United States Navy

Submitted in partial fulfillment of
the requirements for the degree of

MASTER OF SCIENCE
IN
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ABSTRACT

Observations have been made of artifically excited fluctuations in a cold-cathode, neon glow discharge over a pressure range of 3.5 to 8 mm Hg and a current range of 0.1 to 2.0 ma. Within this range of discharge operation was a region of operation free of striations. The positive column was excited with 0.2-10 μsec pulses through a small coil wound around the positive column. Photomultiplier outputs, floating probe voltage, and samples of the discharge current were monitored on an oscilloscope. There are indications that a diffusing-impulse type disturbance with a velocity on the order of 10^7 cm/sec originates at the pulsed coil, travels toward the cathode, and initiates waves of stratification in the cathodic region. A transverse magnetic field of about 1000 gauss interupts the propagation of the fast-traveling disturbance and of the wave of stratification. Data are presented showing stratification group velocity, phase velocity, wavelength, and frequency as a function of pressure and current.

ACKNOWLEDGEMENT

The author wishes to express his thanks to Dr. Norman L. Oleson for suggesting this investigation and for his guidance through the course of the investigation. Thanks are also due to Naval Postgraduate School technicians, Messrs. John Calder, Robert Moeller, Kenneth Smith, and Robert Smith.

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1.0 Introduction.

The production of a plasma in a low pressure gas discharge is receiving considerable attention today, for a discharge affords the researcher with a plasma under laboratory conditions. The ever increasing importance and growth of plasma physics is attested to by the recent interest in such fields as controlled thermo-nuclear fussion, astrophysics, upper atmosphere and deep space radio communications, and in some specialized applications of space propulsion and electromagnetic wave generation, to name a few areas where plasma processes have a fundamental importance.

However, a plasma is a complex medium since its properties involve many degrees of freedom associated with its internal space-charge and ionization processes as well as its hydrodynamic properties of a conducting fluid. Although a great deal of research and investigation has been expended, satisfactory theories and understanding of some fundamental properties of a plasma are still lacking.

One frequent feature of a plasma is the phenomena that many parameters; such as, number density, terminal current and voltage, fluctuate with amplitudes greater than that expected from simple thermal noise effects in regions where classical theories postulate steady operation. In applications where it is desired to suppress these fluctuations and, more basically, in order to gain further know-

ledge of the physics of a plasma, it is necessary to determine the mechanism of these fluctuations and to determine what processes associated with these instabilities are essential in maintaining a discharge.

At the Naval Postgraduate School, Dr. N.L. Oleson has been pursuing research and guiding investigations in oscillatory phenomena in low pressure, rare gas, d.c. glow discharges. This project is a part of this continuing investigation.

2.0 Background

2.1 Characteristics of striations

As indicated above, one of the phenomena for which a mechanism is yet to be adequately determined and for which a satisfactory theory is still to be developed are the instabilities exhibited in a glow discharge whereby oscillations are spontaneously generated. In low pressure, low current gas discharges one type of instability is characterized by striations; that is, the positive column is periodically striated by alternate bands of high and low light intensity.

Depending on such parameters as tube geometry, electrode configuration, and type of gas, these striations may be stationary or moving. Stationary or standing striations, though not exclusively, are more commonly found in discharges of molecular gases or vapors.

The moving striations are generally found in rare gas discharges at not too high pressures or currents. The striations usually travel from the anode to the cathode at velocities from 10 to 1000 meters/second, although observations have been made of striations traveling from cathode to anode and of both directions of propagation occurring simultaneously /6/, /8/. The cathode-directed striation is commonly called a positive striation, and the anode-directed striation, a negative striation. Because of their velocity, the striations are not visible to the naked eye, and the positive column appears homogenous. These velocities

are never greater than the electron drift velocity nor less than the ion drift velocity, and the negative striation has a greater velocity than the positive striation.

Under varying conditions the frequency of the striations range from hundreds of cycles per second to hundreds of kilocycles per second, but the frequency at a given ion density is never greater than the ion plasma frequency which is a few to several orders of magnitude greater than the striation frequency.

The wavelengths of the striations are associated with the tube geometry. For discharges in cylindrical tubes the wavelength is commonly a few times larger than the tube diameter but less than the length of the positive column. A wavelength equal to the length of the positive column, however, has been reported /4/.

Also, associated with the striations are significant fluctuations of discharge potential and current, electron temperature and density /34/, and longitudinal electric field intensity /39/. Thus, moving striations cannot be considered as small signal fluctuations.

Except at cut-off regions, which will be discussed below, the growth of the striations to an equilibrium or saturation value is very rapid. The positive striations achieve full amplitude before traversing the anode sheath /5/; the negative striations reach their full amplitude within a centimeter of travel /13/. For geometries where portions of the discharge are above and below cut-off,

striations reach full amplitude within a wavelength of entering the noncut-off region /3/.

Moving striations are not a universal property of discharges, however; there are regions of operation of a discharge where the positive column is homogenous and stable. Above a critical current, which is inversly proportional to the pressure of a given gas, striations are absent /32/. At currents below this critical current there may be other regions of stable operation which, for a given discharge geometry and gas, is a function only of gas pressure and discharge current. This region of stable operation on a pressure versus current plot may be a simple, continuous region when the discharge contains simple electrode configuration; however, for irregular electrode configurations the region of stable operation may become more complex /8/. Figure (4) is a pressure versus current plot showing regions of stability and instability in neon for the tube employed in this investigation.

The presence or absence of moving striations at a given position in a cylindrical discharge also depends on the local tube diameter and the distance from the cathode, and it is possible for striations to exist in a positive column of nonuniform diameter and to be isolated by stable homogenous sections of the column /3/.

When the discharge current or pressure is varied so that the discharge operation shifts from a stable to an unstable region, an hysteresis effect is apparent in the

exact point of the onset and the extinguishing of the striations. However, if the operation of the discharge is varied so that the boundary of the stable-unstable region is approached from the same direction, the conditions for which the boundary occurs is markedly reproducible when the same gas in the same tube is used.

Emeleus and Oleson /10/ summarize some empirical relations from experimental data available up to 1958. They also account for one of these relations with brief, general justifications.

2.2 Characteristics of waves of stratification

If a discharge is operated in a stable region just below a minimum current boundary, below which striations are not present, an impulsive fluctuation, whether from random noise sources or from a deliberate perturbation, produces a disturbance which propagates along the positive column. This disturbance is a packet of striations and has been termed a wave of stratification /23/. The wave of stratification moves from the cathode to the anode while the striations which make up the structure of the packet move from anode to cathode.

In the rare gases the velocity of the wave of stratification is characteristically several times the velocity of the striations and in the opposite direction. This is generally true of a mercury discharge, but there have been observations that the velocities are about equal in a mercury-argon discharge /45/. Because of the resemblance

to wave propagation in dispersive media the velocity of the wave of stratification is often called the group velocity and the velocity of the striations is called the phase velocity. Both velocities are essentially uniform throughout the positive column and increase with a decrease in pressure.

The amplitude of the wave of stratification is related to the strength of the exciting impulse--the stronger the impulse the greater the amplitude. Further, the amplitude as the waves travel along the positive column may attenuate, remain constant, or increase depending on how near the boundary of instability the discharge was before the impulse. The closer the discharge is to the boundary of the onset of striations the less is the attenuation.

Frequently the initial wave of stratification will be followed by a series of similar packets equally displaced in time and of diminishing, constant, or increasing amplitude. These secondary waves of stratification are presumably feedback phenomena whereby the packet arriving at the anode causes a new disturbance at the cathode which in turn propagates as a new wave of stratification down the column to the anode. As with the amplitude gain of the initial wave of stratification, the change of amplitude of the secondary feedback waves of stratification depend on how close the discharge is to the boundary of onset of striations.

2.3 Historical development

Standing and moving striations were initially observed

in the mid to latter part of the 19th century /40/; however, the attention of investigators was primarily directed to the standing striations until the early 1920's when Aston /2/ and Kikuchi /16/ investigated moving striations in helium and neon. Also at this time, Appleton and West /1/ found that striations are accompanied by a high level of low-frequency electromagnetic disturbance.

In the mid 1920's Langmuir and Mott-Smith /17/, /19/ developed the theory and technique of properly employing a small probing electrode in a discharge. This was a significant development, for it introduced another research tool besides the rotating mirror and some limited use of "wireless receiving devices."

When in 1929 Langmuir and Tonks /18/ published their theory of ion and electron plasma oscillations, a renewed interest in plasma instabilities and moving striations was generated. This interest was also fostered by the new field of electronics in this period which was producing more sophisticated hardware and techniques for the investigator to employ.

In this period some of the more notable contributions were by Pupp /34/, Webb and Pardue /42/, and Sloane and Minnes /37/. Pupp, working primarily in rare gases, used the Langmuir probe in conjunction with a cathode ray oscilloscope and was able to show moving striations are associated with potential fluctuations of several volts and large changes in electron temperature and concentration. Pupp /32/, using

phototubes and an oscilloscope, had also shown that there is a critical discharge current inversly proportional to pressure, above which striations were absent.

Webb and Pardue for the first time employed radio receivers and amplifiers attached to external capacitive probes in an attempt to correlate ionic oscillations and moving striations. Fox /11/, /12/ shortly after, successfully used this technique to observe the pressure dependance and the effect of a transverse magnetic field on moving striations in neon and argon.

Sloane and Minnis used time-resolved spectroscopy to investigate the dependance of moving striations on the motion of a wave of ionization and excitation.

Druyvesteyn and Penning /9/ have published a review and summary of the work done up to 1940. During the years of the Second World War and shortly after, little work on moving striations is recorded.

Around 1950 several investigations on moving striations are reported, and since then interest in striations has been high. Unfortunately, though, the reports occasionally are contradictory and present diverse views of the phenomena.

Donahue and Dieke /8/ in 1951 reported on extensive investigation of moving striations in several geometeries and several gases, but primarily in argon. Their main method of investigation was with a single photomultiplier and an oscilloscope, the sweep of which was triggered by the

terminal voltage of the discharge tube. They suggested that the striations are not an abnormal phenomenon but are actually a necessary mechanism to maintain a discharge over most ranges of pressure and current, since moving striations are a universal phenomenon in so many gases. They indicate that the anode-directed striations may result when electrons, trapped in the negative glow, produce bursts when the cathode-directed striations, being a region of high positive space charge, lower the potential barrier at the negative glow.

Oleson /20/, correlating probe and photomultiplier outputs from a striated argon discharge, showed that there is a burst of electrons before a maximum light intensity and maximum ion current near maximum light intensity.

Zaytsev /46/ reported the effect of a magnetic field diminishing moving striations in rare gases and in air. Also, having observed in neon that natural oscillations and moving striation modulate each other so that another set of moving striations at the beat frequency was created and having been able to induce moving striations with an external artificial oscillation, he concluded that striations are a result of oscillations originating in the anodic region and that the presence of moving striations is an intermediate state between a homogenous discharge and one with standing striations.

In 1952 Gordeev /14/ postulated that positive striations

are initiated by electrons changing velocity in the anode fall and that negative striations are reflections of the positive striations in the cathodic region. Thus, he associated striations with electron oscillations.

In 1955, Watanabe and Oleson /41/ mathematically established that both traveling ion density waves and electron density waves can exist in the positive column. This was a linearized derivation from diffusion equations; the ion and electron equations were coupled by coulomb interaction of space charges and the effects of ionizing collisions. The authors, however, do not implicitly associate these traveling density waves with striations.

In the same year Stewart /38/, using a photomultiplier, made a study of mercury, argon and other rare gas discharges modulated at audio frequencies. He was led to conclude that excesses of positive and negative charges, in addition to the charges whose motion accounts for the steady current, produce the positive and negative striations.

The following year Stewart /39/, using probes, made an extensive study of plasma potential and electron temperature and density as a function of time and position in striated argon. He concluded that positive striations move as a result of ionization occuring in front of a moving charge density maximum. He arrived at this conclusion from a diffusion-mobility derivation, the feature of which is that it is not a linearized development and recognizes striations

as a large signal phenomenon.

In 1957 Robertson /36/ presented a theory based on an intuitive development of microscopic processes in a plasma. It is not an entirely satisfactory theory since it has weaknesses which Robertson himself points out; however, it does postulate an instability which would give rise to moving striations in metastable dependent plasmas, and it postulates that the instability can originate in the positive column itself. Briefly, he couples three continuity equations for electrons, positive ions, and metastable atoms with approximations and assumptions for mobility and loss mechanisms. A plane wave solution is assumed, and two equations are obtained which can be used to characterize the propagation of striations.

About the same time another proposed process, substantiated by the same authors with observations on an arc discharge, was given by Yoshimoto, Sato, and Nakao /43/, /44/. They postulate that an electric field intensity wave, which is a periodic function of time and longitudinal position, is modulated by an electron density wave, which is a periodic function of time only. The result is a light intensity wave that they assert has the characteristic properties of moving and stationary striations.

