EXPERIMENTAL INVESTIGATIONS OF PLASMAS
IN ELECTROMAGNETIC SHOCK TUBES

by

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B.A.Sc., University of British Columbia, 1957
M.A.Sc., University of British Columbia, 1961

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We accept this thesis as conforming to the
required standard

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EXPERIMENTAL INVESTIGATIONS OF PLASMAS IN ELECTROMAGNETIC SHOCK TUBES

ABSTRACT

The plasmas produced in electromagnetic shock tubes have previously been studied in this laboratory and elsewhere. In general the temperatures and electron densities deduced from time-resolved spectra emitted by the plasma do not agree with the values calculated from shock theory. Photographs taken with a Kerr cell shutter revealed that luminous discharge gases with a very irregular front were driven down the tube and that no separate shock front could be seen ahead. The plasma behind the luminous front consisted of a mixture of rest gas and a considerable amount (\textasciitilde50\%) of impurity from the driving discharge.

In the work reported here, further attempts were made to produce shock heated plasmas. Various electrode configurations were tried but no improvement was observed. Some measure of success was attained with an electrodeless driver on the shock tube. Kerr cell photographs showed that with argon in the tube a shock wave appeared to be formed ahead of the discharge plasma. The shock speed was much slower than the speed of the advancing luminous front in the tubes with electrodes. However, no shock wave could be observed with helium.

With argon in the electrodeless tube radiation could be observed from the gas ahead of the shock wave. Time resolved spectroscopic measurements on this radiation allowed rough determination of electron density and of the population of excited states of argon atoms and ions ahead of the shock front. This "preheating" of the gas is presumably due to ultraviolet light emitted from the discharge and the shock plasma. The values of electron density and temperature expected behind the shock front were calculated from shock theory, taking into account the preheating of the gas. The expected values agreed well with the electron density and temperature determined from spectroscopic measurements on the shock plasma.
The study of the precursor radiation was continued in a shock tube with electrodes. In this tube the driving discharge was more luminous and the excitation and ionization of helium and argon ahead of the luminous front could be more readily observed than with the electrodeless tube. The number densities of helium atoms in various excited states were determined from the time resolved line intensities before and after the passage of the luminous front. The ratios of atoms in different levels differ from the expected ratios for thermal equilibrium conditions, both ahead of the luminous front and behind it. An estimate was made of the time required for the attainment of equilibrium by electron impact. The calculation indicates that ahead of the luminous front there is not sufficient time to attain equilibrium. On the other hand, for the high electron density found behind the luminous front, the equilibrium distribution is expected to be reached in times shorter than the observation times, in disagreement with the behaviour observed.
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CHAPTER I

INTRODUCTION

Much work has been done in recent years on plasmas formed in electromagnetic shock tubes. In these experiments electrical energy is stored in a charged capacitor bank and released to form a discharge in the shock tube. The capacitor bank may be discharged directly into the tube by means of electrodes of various configurations. Alternatively, an electrodeless arrangement may be used; the capacitor bank is switched through one or more coils outside the tube, inducing a discharge in the shock tube. The highly luminous discharge is driven down the tube as a result of electromagnetic forces and/or from the actual heating of the gas. Many workers (such as McLean et al (1960), Barnard, Cormack, and Simpkinson (1962)) have conducted spectroscopic investigations on the plasma behind the advancing luminous front. In these investigations the electron density has been determined from spectral line broadening, and the electron temperature from the relative intensity of various spectral lines. The accurate determination of electron temperature by this method requires equilibrium between the electrons and the excited atomic and ionic states. The spectroscopically determined values of the above quantities were found to be in poor agreement with values calculated theoretically by treating the advancing luminous front as a shock wave.
Subsequent to the above work at this laboratory fast shutter photographic studies of the development of the "shock wave" in electromagnetic shock tubes were carried out (Barnard and Cormack, 1963). These were done for many different configurations of driving electrodes and showed that the shape of the advancing luminous front at positions far down the shock tube bore a relationship to the shape of the arc which initially developed between the electrodes in the driver section. Thus, the luminous front did not appear to be a shock wave but seemed to be the boundary between arc heated gas advancing down the tube and the cold rest gas initially in the tube.

A more detailed investigation of plasmas in electromagnetic shock tubes was therefore undertaken. The theory used in this work will be found in Chapter II. The theory is on the whole well known and is only briefly outlined. Relevant equations are quoted from the theory of Stark broadening and of electron temperature determination from spectral line intensities. The standard theory of shock heating was developed in a convenient form for the case of a shock propagating into a gas which is pre-ionized to a small extent.