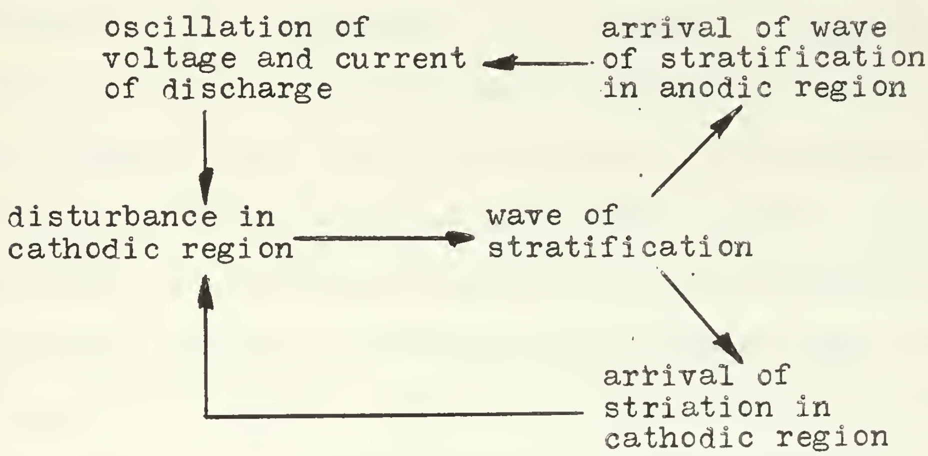
Rademacher and Wojaczek /35/, after conducting a series of experiments on discharges in cross-shaped tubes, reported their observations on striations in argon. They, however, did not indicate any observations of new phenomena.

Coulter /5/, /7/ in the late 1950's carried out investigations that indicate striations originate in the anodic regions and, in fact, were observed to originate at oscillating anode spots. It is interesting to note that in 1933 Pupp /33/, whose early work on striations was so extensive and is still useful, had inferred from some of his observations on argon a relation of anode spots to striations. Garscadden /48/ very recently has definately shown by image converter measurements on moving striations that moving striations do not require the existence of anode spots.

Cooper and Oleson /3/ in 1961 reported the results of investigations on a discharge in a tube of various diameters. They were able to obtain striations in sections of the tube isolated from the electrodes by striation free sections and to show that the presence of an oscillating anode fall region was not necessary for the existence of striations. They also noted that striations do not appear throughout the whole positive column when the critical current is reached; rather, the striation first appears at the anode end, and, as current is increased, the region of striation moves toward the cathode.

In the 1950's Pekarek /23/ began investigations into the mechanism of self-excitation of striations in neon. In order to observe the phenomenon of striation generation in time succession he applied an impulse to a discharge that

was in a stable region of operation but close to the operating point of the spontaneous emergance of striations. He observed a fast and a slow anode-traveling wave packet and developed the wave of stratification concept. He proposed that the wave of stratification is part of two possible feedback loops which allow a progressive generation of striation.



He hypothesized that the fast waves of stratification are the result of direct ionization of atoms by electrons and that the slow waves of stratification are the results of step-by-step or cumulative ionization. The results of some of his investigations with the influence of external illumination tend to support this hypothesis /27/.

Initially he pulsed the terminal current of the discharge; later he applied the pulse through an external ring electrode and observed a wave of stratification not only originating at the cathode region but also from anywhere in the positive column where the ring electrode was placed /26/.

Since his initial papers, Pekarek /24-28/ has presented several papers dealing with observations and discussions on the production and decay of striations from the view point of a transitory process with small perturbations. This transient analysis allows Pekarek to relate five independent parameters; the velocity of propagation of the wave of stratification, the velocity of the striations, the wavelength of the striations, the lifetime of the nth striations, and the ratio of amplitudes of adjacent striations; whereas, the steady state analysis only allows the determination of velocity and wavelength of the striations. He developed a linearized theory of successive production of alternate regions of positive and negative space charge in the positive column. These he associated with the striations. The wave of stratification he associated with the polarization of the plasma arising from the alternate space charges. He presents evidence that the production of moving striations are influenced by:

1) the tendency of the plasma to stratification
2) the length of the positive column
3) processes in the regions of the electrodes
4) the external circuit
5) the presence of metastable atoms

In recent years Pekarek with Krejci /29-31/ continued the development of a theory of striation processes. They focus their attention on electron temperature, ionization

rates, and the development of space charges in a plasma. Making progressively more sophisticated developments and assumptions about the interaction of these phenomena, they have proposed mechanisms for some experimental results which they and others have observed, but they have not successfully unified their whole analysis. They have developed an involved intego-differential equation that they postulate is a basic microscopic equation. They intend to develop a solution that is consistant with macroscopic and experimental observations.

In 1961 Yoshimoto and Yamashita /45/, using an impulsive perturbation method on a mercury-argon discharge, were able to observe waves of stratification even when their discharge was initially in a region of moving striations. The wave of stratification in these cases amplified as it traveled to the anode. They also noted that a transverse magnetic field in the anodic region caused the secondary feedback waves of stratification to damp away but did not change the propagation characteristics of the main wave of stratification.

In the same year Zaytsev and Vasil'yeva /47/ examined the effect of a longitudinal magnetic field on striations in helium, argon, hydrogen, and a mercury-argon mixture. They found the magnetic field retarded the formation of striations. It decreased the striation frequency and velocity and increased the wavelength. The magnetic field also decreased the velocity of the wave of stratification. The

effect on standing striations was the same. Because the effects were more pronounced at lower pressures and in gases of lighter atomic weight, the authors concluded that carrier diffusion processes play an important role in the establishment of striations.

Very recently Kenjo and Hatta /15/ report results of experiments on mercury discharges in tapered tubes. They find that striation wavelength is proportional to r^n, where r is the tube radius and n varies from 1.5 to 2.0 over their range of observations. Further, when near cutoff they were able to excite striations with an external coil at the cathode in a tube with the radius of the cathodic end smaller than the anodic end but not in a tube with the cathodic end larger in radius than the anodic end. They indicate that they may be able to explain this in terms of electron temperature and ionization phenomena.

2.4 Discussion

From the number and diversity of observations and reports on moving striations it must be assumed that moving striations are a fundamental phenomena in glow discharges. Moving striations are observed over wide ranges of operation of a discharge and under conditions that are not extreme. The literature on the subject contains many contradictory reports and discussions, often among reliable workers. It may be possible that more than one phenomena and process is involved and that researchers have not always been investigating the same phenomena. The

problem is obviously complex; the theories that are proposed only agree in a limited way with specialized situations. At present a satisfactory understanding of the basic process or processes involved has not been achieved.

3.0 Experimental equipment and procedures

3.1 Vacuum system

The vacuum system was a pyrex system designed by Dr. A.W. Cooper and constructed by Mr. J. Calder, Naval Post-graduate School glass blower. It is a flexible system, allowing changes of discharge tubes and gas bottles with minimum contamination of the rest of the system.

The system was evacuated by a Consolidated Vacuum Corporation two stage, air cooled, oil diffusion pump with a Welch Manufacturing Company mechanical fore pump. Octoil-S diffusion pump oil was used in the diffusion pump. The pumps in conjunction with two liquid nitrogen traps were capable of bringing the system into the 10^{-7} millimeters of mercury range.

An all-metal Granville-Phillips valve was used to isolate the discharge tube from the rest of the vacuum system; all other valves in the system were vacuum type, glass stopcocks lubricated with Apiezon Type-N grease.

The discharge tube had been baked for several hours at 400° Centigrade and the electrodes decontaminated by resistive heating of the filaments and an induction heater. The rest of the system down to the diffusion pump was baked with heating tapes at about 300° Centigrade.

Vacuum pressures were measured by means of a Consolidated Electro-dynamics Corporation ionization gage, type GIC-110, with a VG1A sensing tube. Gas pressures were

measured by means of a standard U-shaped manometer filled with Octoil-S diffusion pump oil. The manometer was read with a cathetometer.

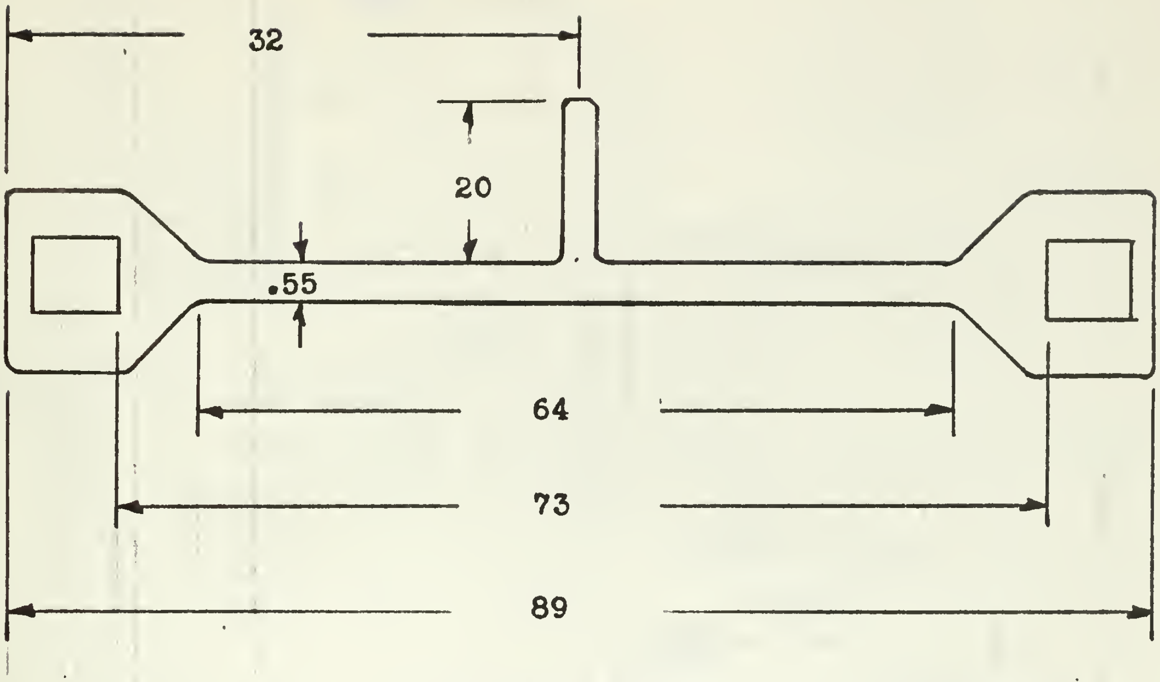
3.2 Discharge tube and electrodes

Figure (1) gives diagrams of the discharge tube and the electrode configuration. The tube was constructed in the Postgraduate School glass blower's shop by Mr. Calder. The probe at the middle of the tube was capable of being moved radially to the discharge; however, in this investigation it was always positioned at the axial centerline of the discharge.

The electrodes were constructed by Mr. R. Moeller, Physics Department machinist. These electrodes were basically patterned after those designed by Pupp /33/ who used them to eliminate positive anode fall and associated oscillations. In the assembly itself, 10 mil tantalum was used for the open-ended cylindrical sleeve while 10 mil annealed tungsten was used in the filament. Either electrode could be utilized as anode or cathode. The discharge was operated with a cold cathode.

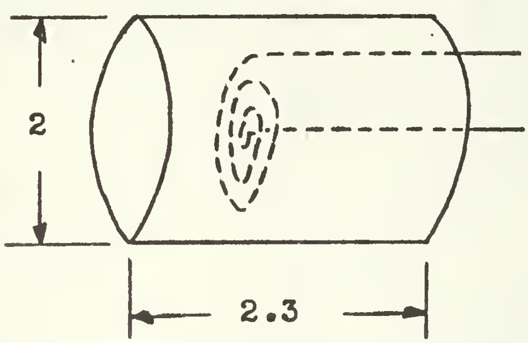
3.3 D.C. circuitry

Because of the current-voltage characteristics of the small radius tube and the low currents desired, a high voltage power supply, along with high series resistance, was used in the d.c. circuitry. A schematic of the experimental circuitry is given in Figure (2). The power



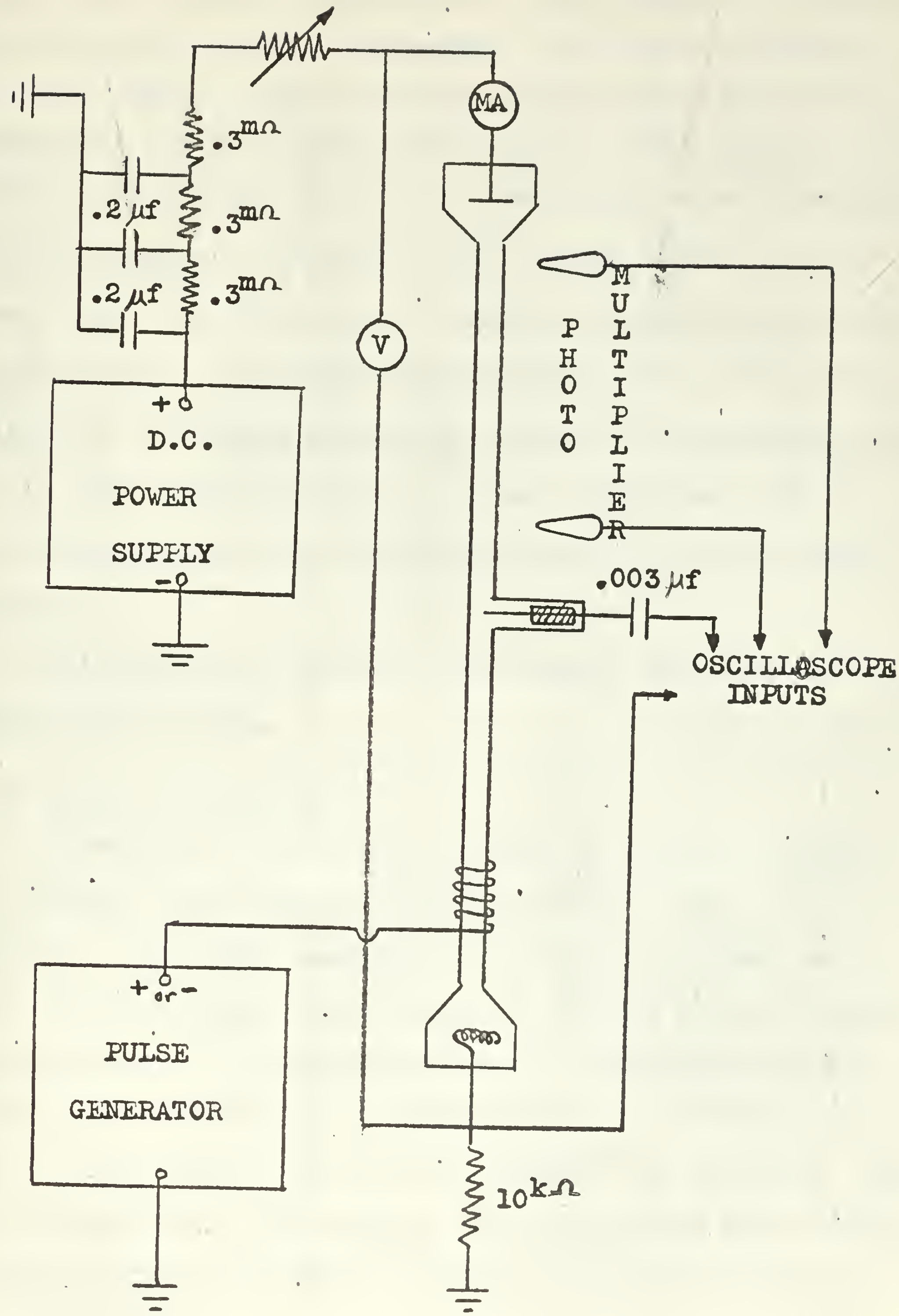
DISCHARGE TUBE

(All dimensions in centimeters)



ELECTRODE CONFIGURATION

Figure 1



CIRCUIT SCHEMATIC

Figure 2

supply was a locally constructed 10 milliampere, 10 kilovolt variable supply. Since the supply was found to have an excessive ripple, three filter sections consisting of 0.3 megohms and 0.2 microfarads were added. The variable resistance was several one and two watt electronic component resistors mounted on General Radio double banana plugs. These plugs were "stacked" in suitable series and parallel configurations. Although any resistance value could be obtained, 1 to 6 megohms was the range of resistance chiefly used in this investigation. A decade resistance box in series was available for fine adjustment of the discharge current.

A 10 kilohm resistor was inserted at the cathode to sample tube current.

3.4 Impulse circuitry

The impulse to initiate the wave of stratification was obtained from a Hewlett Packard, model 212A, pulse generator. The pulse amplitude was variable from 0-70 volts, and the pulse length could be varied from a fraction of a microsecond to 10 microseconds. Although any pulse repetition frequency up to 5000 cycles per second was possible with either the built-in trigger or an external trigger, a repetition frequency of about 50 cycles per second was most commonly employed. This insured that all the observable effects, such as, feedback echos, had completely died away before another pulse was applied. If the repe-

tition frequency was too high, the waves of stratification would interact and be modulated by echoes of a preceding wave of stratification. When such a modulated wave was traced on the oscilloscope, it frequently had the same gross characteristics of, and could be mistaken for, an unmodulated wave of stratification and its echoes.

The pulse was applied to one lead of a coil wound around the discharge tube. The other end of the coil was open-ended. Either a positive or negative pulse with respect to ground could be applied to the coil. The initial intention was to apply the pulse to a single turn electrode in order to achieve a localized excitation in the positive column. However, a single turn, properly loaded to match the output impedence of the pulse generator, failed to produce any perceptible impulse in the discharge. Thus, several configurations of coils were tried in order to obtain the strongest coupling of the pulse to the plasma--various terminating impedances, single turn loops, rings, open-ended and closed-loop coils. The most satisfactory arrangement was found to be an open-ended coil of about 200 turns of #48 wire in two layers. The coil was 5.5 centimeters long. A narrow coil of the same number of turns but wound into several layers of five to six turns each did not give as good a coupling as the coil of longer extent. Although more turns and/or a coil of longer extent were found to increase the coupling, any increases in the coupling were not significantly larger than that achieved with the

given coil. The pulse to the coil could be displayed on the oscilloscope.

Actually two coils were wound on the tube--one on either side of the probe. Both coils could be moved from the electrode region to the probe. Thus, by connecting one or the other coil to the pulse generator, a coil could be positioned at any point along the positive column.

3.5 Measuring equipment

The discharge parameters of interest were measured with a milliameter, a voltmeter, an oscilloscope, and photomultipliers. Steady state discharge current was measured on a Weston model 622 milliameter which had the feature of not interrupting the electrical circuit when the scales were changed. The discharge potential was measured with an RCA type WV-98B vacuum tube voltmeter.

The principal measuring device was a Tektronix dual-beam oscilloscope, model 551A, with type CA preamplifiers. With this combination four inputs could be simultaneously observed on the scope face. Occasionally some of the inputs under certain operating conditions of the discharge required amplification before being applied to the oscilloscope. This was accomplished with Scott decade amplifiers, type 140-A. In these cases it was ascertained that the decade amplifier was not distorting the signal.

Since the d.c. potential level of the probe exceeded the input level of the oscilloscope, a .003 microfarad

condenser was inserted in the probe circuit. The time response of this circuit input to the oscilloscope was checked by applying a pulse from the pulse generator directly to this input with the discharge extinguished. Only slight rounding of the edges of the pulse were observed on the oscilloscope sweep. There was negligable rounding of edges when this check was made with the other circuit inputs to the oscilloscope.

The photomultipliers were RCA 1P21 tubes. The power supply for these tubes was a locally constructed supply especially designed for photomultiplier applications. One photomultiplier was mounted on a track calibrated with a centimeter scale. This was useful in some of the measurements where slow and small movements along the discharge were needed.

3.6 Procedure for establishing waves of stratification

The operating point of a discharge was placed in the striation-free region but close to the boundary of the onset of stable striations. Pulses were applied to the exciting coil. The discharge current was slowly increased until the oscilloscope traces of probe current, tube current, and photomultiplier output indicated a maximum wave of stratification signal but did not indicate that the spontaneous onset of striations had occured.

3.7 Phase wavelength measurements

The photomultiplier mounted on the scaled track was used to measure the wavelength of the internal structure of the waves of stratification. The output of the photomultiplier was displayed on the oscilloscope, the sweep of which was triggered by a synchronizing signal from the pulse generator. As the photomultiplier was moved parallel to the discharge, the waves which made up the internal structure of the stratification waves went in and out of phase with reference to a given point on the oscilloscope face. The distance that the photomultiplier moved when the oscilloscope trace went through one phase change was the wavelength. Since the wavelength was small, the photomultiplier was moved through several wavelengths, and the distance moved was divided by the appropriate multiple.

3.8 Frequency measurements

The frequency of the internal structure of the wave of stratification was obtained directly from the oscilloscope traces of the probe current, photomultiplier output, and discharge current.

3.9 Velocity measurements

The velocity of the internal structure of the waves of stratification was determined from the wavelength and frequency data by the simple relation:

$$v_p = \lambda_p \nu_p$$

where λ_p is the wavelength of the phase wave and ν_p its frequency.

The velocity of the wave of stratification was measured with the probe current and photomultiplier outputs traced on the oscilloscope. The photomultipliers were positioned known distances from the probe. The velocity was calculated from the time displacement of the waves of any two traces and the longitudinal distances between the two appropriate detecting devices. Since the probe could not be moved along the length of the discharge, the two movable photomultipliers were used to measure velocity between various longitudinal positions on the positive column.

As seen in Figure (7) the envelope of the wave of stratification is somewhat gaussian in shape. Throughout the investigation photographs were taken of the oscilloscope traces. On the photographs the envelopes were estimated, and the distance between the maxima of these envelopes was measured with dividers. This distance was the time displacement.

3.10 Measurements of effects of magnetic fields

Transverse magnetic fields were obtained with a small Alnico horseshoe magnet and two surplus magnetron magnets. These magnets had fields of about 900, 1300, and 2000 gauss at their pole faces. When any of the magnets were used, they were positioned at the tube so as to produce a maxi-

mum effect as indicated by the various traces on the oscilloscope. This maximum effect occured when the magnets were positioned so that the discharge was between the pole faces and one of the pole faces was next to the discharge tube. Thus, the discharge was subjected to the maximum flux of the magnet.

The longitudinal field was produced by four narrow coils mounted so that the discharge was along the axes of the coils. One coil was placed adjacent to the probe; one, at an electrode; and the other two, equally spaced between these. Thus, only one half of the positive column was within the physical extent of the coils. The coils had a mean radius of 12 centimeters and consisted of 160 turns of #10 wire. With a 15 ampere supply, a magnetic field of 350 gauss could be achieved at the discharge tube.

4.0 Observations

4.1 Background

During 1962-63 Panzer and White /22/ had investigated the low pressure, low current range of neon glow discharges in which they found regions of operation free of striations. It was decided to use one of their discharge tubes and to employ an impulsive technique described by Pekarek /26/ in order to investigate the transitional region between a steady non-striated discharge and a discharge with fully developed moving striations.

The range of operation investigated was from 3.5 millimeters of mercury to 8 millimeters of mercury and from 0.15 milliampere to 2 milliamperes. The most interesting region was the lower pressures and higher currents, for at these pressures the discharge could be placed in a stable-striation region, striation-free region, or unstable-striation region, as seen in Figure (4). Also some of the parameters measured in this region varied widely.

Photomultiplier and rotating mirror observations were to be used in the investigations. Because the waves of stratification had very low light intensity, the waves of stratification were not discernible in the rotating mirror. Time exposure photography was not successful probably because the mirror rotation and the pulse repetition rate could not be synchronized, and thus successive revolutions of the mirror smeared any low-intensity phenomena. Frequently the wave of stratification signal from the photo-

multiplier was nearly masked in the noise, because of the low light intensity of the wave of stratification.

Since the tube had been constructed with a probe, the probe was placed at the axial centerline of the discharge. The probe was allowed to float electrically, and its potential was monitored throughout the course of the investigation.

Although it was hoped that the impulsive technique could be used to investigate the transition across the boundary of the stable-striation region and the striation-free region and the boundary of the unstable-striation region and the striation-free region, no effect was noted in the latter case. Oscilloscope traces of the outputs from the 10 kilohm sampling resistor, photomultiplier, and probe did not indicate any changes in the discharge when the operating point of the discharge was placed on either side of the unstable-striation and striation-free boundary while both positive and negative pulses were applied. Thus the boundary between the stable-striation region and striation-free region was principally investigated.

4.2 Discharge tube characteristics

Figure (3) is a graph of discharge current versus discharge voltage for pressures at about the middle and near the limits of the range of pressures observed in this investigation. There is a general decrease in current with an increase in voltage. The lower pressures have

CURRENT vs VOLTAGE

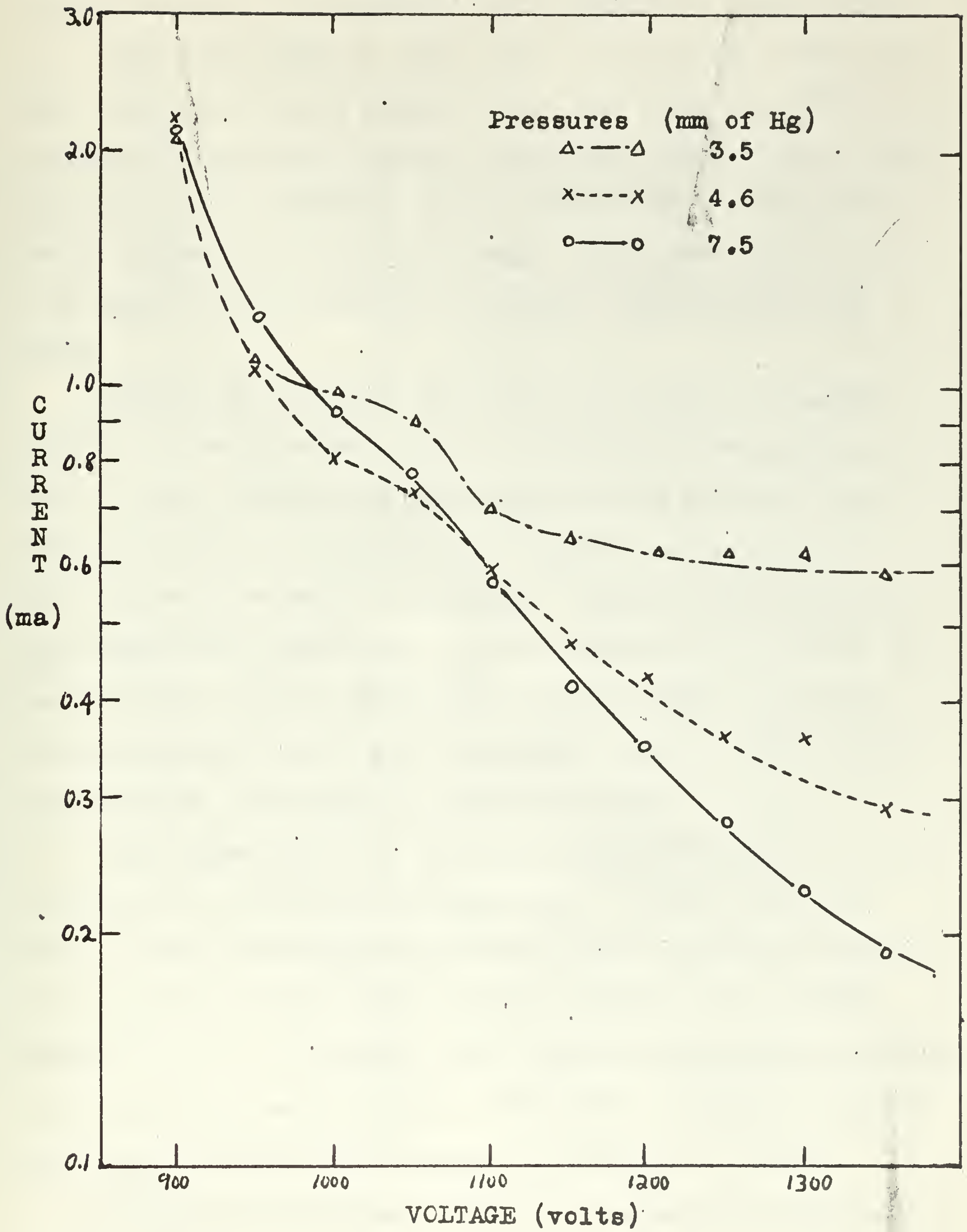


Figure 3

higher currents in the upper voltage range, and at the lower pressures the currents tend toward the same values.