Chapter III discusses the arrangement of the apparatus employed. The optical, spectroscopic, and electronic equipment are standard items. Various shock tube
driving electrode configurations are shown, one of which has been used previously (Neufeld (1963)), while the other two were made for these experiments. Also shown is a simple electrodeless driver designed by the author.

The experimental work done is presented in Chapter IV. The work began with a rough spectroscopic determination of the impurity content of the plasma generated in the tube used by Neufeld (1963). Carbon was chosen as a representative impurity and the strength of a carbon line was compared with that of a line from the rest gas. This analysis shows the carbon content of the plasma to be greater than 35%. Two other driver electrode configurations were tried in an attempt to reduce the impurity content. This was not successful so an electrodeless shock tube was built to eliminate electrodes and insulating material from the inside of the tube.

The second section of Chapter IV deals with investigations carried out on the electrodeless shock tube. Current traces are presented showing the two waveforms used in the driving coil current; in one of these the capacitor bank is shorted at such a time that only two discharge pulses flow within the tube. Next, photographs taken through a Kerr cell shutter are shown. These indicate the development of the discharge, its subsequent travel down the tube, and the effects of a magnetic field "shaper" put
near the driver and of short circuiting the capacitor bank at the above time. The photographs reveal that under certain experimental conditions, i.e. with argon in the tube and shorting the bank after two current pulses, a shock front appears to advance ahead of the arc heated gases.

The second section of Chapter IV continues with an account of the spectroscopic measurements made of the impurity (carbon) content, electron density, and temperature of the argon plasma behind the suspected shock front. The carbon content of the discharge in this tube is shown to be of the order of 6%. Also reported are rough spectroscopic determinations of electron density and temperature made from the light found to be coming from the gas ahead of the plane luminous front. Intensity histories of argon atomic and ionic lines and of hydrogen lines are presented in which this "precursor" radiation is compared with that from after the luminous front. The results of the spectroscopic measurements on argon are then compared with the theory for a shock wave moving into a "preheated" gas and good agreement was found.

The presentation of work on the electrodeless tube closes with a brief report on the results obtained with helium in the tube. Photographs are shown which indicate a much more irregular shaped discharge than in the case of argon. Some spectroscopic measurements are included.
The final section of Chapter IV deals with studies of the precursor radiation carried out using the shock tube with co-planar electrodes. Intensity histories for spectral lines from argon atoms, first and second stage ions and from hydrogen are shown from the results of these measurements. Somewhat more extensive measurements are presented for helium because more of its atomic parameters are known than for argon, and it was believed some comparisons could be made between the observations and theoretical calculations of times for a helium plasma to reach equilibrium. Chapter IV closes with a set of tables of ratios of population of certain excited states of neutral helium at various times after the initiation of the driving discharge. These tables contain for each ratio the value which would be expected at equilibrium. Even behind the luminous front the observed ratios depart considerably from the expected values. It is felt that the careful study of the precursor ionization is the most significant contribution of this research. Other workers (McLean (1961)) have observed this precursor radiation but to the author's knowledge no measurements as detailed as those presented here have been conducted.

The final chapter of this thesis contains a discussion of the results. An attempt is made to show from the results that photo-excitation is the dominant mechanism of excitation and ionization ahead of the luminous front. Also
included in Chapter V is a calculation of the time to establish excitation and ionization equilibrium by electron impact for typical experimental conditions. This indicates that equilibrium should prevail behind the luminous front and does not help to explain the anomalous behavior observed. The chapter closes with suggestions for future work.
Spectroscopic Theory

(a) Stark Broadening of Hydrogen Lines

Hydrogen line broadening is used in these experiments as a measure of electron density. Hydrogen is present as an impurity in the plasmas studied. It can be shown, that at the temperatures and densities attained in this experiment, the Stark effect is the dominant broadening mechanism for the broadening of hydrogen spectral lines (see for example the review article by R.G. Breene Jr. (1957)).

Grien, Kolb, and Shen (1959) extended the Holtsmark (1919) theory and computed the profiles of Hydrogen lines for different electron densities and temperatures. By fitting the experimental profile of a hydrogen line emitted from a plasma containing electrons, atoms, and singly charged ions one can thus determine the electron density, \( N_e \).