The slight hump at about 1050 volts occurs close to the transition from striation-free operation to stable-striation operation; however, the small hump in the 7.5 mm Hg curve has no relation to the transition at that pressure. Except for the small humps, the curves agree with the values found by Panzer and White /22/ for the same tube.

Figure (4) presents the pressure-current operating points of the discharge for the striation-free region. This is very nearly the same region found by Panzer and White in their investigations. Above 5 mm of Hg pressure there is excellent agreement. Below 5 mm of Hg the striation-free region has the same shape but was found to be a little larger. The striation-free region could be extended down to 3.5 mm of Hg rather than the lower limit of 4.0 mm Hg indicated by Panzer and White.

One explanation for the slight deviation may be attributed to electrode configuration. In the very early part of this investigation, one of the cylindrical sleeves of an electrode was inadvertantly tilted by an external magnetic field. Although the sleeve was presumably restored to its initial position, the electrode configuration may have been sufficiently altered to produce the change.

In light of this same argument, another observation

CURRENT vs PRESSURE

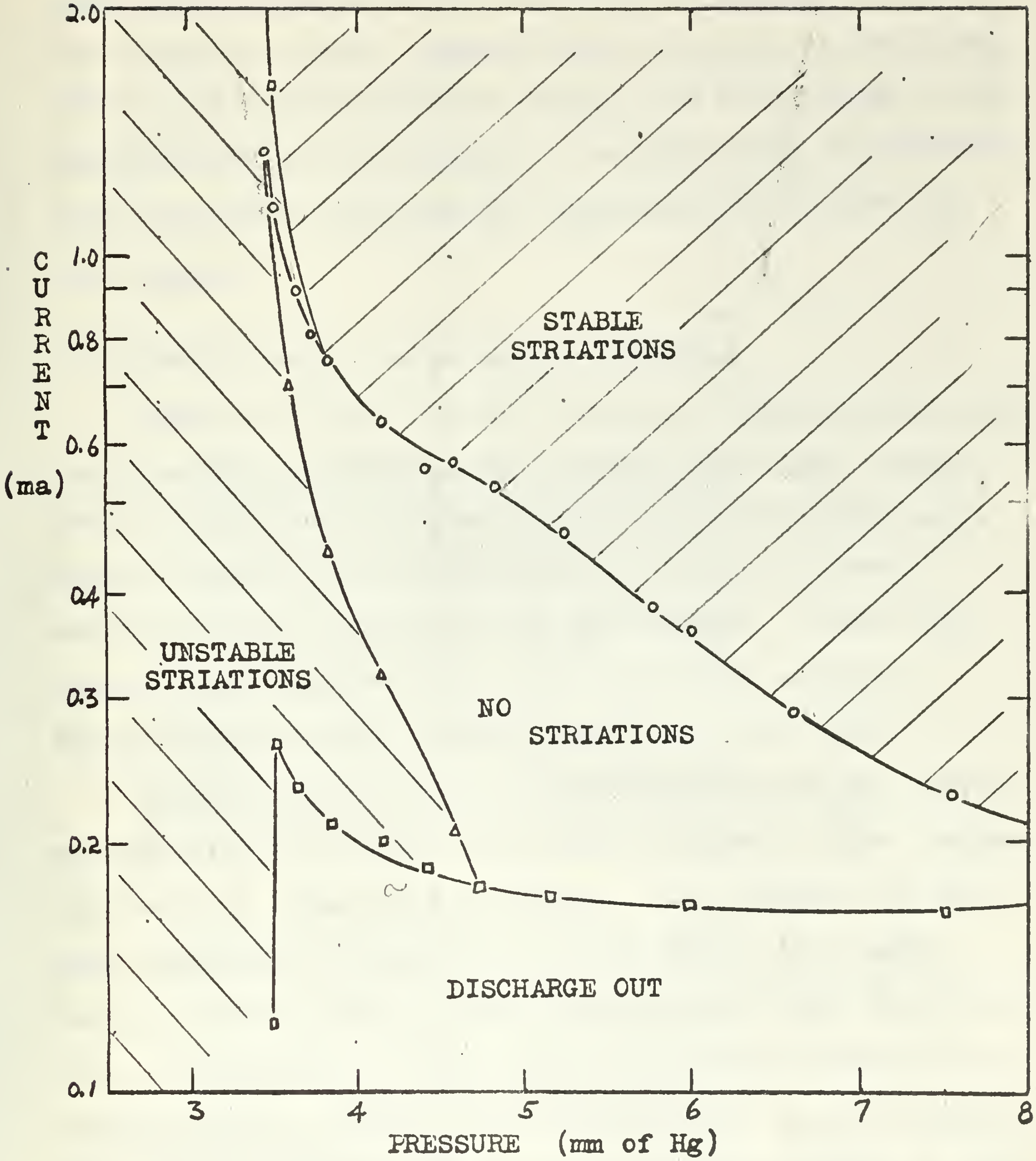


Figure 4

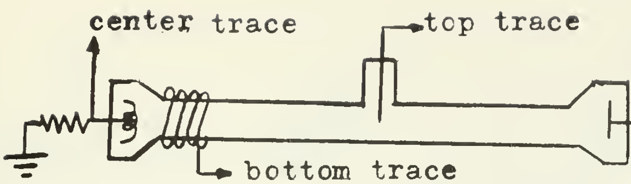
was noted. Although the discharge tube and the electrodes were generally symmetrical and either electrode could be the cathode or anode, sufficient differences in the boundaries of the striation-free region were noted after a few observations with both electrode arrangements to determine which electrode the previous investigators had used as the cathode.

4.3 Oscilloscope photographs of impulse

Figures (5) and (6) are a series of photographs of the oscilloscope sweeps of probe current, discharge current, and a 10 microsecond pulse applied to the exciting coil. Positive pulses are presented in the top photographs; negative pulses, in the bottom photographs. Figure (5) shows traces when the coil is close to the cathode; Figure (6), when the coil is adjacent to the probe.

The photographs indicate that the form of the traces are associated with the direction of change of the leading and trailing edges of the impulse. For instance, if the edge represents a transition from a higher to a lower value, the wave form of the probe current after the transition is the same for that type of transition whether the transition is a leading or a trailing edge of the impulse. The discharge appears to react to the differential of the impulse.

When the differential is positive, the probe indicates a slight ion current; the tube current shows a positive

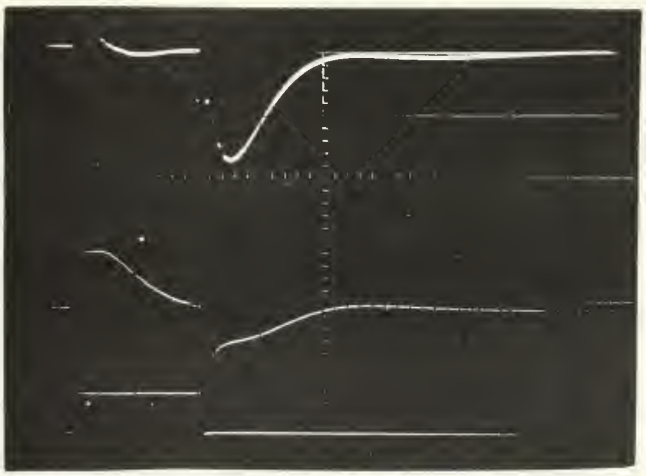


Pressure:
4.8 mm of Hg

Discharge current:
.53 ma

(a) Physical Arrangement

Time base: 5 usec/cm

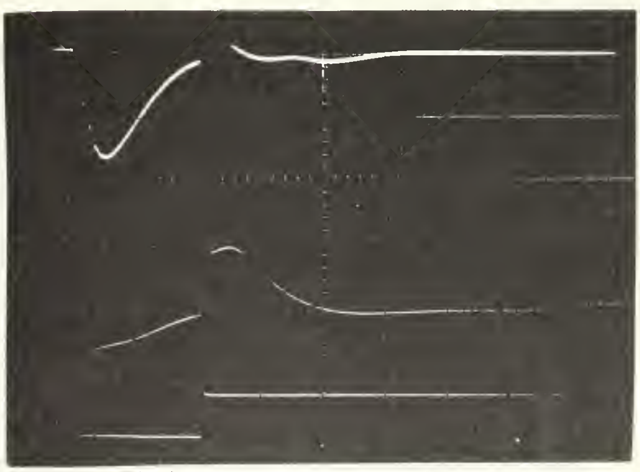


.02 ma/cm

.2 ma/cm

100 volts/cm

(b) Positive Pulse



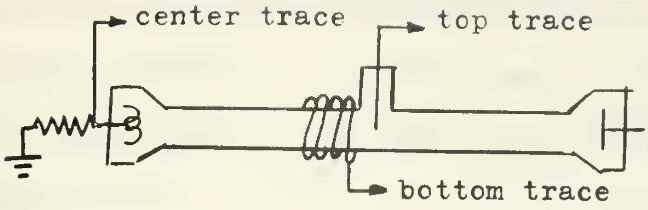
.02 ma/cm

.2 ma/cm

100 volts/cm

(c) Negative Pulse

Figure 5 - Discharge response with exciting coil close to the cathode.

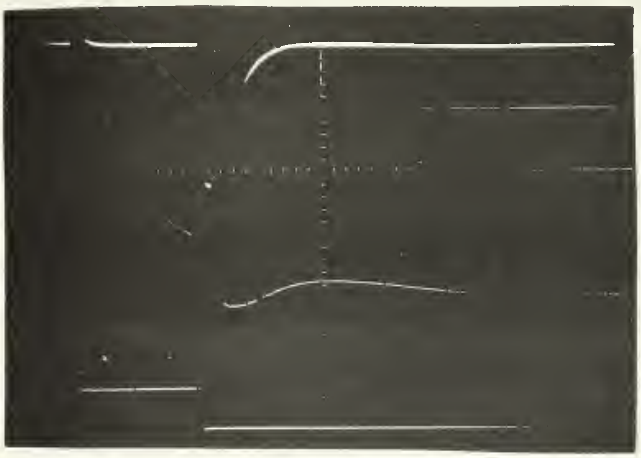


Pressure: 4.8 mm of Hg

Discharge current: .53 ma

(a) Physical arrangement

Time base: 5 usec/cm

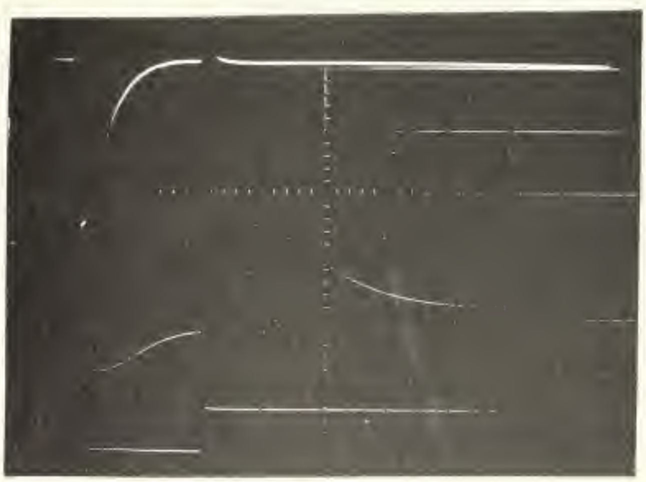


.1 ma /cm

.05 ma/cm

100 volts/cm

(b) Positive Pulse



.1 ma/cm

.05 ma/cm

100 volts/cm

(c) Negative Pulse

Figure 6 - Discharge response with exciting coil close to the probe.

excursion of as much as 50% of the steady state d.c. current. When the differential is negative, the probe indicates an electron current of at least several percent of the steady state d.c. current, and the tube current has a negative excursion of slightly less amplitude than the positive excursion.

The small ion current in the probe is understandable from the low ion current saturation characteristics of a probe.

The amplitudes of the excursions of tube and probe currents could be changed by varying the pulse height with a roughly one to one correspondence. In these cases only the amplitude of the probe and tube current traces changed while the wave forms retained their general shape. Both amplitudes and wave forms were changed by the relative position of the exciting coil from the cathode. The closer the coil was to the probe, the greater were the amplitudes of the excursions, the steeper were the leading sides of the excursions, and the shorter was the time decay of the trailing edges. These same comments apply to the wave form of the tube current when the exciting coil was moved closer to the cathodic end of the positive column. The amplitudes changed an order of magnetude when the exciting coil was moved about 25 centimeters.