If the plasma should have many stages of ions present, an "effective" charge density, \( N_{\text{eff}} \), is obtained from the fitting of the profile. Following Chandrasekhar (1943) one finds

\[
(1) \quad N_{\text{eff}} = N_1 + 2^{3/2} N_2 + 3^{3/2} N_3^+ \ldots = \sum_{i=0} \frac{1}{i^{3/2}} N_i
\]

where \( N_i \) is the number density of \( i \)-th stage ions. Provided the ratios of the \( N_i \) are known, the electron density may be
(2) \( \sum \frac{3}{i \neq 0} iN_i \)  

(b) Temperature Determination from Spectral Intensity

The electron temperature in a plasma can be determined from the intensities of spectral lines in light emitted by the plasma provided that thermal equilibrium prevails. In the theory to be developed here it will be assumed that the electron temperature is equal to the excitation temperature though there is some doubt whether this assumption is true in the plasmas encountered in this work. The excitation temperature is the temperature, \( T_{\text{ex}} \), which exists if the populations of the excited states of the atoms or ions in the plasma are all proportional to Boltzmann factors, \( g \exp (- \frac{E}{kT_{\text{ex}}} ) \), where \( E \) is the energy of the excited state above the ground state and \( g \) its statistical weight.

The conditions for equilibrium to be attained between electrons and excited states of atoms and ions have been studied by Griem (1963).

The absolute intensity of a spectral line resulting from a transition between the energy levels \( E_m^i \) and \( E_n^i \) of an \( i \)-th stage ion is given by (see for example Condon and Shortley (1935))

\[
(3) \quad I_{m,n}^i = \frac{N_i(m)}{g_m^i} \frac{64 \pi^4 c}{3 \lambda_i^4 (m,n)} S_i(m,n)
\]
where \( N_i^1(m) \) is the density of the \( i \)-th stage ions of energy \( E_i^1 \), \( g_i^1 \) is the degeneracy of the energy state \( E_i^1 \), \( \lambda_i(m,n) \) is the wavelength of the line, \( c \) is the speed of light, and \( S_i^1(m,n) \) is the theoretical line strength of the transition \( E_i^1_m - E_i^1_n \) (\( E_i^1_m \) will always be taken as the upper level). The line strengths for the helium and argon lines studied in this experimental work are tabulated in Appendix I.

At the temperature \( T \) we have the following relation involving the \( N_i^1(m) \) and \( N_i^1 \):

\[
(4) \quad \frac{N_i^1(m)}{g_i^1} = \frac{N_i^1}{Z^i} \exp \left( -\frac{E_i^1}{kT} \right)
\]

where \( Z^i \) is the partition function for \( i \)-th stage ions and \( k \) is the Boltzmann constant. The ratio of ions in different stages of ionization is given by the Saha equation,

\[
(5) \quad \frac{N_i^{1+1}Z^{1+1}}{N_i^1Z^1} = \frac{2}{N_e} \left( \frac{2\pi m_e kT}{h^2} \right)^{3/2} \exp \left( -\frac{E_i^1}{kT} \right),
\]

where \( m_e \) is the mass of the electron, \( h \) is Planck's constant and \( E_i^1 \) is the ionization energy of the \( i \)-th stage ion.

Combining equations (3), (4), and (5) and inserting numerical values we arrive at the relation

\[
(6) \quad kT = \frac{\left( E_i^1 + E_i^{1+1} - E_i^1 \right)}{2.303 \log_{10} kT + 21.8 + \log_{10} \left( \frac{\lambda_i^{1+1}(m,n) S_i^{1+1}(m,n)}{\lambda_i^{1}(m,n) S_i^{1}(m,n)} \right)}
\]

where \( kT \) and other energy terms are in electron volts.
Equation (6), on substitution of the observed spectral intensities and other parameters is easily solved for kT by graphical or numerical means.

Shock Theory

We will consider here a strong, one dimensional shock wave propagating with velocity $v_s$ into a gas at rest. Following the notation on Figure 1, the subscript $0$ will denote quantities before the shock. The symbols $p$, $T$, $U$, $N$, $N_e$ and $v$ denote respectively pressure, temperature, internal energy per heavy particle, number density of ions and atoms combined, electron density, and flow velocity. As we wish to consider the effects of ionization ahead of the shock wave we will not immediately invoke the strong shock approximation where $p_0 \ll p$ and $U_0 \ll U$ and so the equations for conservations of mass, linear momentum, and energy are

$$ (a) \quad N_0 v_s = N(v_s - v) $$

$$ (7) \quad (b) \quad p - p_0 = m N_0 v_s v $$

$$ (c) \quad pv = N_0 v_s (U - U_0 + \frac{mv^2}{2}) $$
where \( m \) is the mass of an atom or ion (neglecting electron mass). From Equation (7) (b) and (c)

\[
(U-U_o) - \frac{p_o v}{N_o v_s} = \frac{mv^2}{2}
\]

To proceed further with this development the processes occurring behind the shock must be considered. The principal processes in this region are collisional ionization and excitation. From the overall charge neutrality of the plasma we may write

\[
N_e = N_1 + 2N_2 + 3N_3 + ... = N(\lambda_1 + 2\lambda_2 + ...) = N\sum_{i=1}^{\infty} \lambda_i = N\lambda
\]

where \( \lambda_i \) denotes the fraction of \( i \)-times ionized atoms \( (\lambda_i = \frac{N_i}{N}) \) and \( \lambda \) is the degree of ionization or ratio of electrons to heavy particles. The values of \( N_e \) and \( \lambda \) ahead of the shock will always be taken as known.

Assuming thermal equilibrium between ions and electrons, \( (i.e \ T_{ion} = T_e) \), Equations (7) (a), (b) and (8) can be supplemented with the equation of state and the equation for the internal energy of an ideal gas:

\[
(a) \ p = (1+\lambda) NkT
\]

\[
(b) \ U = \frac{3}{2} (1+\lambda)kT + U_{ie}
\]

where \( U_{ie} \) is the ionization and the excitation energy per ion.

Solving Equations (7) (a), (b), (8), (9) and (10) for \( N_o \)
and $v_s^2$ and introducing numerical values, one finds

\[ N = \frac{N_e (1+\alpha)}{kT (4(1+\alpha)+2 \frac{U_{ie} - U_0^1}{kT})} \]  

(11)

\[ v_s^2 = \frac{1.92 M kT (2(1+\alpha))}{3/2(1+\alpha)kT(U_{ie} - U_0^1) - \frac{p_0 (N-N_0)}{2N_0 N}} \]

Here $M$ is the atomic weight of the rest gas, $kT$, $U_{ie}$, and $U_0^1$ are in electron volts, and $U_0^1$ is a convenient abbreviation for

\[ U_0^1 = \frac{p_0}{mN_0 v_s} \sqrt{2m(U-U_0)} - \frac{p_0(N-N_0)}{2N_0 N} \]

In Equation (11) (b) only the linear terms in \( \frac{p_0}{kT} \) and \( \frac{p_0}{mN_0 v_s} \) have been retained. The approximation is valid if

\[ p_0^2 \ll ( (1+\alpha)kT )^2 \quad \text{and} \quad p_0^2 \ll ( \frac{mN_0 v_s^2}{2} )^2 \]

ie if $p_0$ is small compared with the static and dynamic pressures in the flow behind the shock wave.

For comparison with the values of $kT$ and $N_e$ obtained from spectroscopic measurements it is necessary to express $kT$ and $N_e$ in terms of the observables, $v_s$ and $N_0$. It should be noted that $\alpha$ and $U_{ie}$ are themselves functions of $kT$ and $N_e$. In this experiment the temperature is of the order
of a few electron volts and so the excitation energy of an ion, given by:

\[
E^* = \frac{\sum_{n} E_{n}^{i} g_{n} \exp \left(-\frac{E_{n}^{i}}{kT}\right)}{\sum_{n} g_{n} \exp \left(-\frac{E_{n}^{i}}{kT}\right)}
\]

is small compared with the ionization energy. Thus, neglecting the excitation energies, \( U_{1e} \) can be expressed in terms of the \( L_{1} \):

(12) \[
U_{1e} = L_{1} E^{0} + L_{2} (E^{0} + E^{1}) + \ldots + L_{r} (E^{0} + \ldots + E^{r-1}) + \ldots
\]

where \( E^{i} \) is the ionization energy of the \( i \)-th stage ion.
Assuming thermal equilibrium, the \( L_{i} \) are given by the Saha equations

(13) \[
\frac{L_{r+1}}{L_{r}} = \frac{N_{r+1}^{T+1}}{N_{r}^{T}} = \frac{2 Z_{r}^{T+1}}{N_{e}} \left(\frac{2\pi m_{e} kT}{\hbar^2}\right)^{3/2} \exp \left(-\frac{E_{r}^{*}}{kT}\right),
\]

and by

(14) \[
\sum_{i} L_{i} = 1.
\]

To solve Equations (11) (a), (b), (12), (13), and (14) for \( kT, N_{e} \), and the \( L_{i} \) a method of successive approximations was adopted. It was found convenient to rewrite
Equation (11) in the form

\[ (a) \quad kT = -\mathcal{B} \cdot \sqrt{\frac{M_1 v_s^2}{1.92}} \sqrt{C} \]

\[ (15) \]

\[ (b) \quad N_e = \frac{N_0 \alpha C}{1+\alpha} (4(1+\alpha)+2 \frac{U_{ie}-U_0^1}{kT}) \]

where \( B, C, \) and \( M^1 \) are given by

\[ B = (4U_{ie} - \frac{3}{2} \frac{M_1 v_s^2}{1.92} - 4U_0^1) \]

\[ C = (4U_{ie} + \frac{9}{4} \frac{M_1 v_s^2}{1.92} - 4U_0^1 - \frac{8p_0(N-N_0)}{N_0 n}) \]

\[ M^1 = \frac{M}{(1- \frac{p_0}{2(1+\alpha)NkT})} \]