When the pulse length was reduced from 10 to 2 microseconds, the wave forms did not change except that the wave

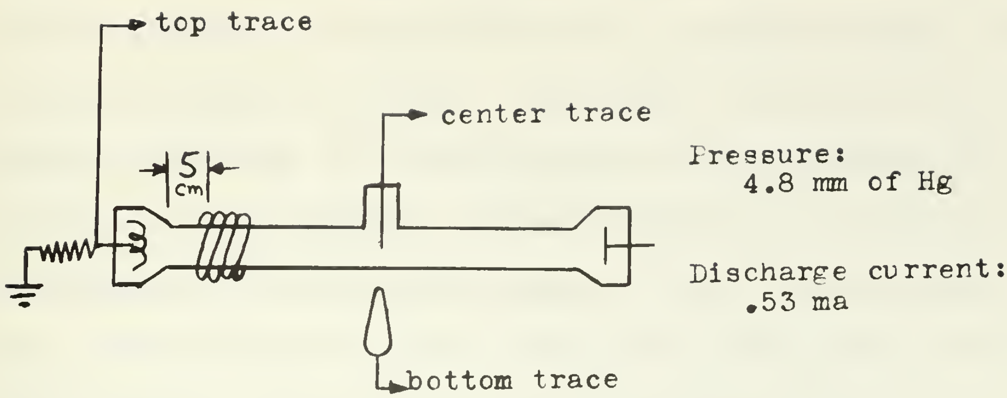
form within the pulse length was terminated sooner. If the pulse was reduced below 2 microseconds, the amplitudes of the excursions began to decrease, even though the pulse height remained at 60 volts.

There is no noticable time delay between the application of the pulse and the initiation of an effect at the probe or in the discharge current. However, the wave forms of the probe and tube currents suggest that there might be a diffusing impulse. The impulse appears to be initiated by the differential of the exciting pulse in the positive column. The peak of such a diffusing impulse seems to occur at a later time the further the exciting coil is from a detecting element. In this sense there is a time delay, and the diffusing pulse would seem to have a velocity of about 15 x 10^6 centimeters/second.

The effect of applying a positive or negative pulse affected only the first 50 microseconds of the oscilloscope traces of the probe and discharge currents. Beyond 50 microseconds a positive or negative pulse produced an identical effect. Observations with photomultipliers did not indicate any light intensity phenomena at the time of the impulse.

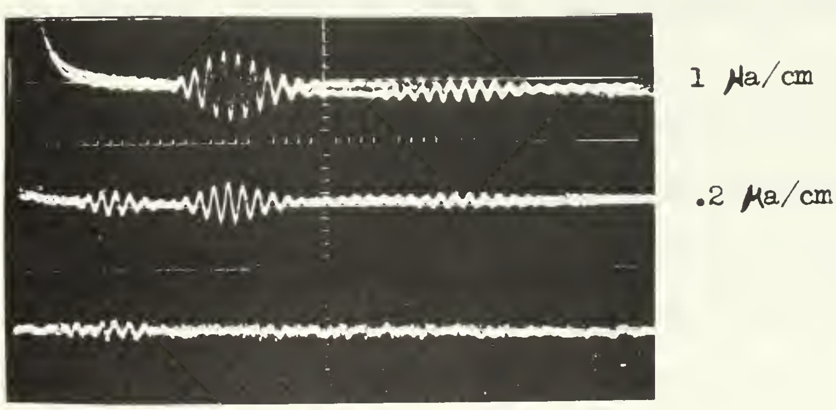
4.4 Wave of stratification observations

Figure (7,b) presents oscilloscope traces of tube current, probe current, and photomultiplier output with waves of stratification present. The physical arrangement



(a) Physical arrangement

Time base; 2msec/cm



(b) Oscilloscope traces of detector outputs

Figure 7

is shown in (7,a). The sweeps are initiated by a synchronizing signal from the pulse generator. The wave of stratification is initiated in the cathodic region and travels toward the anode. In a short interval after the impulse the wave of stratification passes through the portion of the positive column at which the probe and photomultiplier were positioned. This is seen on the probe and photomultiplier traces as a wave packet at 3.5 milliseconds. The probe trace indicates there is a current and voltage fluctuation associated with the wave of stratification; and the photomultiplier trace indicates a light intensity fluctuation. If the photomultiplier was moved closer to the anode, the wave of stratification occured later in time on the photomultiplier trace. This is indicated in Figure (8).

When the wave of stratification reached the anode, there was a fluctuation of discharge current and voltage simultaneously throughout the whole positive column. These are the large packets at 7 milliseconds on the probe and tube current traces of Figure (7). There was no light intensity fluctuation observed with this current-voltage fluctuation. The current and voltage fluctuations are a small fraction of a percent of the steady state d.c. values.

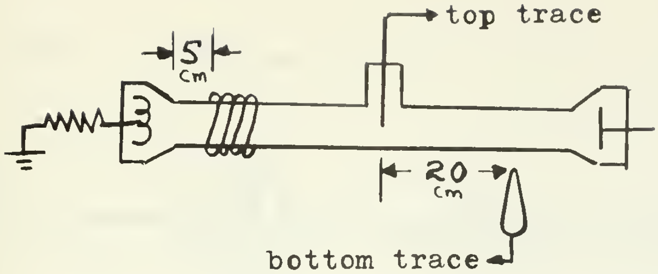
At the time of these fluctuations, a new wave of stratification spontaneously emerged from the cathodic

region, and the process was repeated. The secondary waves are quite noticable in Figure (8). A schematic of these observations is shown in Figure (9). (The small fluctuation observable at about 3.5 milliseconds in some of the oscillograms of the tube current was eliminated when the probe was disconnected, thus eliminating the small current path through the probe.)

The internal structure of the waves of stratification moved from anode to cathode. The oscilloscope traces, except for the initial impulsive disturbances, were identical whether a positive or a negative pulse was applied to the exciting coil.

The wave of stratification increased in amplitude as it traveled toward the anode. In the cathodic half of the positive column the wave of stratification was seldom discernible with the photomultiplier because of the low intensity. In all cases the wave of stratification had sufficient intensity when it was within 15 centimeters of the anode to produce a coherent signal in the photomultiplier. The voltage and current fluctuations associated with the wave of stratification were small perturbations and were fractions of a percent of the steady state d.c. discharge values

Pekarek /26/ reported observations of waves of stratification initiating at the cathode and in the region of the positive column around which an external exciting ring

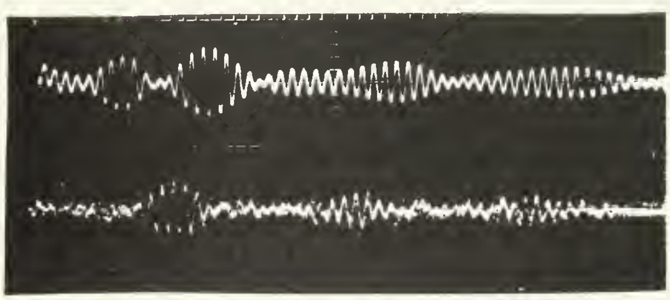


Pressure: 4.1 mm of Hg

Discharge current: .64 ma

(a) Physical arrangement

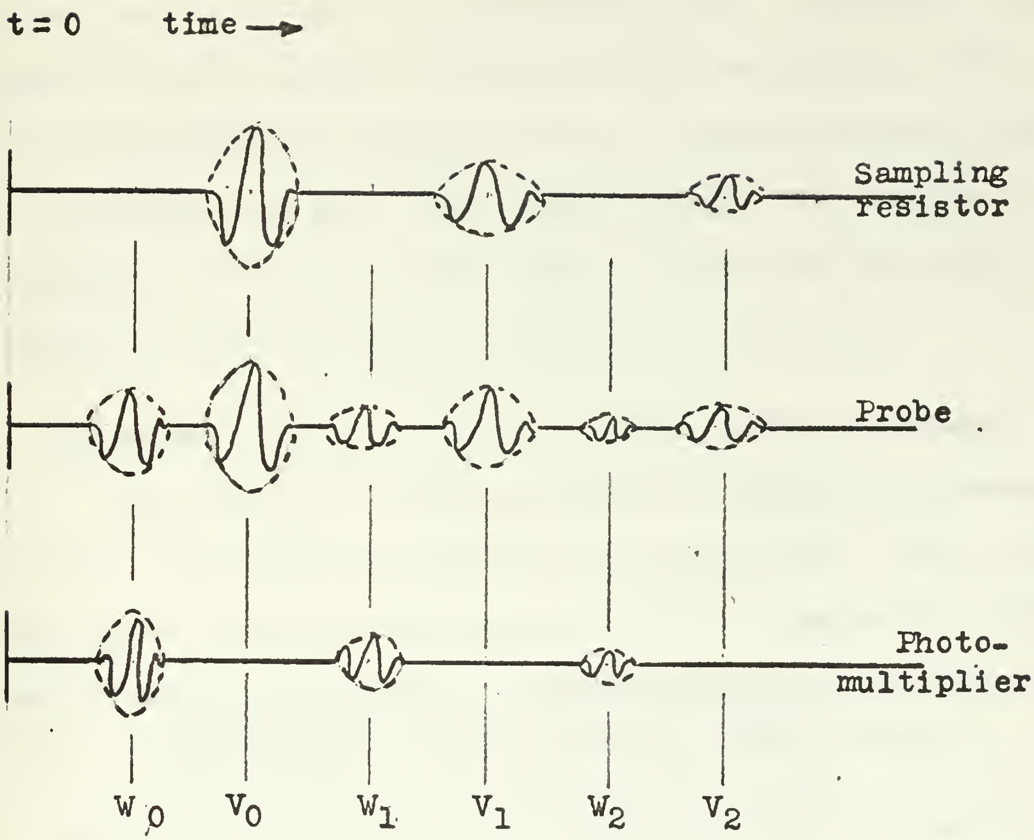
Time base: 2 msec/cm



.2 μa/cm

(b) Oscilloscope traces

Figure 8 - Oscillogram showing time displacement of wave of stratification.



(The physical arrangement of the detectors is indicated in Figure (7,a).)

Wave packet symbols:

- W_0: Initial wave of stratification
- V_0: Initial voltage and current fluctuation when W_0 reaches anode
- W_1, W_2: Waves of stratification generated by feedback mechanism
- V_1, V_2: Secondary voltage and current fluctuations associated with W_1 and W_2

Figure 9 - Schematic of detector traces

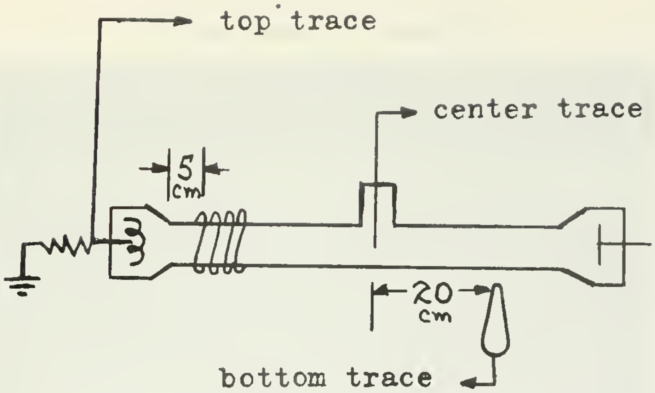
was placed. Repeated efforts in this investigation failed to indicate that any waves of stratification were emerging from the vicinity of the exciting coil. No matter in what part of the positive column the coil was placed, the waves of stratification emerged from the cathodic region only. If the exciting coil were placed around the enlarged electrode portions of the tube or around an external circuit lead, no waves of stratification were observed.

4.5 Waves of stratification versus impulse strength

The effect of varying impulse strength is presented in the photographs of Figures (10) and (11). When either the pulse height or the pulse width was diminished, the amplitude of the waves of stratification decreases roughly as the square root of the strength of the impulse.

4.6 Wave of stratification versus position of exciting coil

There was no observed change in the wave of stratification or its phase structure when the exciting coil was moved to any position along the positive column within the narrow radius of the tube. If the positive column in the tapering electrode portion of the tube were excited, the amplitude of the waves of stratification were slightly decreased, but this was probably an effect of the geometry.