Inserting estimated values for the \( \alpha_1 \) in Equations (12) and (15) with \( U_0^1 = U_0, \frac{p_0(N-N_0)}{N_0 n} = kT_0 \) and \( M^1 = M \) gives a first approximation to \( kT \) and \( N_e \). Substitution of these first approximations in Saha's equation yields better values for the \( \alpha_1 \). This process is continued until self consistent values of \( \alpha_1 \) are obtained, then the values of \( kT, N, \) and \( U \) are inserted in the equation for \( U_0^1, M^1 \) and \( C \) and the process repeated.
CHAPTER III

APPARATUS

Shock Tubes

Two shock tubes were used in the experimental work to be described here. Both tubes were of glass and quartz tubing, of 2.5 cm inside diameter, approximately 100 cm long, and could be fitted with various electromagnetic drivers. One tube was used with drivers of co-planar and co-axial electrode configurations, and was powered by a condenser rated at 5 μf and charged to 12 kv. The design, construction, and operation of this tube were described by Neufeld (1963). A schematic diagram of the arrangement of the apparatus is shown in Figure 2.

The two velocity measuring photomultipliers view the shock tube through collimated slits separated by five centimeters. The time interval between the responses of the photomultipliers was used to compute the speed of a luminous front of gas advancing down the tube. The three drivers used with this shock tube are shown in Figure 3.

The other shock tube was used with an electrode-less driver and was powered by a condenser bank of 9.6 μf, charged to 14 kv, switched through a vacuum spark-gap switch and with provision for shorting the bank at any time after the discharge with a second vacuum spark-gap switch. This shock
Figure 2—Schematic of Shock Tube with Electrodes

- Quartz
- Objective Lens
- Velocity Measuring Photomultipliers
- Shock Driver
- Trigger Unit
- Spark Gap Switch
- Capacitor Bank
- RCA IP28 or Phillips 150CVP Photomultiplier
- Cathode Follower
- To Oscilloscope
- To Gas Metering and Vacuum System
Figure 3 - Driver Electrode Configurations

- Co-axial Configuration
- Quartz Tube
- "O"-ring
- Epoxy
- Lucite
- Copper
- Aluminum Backing Plate
- Co-planar Configuration
tube with its condenser bank with switches and electronic timing circuits is described by Cormack (1962). A schematic diagram of the arrangement of apparatus is shown in Figure 4 and the details of the electrodeless driver are shown in Figure 5.

The arrangement of the velocity measuring and spectroscopic apparatus was the same for both shock tubes.

**Spectroscopic Equipment**

Time integrated spectra used in preliminary investigation of radiation from the plasma were obtained using a Hilger El spectrograph.

Two grating monochromators, a 500 mm Bausch and Lomb and a 500 mm Jarrel Ash were used to study time variation of spectral intensities. These monochromators could be fitted with either a Phillips 150 CVP photomultiplier, sensitive in the infra-red, or an RCA IP 28 for use in the visible and ultra violet regions of the spectrum. A Corning 2-62 red filter was used to eliminate second order spectra when using the instruments above 6200Å. The dispersion of both the monochromators was 16Å/mm throughout the spectrum. The Bausch and Lomb monochromator was capable of resolving lines of approximately 1.5 Å half-width separated by 4 to 5 Å while the Jarrel Ash instrument could resolve lines of 0.5 Å half-width separated by 0.75 Å. The latter monochromator was used to obtain profiles of lines having half widths of approximately 1 Å.
Figure 4 - Schematic of Electrodeless Shock Tube

Electrodeless Driver

Magnetic Pick-up Coil

Shorting Switch Timing Circuit

Shorting Trigger

Vacuum Spark Gap Switches

To Gas Metering and Vacuum System

Capacitor Bank

Figure 5 - Electrodeless Driver

Clamped Conductors (Clamps not shown)

One turn Driving Coil

Split Ring set 3/16 inch from Driving Coil

Mylar Insulation between Conductors and inside rings
Electronic Ancilliary Equipment

The output of the velocity measuring photomultipliers was fed through shielded cable to the difference amplifier on a Tektronix type 551 oscilloscope fitted with a trace recording camera (Dumont). The outputs of the photomultipliers on the monochromators were fed into cathode followers of standard design. The output of the cathode follower was fed through shielded cable to the single input preamplifier. The rise time of the photomultiplier, cathode follower, and preamplifier circuit was of the order of 0.1 microsecond. The oscilloscope and the timing unit for the bank shorting switch were triggered by a pick up coil coupled to the current in the shock tube discharge. Theophanis (1960) High Voltage Pulse Units were used to trigger all the spark gap switches save the main switch for the electrodeless shock tube. The Kerr cell timing unit was triggered from a Tektronix 1000:1, 25 kv probe attached across the driver leads on the shock tube.

The variable high voltage (0-1.5 kv) power supplies to the photomultipliers allowed adjustment of spectrophotometer sensitivity to accommodate a great range of spectral intensities without changing the spectrophotometer entrance slit.

High Speed Photographic Equipment

Photographs of the discharges advancing in the shock tubes were taken with an Avco Kerr cell followed by a
standard Polaroid camera. The Kerr cell high voltage supply was triggered from a Theophanis unit which in turn was triggered either by the camera timing unit or from a variable auxiliary output on the bank shorting switch timing unit.
CHAPTER IV

EXPERIMENTAL INVESTIGATION

Preliminary Investigation

Previous spectroscopic studies of plasmas in this laboratory (Simpkinson (1961), Barnard, Cormack and Simpkinson (1962)) showed many spectral lines from various impurities such as Hydrogen, Carbon, Silicon, and Copper. Time resolved intensity measurements showed that there was no significant time lag between lines from the rest gas and carbon lines, as expected for a shock plasma followed by a driving plasma. The plasma appeared to be a slug driven from the electrodes sweeping up the gas in front of it. Photographs made through a Kerr cell by Barnard and Cormack (1963) supported the above "slug" theory. The front of the advancing plasma was not plane, and retained, for tens of centimeters of its travel down the tube, certain characteristics caused by the original discharge between the electrodes.

It was decided to make a rough spectroscopic analysis of the impurity content of the plasma generated in the shock tube which was used in the above work. Carbon was a convenient impurity to work with and should be indicative of the general level of impurity. The monochromator entrance slit was focused inside the tube at a point approximately 15 cm from the co-planar electrode driver. The instrument was set on the wavelength of a carbon line (CII4267Å) and the oscilloscope trace compared with that from an argon line.
(AII4806A°), in each case the background signal from a point near the line being subtracted from the signal at the line centre. The results of this analysis with intermediate calculations, will be found in Appendix IV. The ratio of carbon to argon was found to be approximately one third. As carbon was just one of the impurities observed in this plasma this would mean that the impurity level could be higher than 50% in the tube.

Next, the two designs of co-axial drivers shown in Figure 3 of Chapter III were tried. The opening of the shutter was timed to take pictures of the luminous front at various distances from the drivers. Time integrated spectra were taken at approximately 12 cm from the driver and the velocity of the luminous front was measured at various points in the tube. These two co-axial configurations did not yield encouraging results. While the luminous fronts produced by these drivers were a little closer to being plane than those from the co-planar driver there was no evidence of a shock wave being formed ahead of the luminous front and there was a three or four fold pressure increase after the firing, as compared with a two or three fold increase for the co-planar driver, indicating a high impurity level. This was supported by the great number of impurity lines in the spectra taken of the luminosity in the tube. These configurations were deemed unsuitable for producing plasma on which to test spectroscopic diagnostic techniques. On the basis of the high impurity level and the fact that no shock wave was evident it was decided to investigate an electrodeless configuration.
Electrodeless Shock Driver With Argon

The driving coil configuration shown in Figure 5 of Chapter III was set up with argon gas in the tube. All measurements made with argon were done at an initial gas pressure of .500 mm Hg. The gas could be left in the tube for up to 50 firings with no increase in pressure, indicating a lack of volatile impurities.

(a) Magnetic Probe Measurements

The output of the magnetic probe coil in the circuit between the shorting switch and the driving coil was fed through a passive integrator network to the oscilloscope and showed a damped sinusoidal discharge of period 4.8 microseconds with a calculated initial peak amplitude of approximately 100 Kiloamperes. The current waveform when the shorting switch was activated is shown in Figure 6 with the unshorted waveform shown dashed.

**Figure 6 - Electrodeless Driver Coil Current**
The current after the shorting switch actuation time exhibits an exponential decay with a ripple due to the bank current oscillating through the parallel circuit of shorting switch and load.

(b) **Photographic Measurements**

Photographs were taken of the development of the discharge by timing the Kerr cell shutter with the variable delay auxiliary output on the shorting trigger timing circuit and are shown in Figure 7. Pictures 3 through 5 show the development of the discharge from a time of 1.6 microseconds after the onset of the oscillatory current in the coil to approximately 9 microseconds after this time. The pictures taken early in the discharge development have the split ring "field shaper" removed to facilitate observation of the discharge. Pictures 7, 1, and 9 are taken at times near the second, third and fourth maxima of \( \frac{dB}{dt} \) (and hence \( E_\phi \)) within the tube through the driver coil. On each of these maxima a surge of azimuthal current flows which causes increased light from the tube at these times. Each surge of current is driven down the tube and rapidly catches up with the front produced by the surge before it. It can be seen that the second surge produces a rather flat front whereas the third results in an irregular front. From pictures 9 and 5 it is seen that the shaper doesn't affect the front speed.