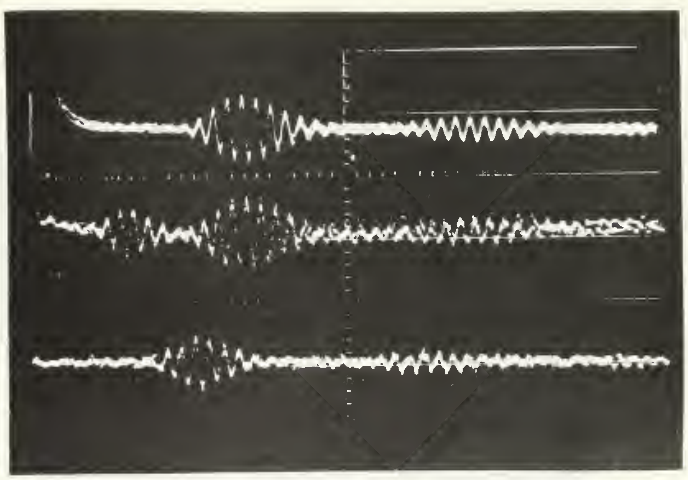


(a) Physical arrangement

Pressure:
4.8 mm Hg

Discharge current:
.53 ma

Time base: 2 msec/cm



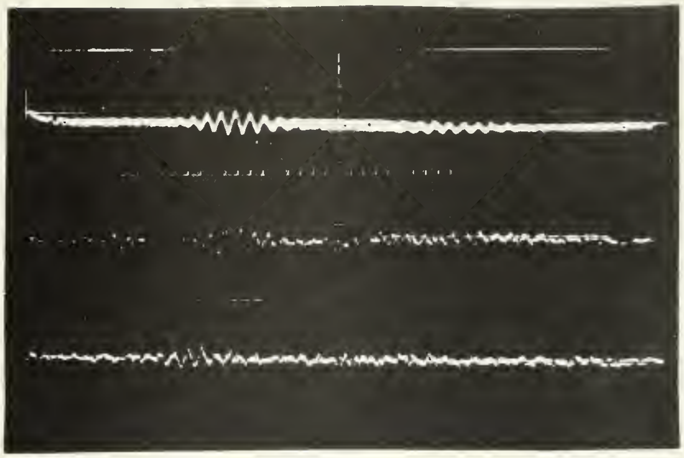
1 ua/cm

.2 ua/cm

(b) Full impulse
Pulse height: 60 volts
Pulse length: 10 usec

Figure 10 - Effect of pulse strength

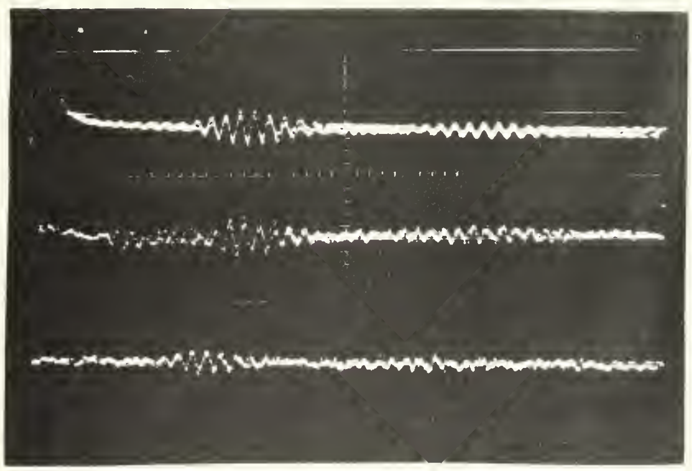
Time base: 2 msec/cm



1 ua/cm

.2 ua/cm

(a) Reduced impulse
Pulse height: 15 volts
Pulse length: 10 usec



1 ua/cm

.2 ua/cm

(b) Shortened impulse
Pulse height: 60 volts
Pulse length: 2.5 usec

Figure 11 - Effect of pulse strength

4.7 Effect of external d.c. circuitry

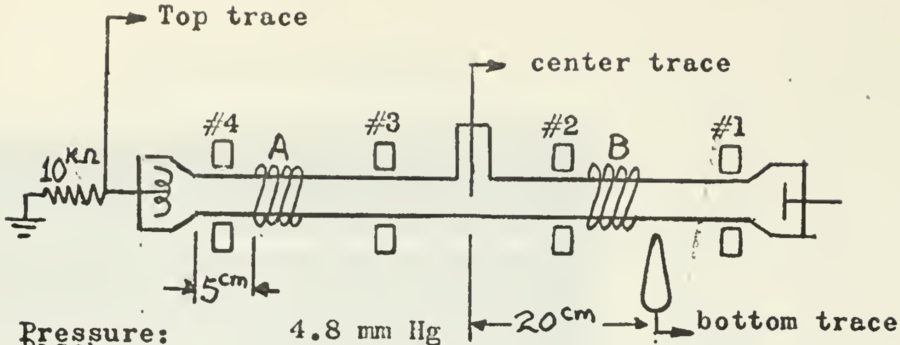
Various values of resistance from 1 to 9 megohms were inserted in series with the discharge tube. No noticable changes to the wave of stratification, the voltage fluctuations, or the secondary figures were noted. Capacitors were placed in parallel with the discharge tube. Values from .003 to 0.1 microfarads produced no noticable effects. When capacitors larger than 0.1 microfarads were used, the discharge either could not be maintained or went into a pulsating mode.

4.8 Effect of magnetic fields

Figures (13) and (14) are photographs of oscilloscope traces of tube current, probe current, and photomultiplier output for various arrangements of a transverse magnetic field. Figure (12) shows the physical arrangements, and Table (1) gives a compilation of the observed results.

A close examination of the oscillogram in Figure (14,b) indicates that there was a slight increase in the velocity of the stratification wave when the magnet was placed between the cathode and the exciting coil. This effect was only occasionally noted and did not appear at any particular pressure or current. The effect was not always apparent even when the discharge was placed at an operating point where the effect had previously been noted.

The magnet used for these photographs was an Alnico



Pressure: 4.8 mm Hg
Discharge current: .53 ma

(#1, #2, #3, #4 designates the positions of one magnet.)

Figure 12 - Physical arrangement for transverse magnetic field oscillograms

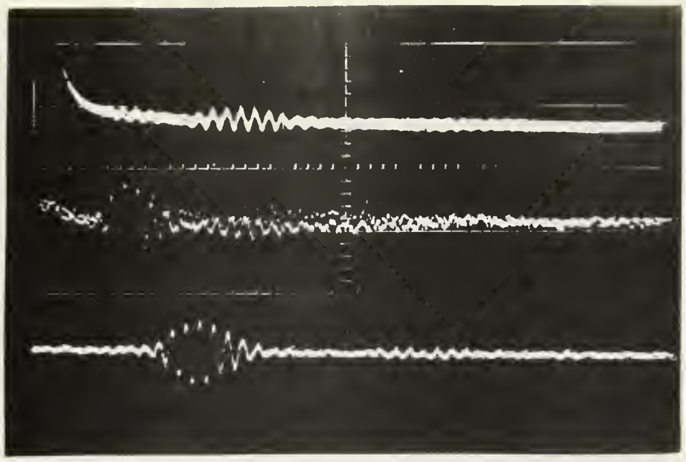
COIL AT POSITION "A"

DETECTOR		POSITION OF MAGNET #4	#3	#2	#1
$10^{K\Omega}$	V_0	Decreased	Decreased	Decreased	Decreased
	$V_{1,2}$	Decreased	Decreased	Decreased	Decreased
PROBE	W_0	Decreased	Decreased	No Effect	No Effect
	V_0	Decreased	Decreased	Decreased	Decreased
	$W_{1,2}$	Decreased	Decreased	Decreased	Decreased
	$V_{1,2}$	Decreased	Decreased	Decreased	Decreased
P.M. TUBE	W_0	Decreased	Decreased	Decreased	No Effect
	$W_{1,2}$	Decreased	Decreased	Decreased	Decreased

(wave packets as designated in Figure (9))

Table 1 - Tabulated amplitude variation with transverse magnetic field, coil at "A".

Time base: 2 msec/cm

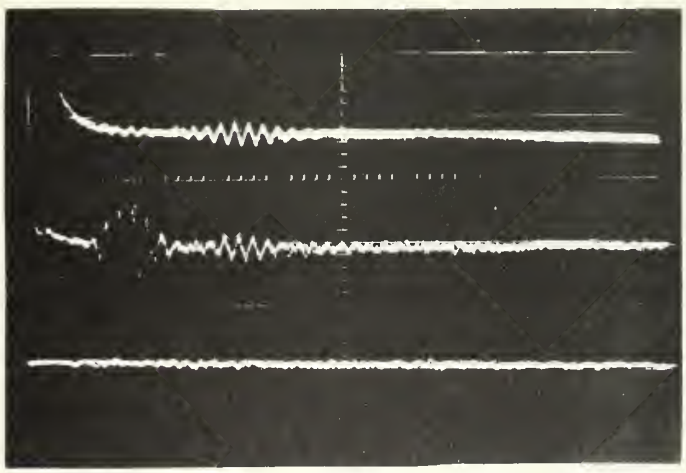


1 ua/cm

.2 ua/cm

(a) Magnet at position #1
Coil at position "A"

(The physical arrangement is shown in Figure (12,a).)



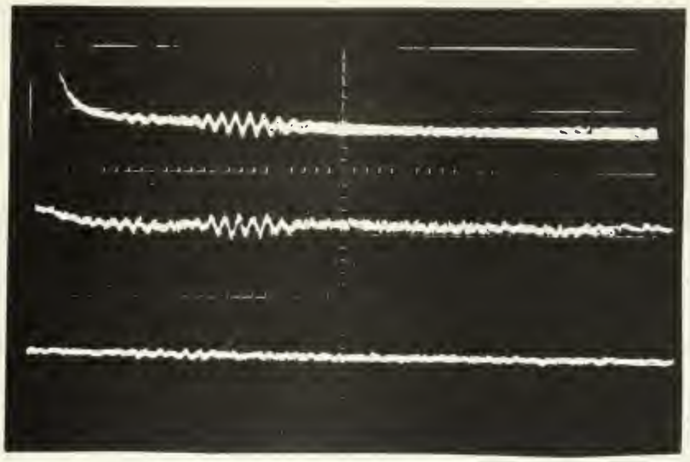
1 ua/cm

.2 ua/cm

(b) Magnet at position #2
Coil at position "A"

Figure 13 - Effect of transverse magnetic field

Time base: 2 msec/cm

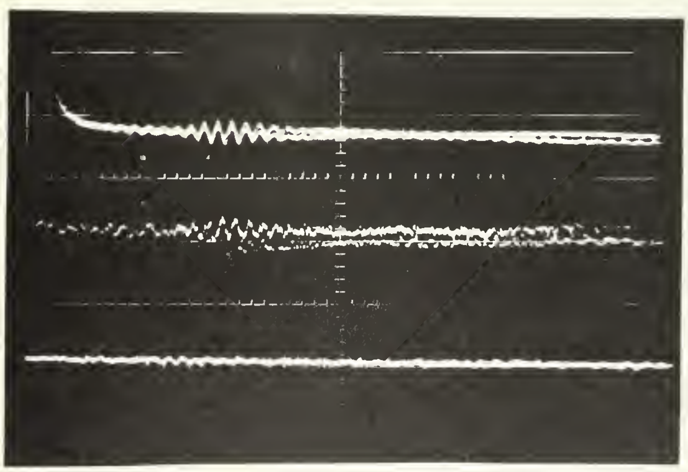


1 ua/cm

.2 ua/cm

(a) Magnet at position #3
Coil at position "A"

(The physical arrangement is shown in Figure (12,a).)



1 ua/cm

.2 ua/cm

(b) Magnet at position #4
Coil at position "A"

Figure 14 - Effect of transverse magnetic field

horseshoe magnet with a 900 gauss field at its pole faces. The attenuation of the waves of stratification was dependent on the field strength, but the exact dependence was not determined.

The transverse magnetic field interupted the wave of stratification in its travel toward the anode. Thus, the amplitude of the wave of stratification was diminished at all sections of the positive column between the magnetic field and the anode. The initial wave of stratification on the cathode side of the magnetic field remained unaffected. When the initial wave of stratification was destroyed or greatly attenuated by the transverse magnetic field before reaching the anode, the fluctuations in discharge voltage and current and the secondary waves of stratification were destroyed or proportionally deminished. The wave of stratification could always be completely reduced with the large 2000 gauss magnet and in most cases with the 1300 gauss magnet.

It was also noted that the transverse magnetic field retarded the formation of striations. At a given pressure if the discharge current had been adjusted so that striations just began to form and then the Alnico magnet was placed transverse to the positive column, it was necessary to increase the current about 10% before the striations again began to emerge.

A tabulation of the amplitude variations of the wave of

stratification with a coil placed between the probe and the anode, as indicated by "B" in Figure (12), and for various positions of a transverse magnetic field is given in Table (2). Note that the probe registers a reduced stratification signal when the magnet is in position #3.

COIL AT POSITION "B"

DETECTOR		POSITION OF MAGNET #2, #3, #4	POSITION OF MAGNET #1
10^K	V_0	Decreased	Decreased
	$V_{1,2}$	Decreased	Decreased
PROBE	W_0	Decreased	No Effect
	$W_{1,2}$ $V_{0,1,2}$	Decreased	Decreased
P.M. TUBE	W_0	Decreased	No Effect
	$W_{1,2}$	Decreased	Decreased

(Wave packets as designated in Figure (9))

Table 2 - Tabulated amplitude variations with transverse magnet field, exciting coil at "B".

Some observations were made of the effects of a

longitudinal magnetic field up to 350 gauss. The effects noted were to decrease the amplitude of the waves of stratification and to retard slightly the formation of striations. Over the range of fields observed the attenuation of the waves of stratification was roughly one to one with the increase in magnetic field.

4.9 Various parameters versus pressure

Figure (15) is a plot of group velocity, velocity of the wave of stratification, versus pressure. Figure (17) is plot of phase velocity, velocity of the internal structure of the waves of stratification, versus pressure. Both velocities in the lower pressures decrease with an increase in pressure. Over the remaining pressure range the velocities are fairly constant. The group velocity ranges from 6×10^3 to 24×10^3 centimeters/second and is about 6 times the phase velocity.

Figure (16) shows the pressure dependence of the wavelength of the internal structure of the wave of stratification. It is fairly constant with a slight decrease as the pressure increases.

Frequency of the phase wave versus pressure is plotted in Figure (18). It has a broad minimum in the middle of the range and rises faster on the low pressure side than on the high pressure side.

The wavelength of the phase wave remained relatively constant as the discharge was brought into the stable-striation region and became the wavelength of the striations.