With the condenser bank shorted immediately after the second maximum of \( \frac{dB}{dt} \) a shock front seems to separate from the luminous front formed by the second surge of current. This is evidenced by the plane front with a relatively homo-
Figure 7 - Photographs of Discharge Development in Electrodeless Shock Tube with Argon and Helium

Same time after start of discharge

Arrows in g to u indicate separated front seen in original photos
geneous area behind it for a distance of about one centimeter (Pictures † and ‡). Pictures § and † were taken with and without the "shaper" at the same time after the onset of the bank current. Thus the shaper results in a higher speed of advance of the discharge only when the bank is shorted. It was felt that the lcm thick, plane fronted plasma slug obtained with the shaper when the bank is shorted near the first negative peak of current was the best that could be obtained without a faster capacitor bank and much more sophisticated driving coil configurations. In picture † the luminous front lies approximately 6.5 cm from the front face of the driving coil. The speed of the front past this point was approximately 0.6 cm per microsecond. It was decided to focus the spectrograph slits in this plane for the spectroscopic measurements.

(c) Spectroscopic Measurements

The entrance slit of the Hilger El spectrograph was focused inside the tube at the 6.5 cm station. Exploratory, time integrated spectra were taken in the visible and near ultra violet, and in the near infra red. The lines seen in these spectra were from the Al, AII, CII, SiII, CaII and NaII spectra. From the above spectra were chosen the lines to be studied with the monochromators.

The entrance slits of both monochromators were then focused at the centre of the tube at the 6.5 cm station
from the front face of the driving coil. One monochromator was moved up or down the tube with relation to the other in order that the beginning of signals originating from the same spectral line came simultaneously from each monochromator. The monochromators could then be used to observe simultaneously two spectral lines. Velocity measurements were made by noting the time difference between the signals from one of the monochromators and a collimated photomultiplier displaced a known distance down the tube from the monochromator. Velocity measurements were not taken on every shot as it was found that if the luminous front arrived at the 6.5 cm station at the same time, its velocity was the same each time. Thus, coincidence between the times of onset of the signal on two separate firings could be used as an indication of the same shock velocities for the two firings.

All monochromator responses which were to be used for comparison of spectral intensities were converted to a common scale. This conversion was done by reducing the response to that which would have occurred at a standard photomultiplier voltage and then dividing by the monochromator-photomultiplier combined sensitivity at the wavelength being studied. The procedures by which the voltage reduction factor or "sensitivity multiplier" and the sensitivity curve were obtained are described in Appendix II.

1 Spectroscopic Impurity Determination

The comparison of the intensities of the
lines CII 4267 Å and AII 4806 Å gave an estimate of 0.06 for the ratio of carbon to argon (see Appendix III for details). Thus, the impurity level would appear to be significantly less in the electrodeless tube than in a shock tube with electrodes.

As it was suspected that the impurity spectra came from a layer next to the walls of the tube an experiment was conducted to determine if this was true. This was done by placing an obstruction consisting of an \( \frac{1}{2} \)" diameter aluminum cylinder in the centre of the tube and examining the time resolved spectra from the flow stagnation region before the obstruction. The aluminum cylinder was mounted with an end face 7 cm. from the driving coil and the monochromator entrance slit was focused \( \frac{1}{16} \)" in front of this face. A silicon line, SiII 4131 Å was chosen to represent the impurities known to come from the wall; the response of the monochromator to light from this line did not change when observed with and without the obstruction in the tube. The peak intensity of the line AII 4806 Å was seen to be approximately three times greater with the obstruction than without it. Thus it would appear that the impurities coming from the wall do not mix into the homogeneous region of plasma following the plane front seen in the photographs.

(2) **Electron Temperatures and Densities**

Typical time variations of intensities for a pair of Al and AII lines are shown in Figure 8. The
Figure 8 - Intensity histories of AI, AII and H lines in tube with Electrodeless driver.

AI 8115Å

precursor signal

ordinate x 10

AI 4806Å

precursor signal

ordinate x 2

Hα 6563Å

time (μsec)

2 4 6 8 10 12 14 (μsec)

0 2 4 6 8 10

10 8 6 4 2 0

16 12 8 4 0

320 240 160 80 0

10
signals shown have been corrected for monochromator sensitivity variation with the wavelength and have had the background spectral intensity subtracted. The AII signal at 14.5 microseconds shows clearly the demarcation between the plane fronted homogeneous layer seen in the photographs and the more luminous discharge gases following. The strong AII lines are in the visible region of the spectrum; increased intensity of these lines will make the gas more luminous than an increased intensity in Al which has its strongest lines in the infrared.