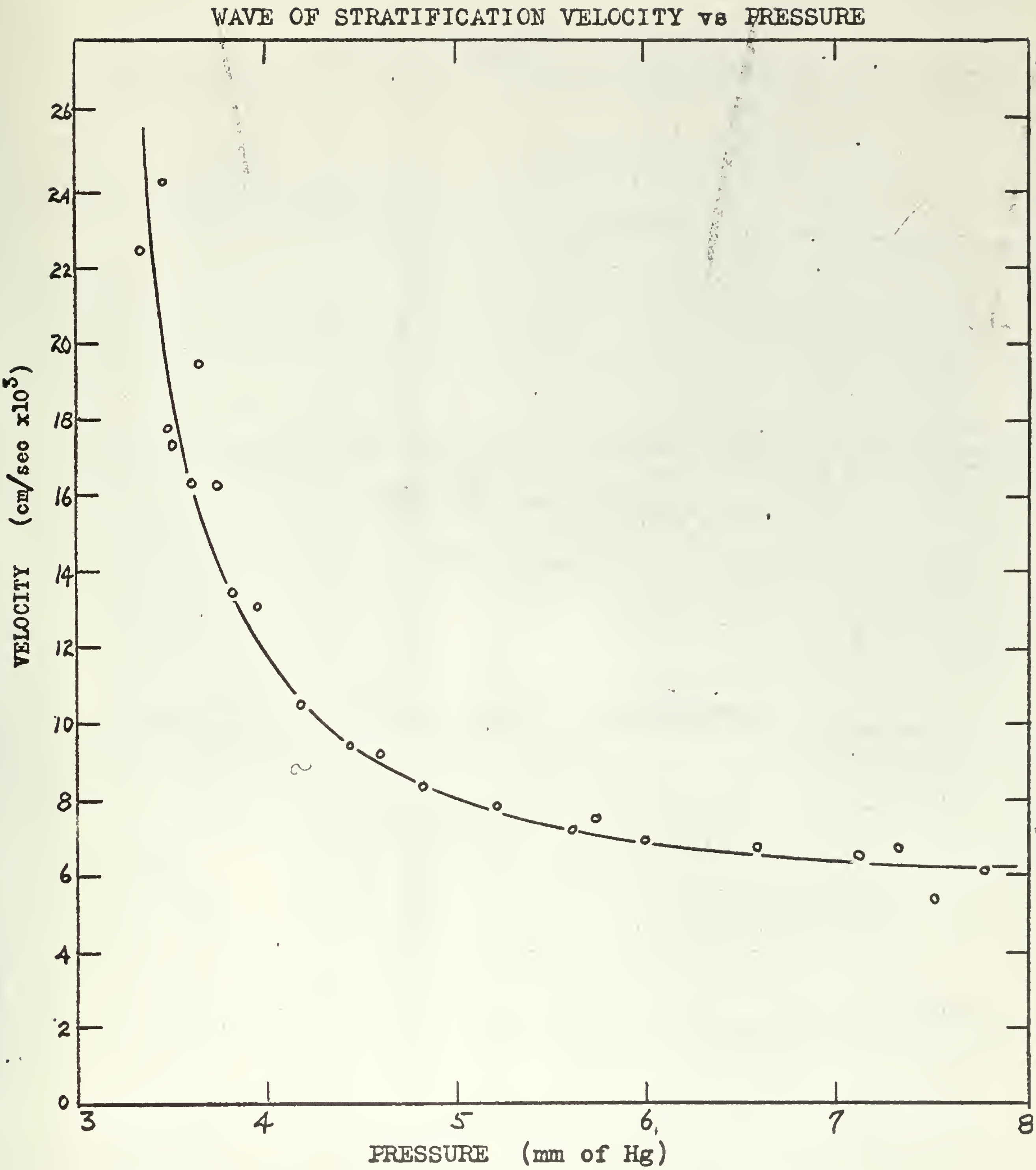

WAVE OF STRATIFICATION VELOCITY vs PRESSURE
VELOCITY (cm/sec x10^3)
26
24
22
20
18
16
14
12
10
8
6
4
2
0
3
4
5
6
7
8
PRESSURE (mm of Hg)

Figure 15

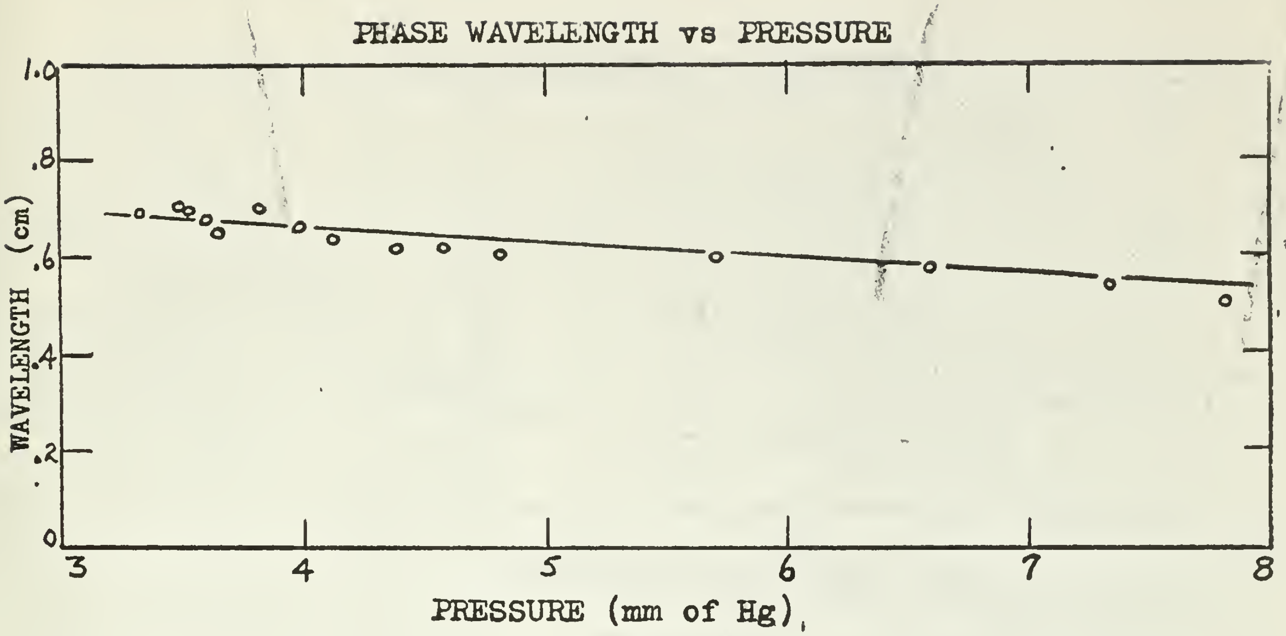


Figure 16

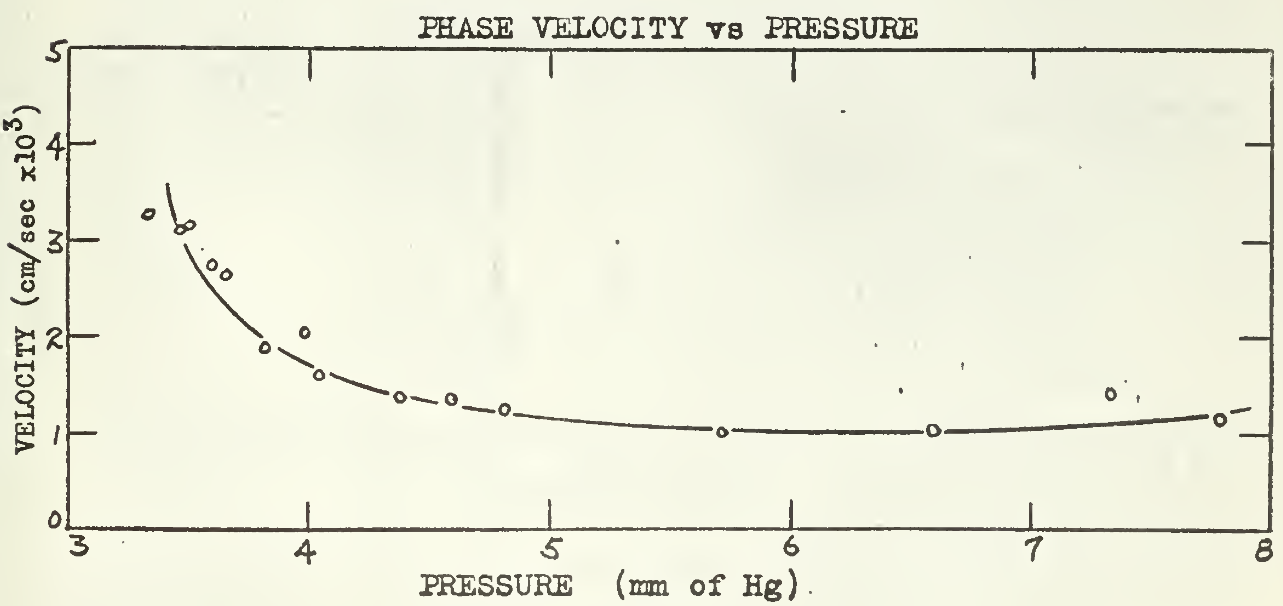


Figure 17

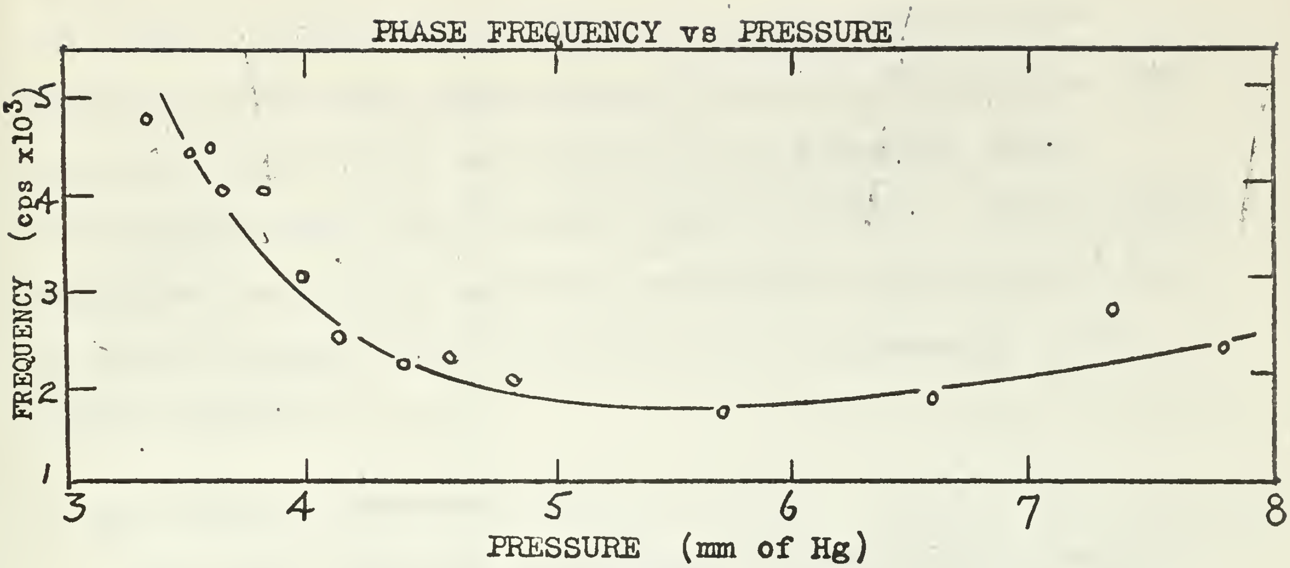


Figure 18

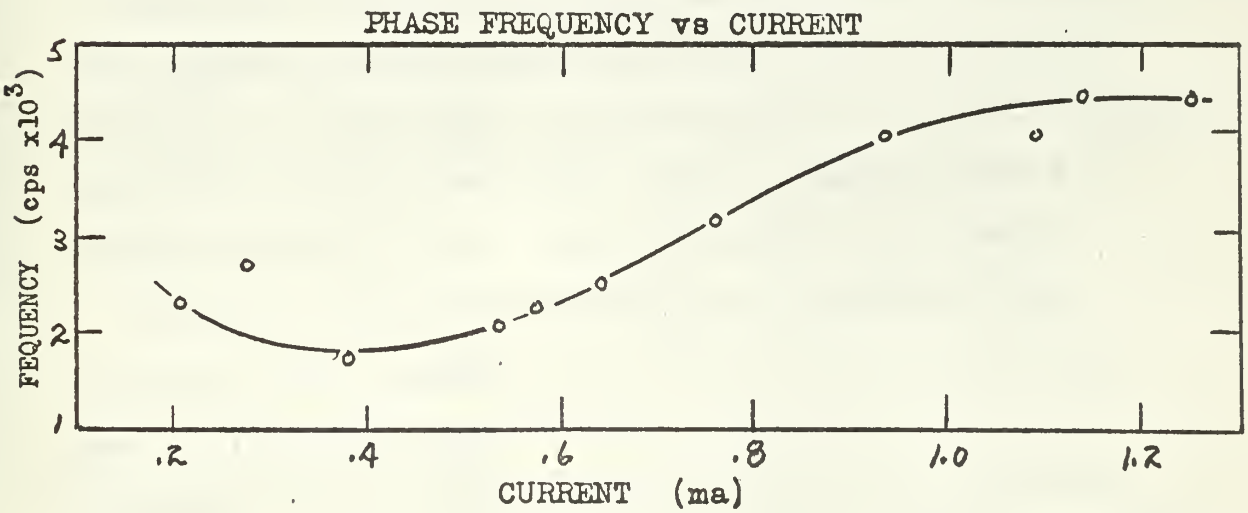


Figure 19

The frequency and velocity of the phase wave became the frequency and velocity of the striations which appeared just at the onset of striations. However, as the discharge was brought further into the striation region by increasing the current, the velocity and frequency went through abrupt transitions where their values roughly doubled. These transitions were extremely sensitive to current and occured within a current change of as little as a few microampere of discharge current.

4.10 Various parameters versus current

When the discharge current was increased in the manner described in section 3.6, the waves of stratification grew in amplitude. Typically the range of currents from the initial indication of waves of stratification to the onset of striations was about .01 milliamperes. The striations first appeared between the wave packets with amplitudes comparable to the wave of stratification but quickly achieved amplitudes orders of magnitude larger than the wave of stratification with any further increase of current.

When the onset of striations was approached, the striations were detected first on the tube current trace, then on the probe current trace, and then on the photomultiplier trace, if the photomultiplier was positioned closer to the anode than the probe. This agrees with other findings /3/ that the critical current for the onset of striations at a position in the positive column increases

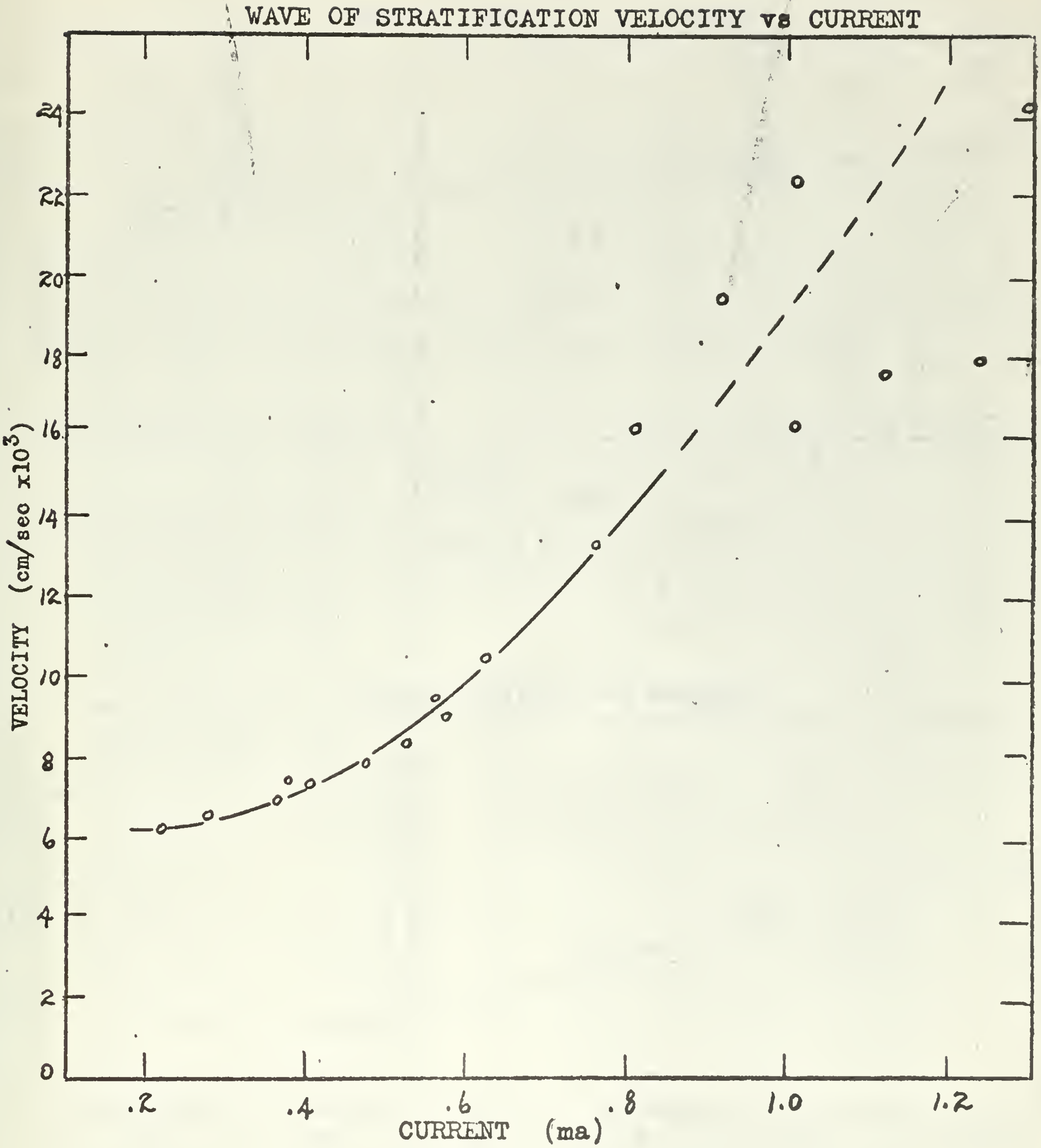

WAVE OF STRATIFICATION VELOCITY vs CURRENT
VELOCITY (cm/sec x10^3)
CURRENT (ma)
0
2
4
6
8
10
12
14
16
18
20
22
24
.2
.4
.6
.8
1.0
1.2

Figure 20

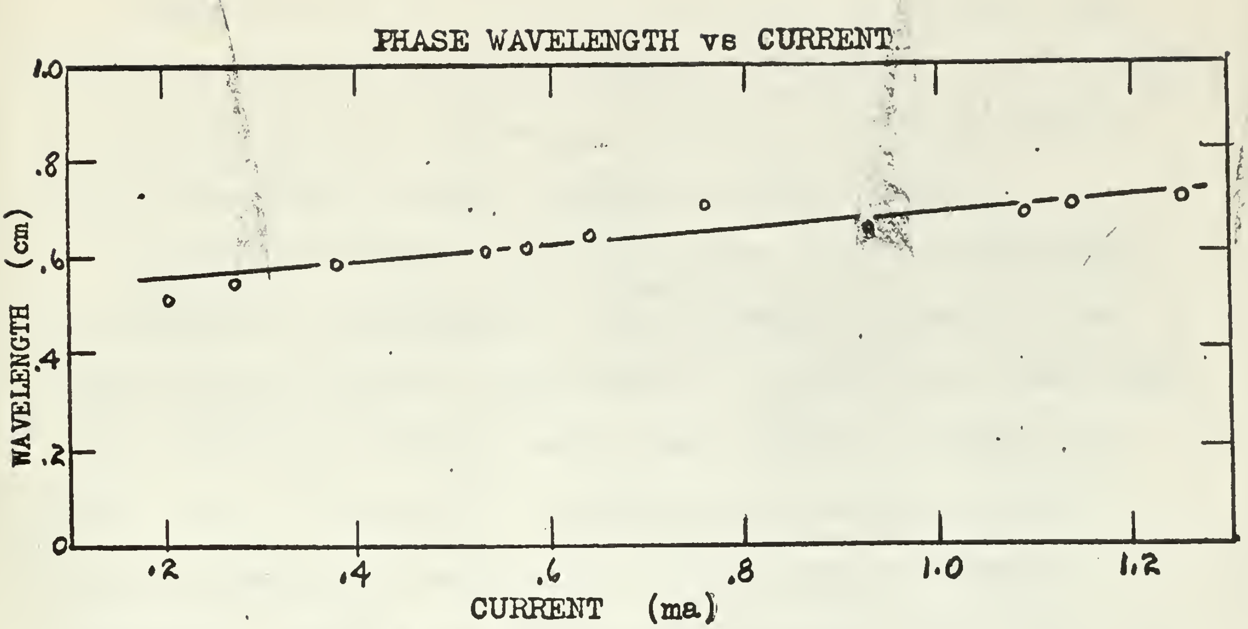


Figure 21

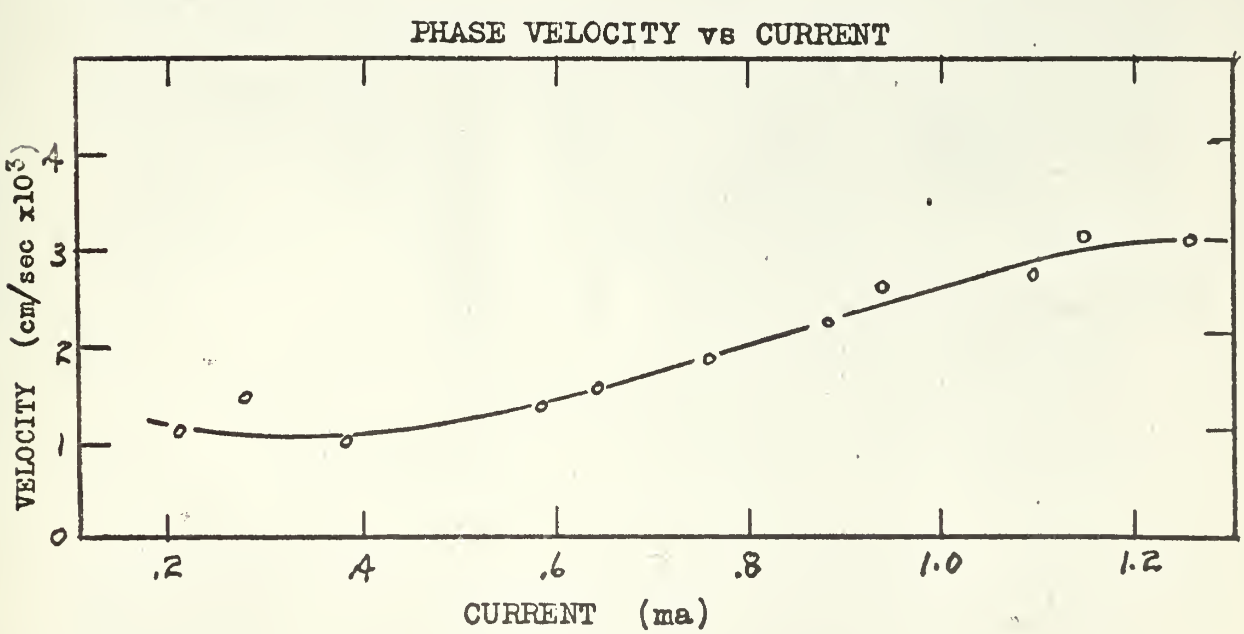


Figure 22

with distance toward the anode.

Figures (19) to (22) are velocity, wavelength, and frequency parameters plotted against current. The criterion for determining the discharge current is given in section 3.6. Note these are not constant pressure curves.

Several attempts were made during the investigation to determine a quantitative relationship between the discharge current and the amplitude of the wave of stratification. However, these attempts were defeated because the power supply did not have sufficient current regulation and the measuring devices did not have the necessary precision. These same limitations prevented any meaningful quantitative measurements of amplification versus distance traveled for the wave of stratification.

5.0 Conclusions

This investigation suggests that when a localized portion of the positive column of a discharge is electrically perturbed, a very fast disturbance, generated by the time differential of the perturbing signal, travels in both directions from the perturbed region. Although there is an inherent, finite time response in a probe, the negative excursions of the probe oscillograms in Figures (5) and (6) did peak later and have smaller amplitudes and wider extents the further the exciting coil was from the probe. This was true whether the coil was on the anode or cathode side of the probe. Although not as apparent as the probe excursions, the excursions on the discharge current oscillograms exhibited the same characteristics the further the coil was moved from the cathode. A velocity on the order of 10^7 cm/sec was estimated from the time interval between the peaks of the probe or current excursions when the coil was placed at two different positions of known distance apart.

If the operating point of the discharge is very close to the onset of striations, the disturbance which travels toward the cathode induces the emergence of waves of stratification from the cathodic region. A transverse magnetic field will reduce the traveling disturbance, and if the cathode-directed disturbance is diminished or interrupted by the magnetic field, the subsequent wave of stratification is proportionally diminished or eliminated. However, reducing the anode-directed disturbance does not prevent the formation of waves of stratification.

A transverse magnetic field interupts the wave of stratification without altering the wave's propagation before reaching the domain of the magnetic field. A small longitudinal field attenuates the wave of stratification. No indication of a velocity change with the longitudinal field was noted; however, other investigators /47/, using larger fields, observed a decrease in velocity.

The velocity of the wave of stratification and the velocity of its phase structure are more pressure dependent at lower pressures than higher pressures within the range of pressures observed. Both velocities are fairly constant over the upper half of the range. In the lower pressure range as pressure decreases, or 1/p increases, the velocities increase. This is quite understandable, for the phase velocity becomes the striation velocity, and it is known that striation velocity increases as E/p increases.

Both transverse and longitudinal magnetic fields retard the onset of striations.

As striations emerge with waves of stratification present, the wavelength of the phase structure of the stratification wave becomes the wavelength of the striation. The velocity and frequency of the phase structure becomes the striation velocity and frequency just at the onset of striations.

As the discharge is brought further into the striation-operating region, the velocity and frequency abruptly increase to roughly twice their values. This change is similar to an effect noted by Panzer and White /22/ at a different operating point of the discharge. The transition noted in this investigation occurs just after the onset of striations and is more sensitive to current than the transitions observed by the other authors.

6.0 Recommendations

The following areas contain interesting questions and are recommended for further investigation:

a. Investigate the fast traveling disturbance excited at the pulsed coil. The nature of the coupling, effects of several parameters; such as, pressure, geometry, magnetic fields, can be determined. Other localized methods of pulsing may be developed, and other than rectangular pulses may be tried.

b. Attempt to find the region at or near the cathode from which the waves of stratification emerge. Very rough extrapolations in this investigation had indicated the waves may originate a few centimeters in front of the cathode.

c. Use an electromagnet to develop a localized transverse magnetic field so that a correlation between the field strength and its effects on the fast traveling disturbance, on the propigation of stratification waves and and striations, and on the onset of striations may be made.

d. Investigations with the longitudinal field may be continued.

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