In the observations of the argon spectra it was noticed that weak emission of both Al and AII lines took place well before the arrival of the luminous front. These "precursor" signals have been observed by other workers (see McLean (1961)) who have concluded that they do not originate from light emitted in the discharge and by the tube walls. In Figure 8 it is seen that these signals become measureable at about 3.5 microseconds after the onset of the discharge, that is at the second peak of the discharge current.

The time history of the $H_\alpha$ line exhibits a different behaviour in the precursor radiation as can be seen from Figure 8. Time resolved profiles of this line were obtained by recording average time histories at wavelengths on the broadened line in the precursor and in the plasma behind the luminous front. For the much narrower profile in the precursor it was necessary to use the Jarrel-Ash instrument with a 10 micron entrance slit and a 25 micron exit slit. With
such narrow slits the instrument was capable of measuring the profile of a line with a whole half-width greater than 0.5A°, i.e., an infinitely narrow spectral line would result in a measured whole half-width of 0.5A°. The procedure by which the measured profile is corrected for the above instrumental broadening is described in Appendix IV. A complete wavelength versus intensity profile of the H_C line shows that in the precursor the line is quite narrow, though wide enough for the monochromator to measure its profile, and hence obtain a rough value (within a factor of 2) for the electron density in the gas ahead of the shock wave. While the amplitude of the precursor signal changes appreciably with time, its breadth does not. This means that the electron density does not change rapidly ahead of the shock wave.

Electron temperatures and densities calculated from the spectral data are displayed in Table 1. Also shown are theoretical values of electron temperatures and densities behind shock waves propagating at 0.6 cm per microsec. and 0.65 cm per microsec. into a gas at the temperature and ionization observed spectroscopically from the precursor radiation. The calculations for the higher shock speed were made to show the expected values at the upper limit of the velocity error envelope.

The main experimental errors in the determination of electron density arise through lack of accuracy in obtaining the line profile and uncertainty in fitting the line profile to the appropriate theoretical profile. As pointed out above,
Table 1

kT_e & N_e for v_s = 0.6 cm/µsec

<table>
<thead>
<tr>
<th></th>
<th>In Precursor</th>
<th>After Shock</th>
<th>Theoretical, After Shock with Preheating</th>
</tr>
</thead>
<tbody>
<tr>
<td>kT_e</td>
<td>lev</td>
<td>1.3 ev</td>
<td>1.18 ev (1.23 ev)#</td>
</tr>
<tr>
<td>N_e</td>
<td>5x10^{15} cm^{-3}</td>
<td>1.4x10^{17} cm^{-3}</td>
<td>6.3x10^{16} cm^{-3} (8.1x10^{16} cm^{-3})#</td>
</tr>
</tbody>
</table>

# Quantities in brackets are for shock speed of .65 cm per microsecond

from the narrow H_x profile seen in the precursor the experimental value for N_e is estimated within a factor of 2. For the wider H_x line emitted from the plasma behind the shock front the uncertainty in matching profiles could result in an error of ±10% in N_e. Errors in obtaining the experimental line profile could result in a further 5% error giving a total uncertainty of ±15% for the value of N_e behind the shock front.

The error in the experimental value of kT_e would be ±15% if the observed spectral intensity ratios are in error by a factor of 10, while a further 5% uncertainty in kT_e is introduced by N_e being in error by a factor of 2. Thus, for the values of kT_e shown in Table 1, the uncertainties due to errors in measurement are ±20% in the precursor and ±15% after the shock.
No calculations were made of the spectroscopic temperature behind the second luminous front but it is apparent from the steep rise in the AlII signal with no attendant rise in the AI signal that the temperature is greater behind the second luminous front than after the shock front.

**Electrodeless Shock Driver With Helium**

No worthwhile results were obtained with helium. This gas having a higher ionization potential is more difficult to breakdown and does not give a luminous discharge on the first maximum of \( \frac{dR}{dt} \) but does so on the second, third and fourth maxima each of which appears very irregular (see pictures \( \text{v to z} \) for progression of discharge in helium).

The combined, irregular fronted discharge advanced past the 12 cm station at a speed of about 1.25 cm per microsecond. The spectroscopic temperature and electron density were measured after the luminous front using the intensities of the lines HeI 5876Å, HeII 4686Å, and the broadening of the HeII 4686Å line. These values were 3.47 ev and \( 5 \times 10^{16} \text{cm}^{-3} \) respectively. This temperature is almost double that of helium heated by a shock with the above speed.

**Observations of Precursor Radiation with a Co-Planar Driver**

From the above work with the electrodeless tube it is apparent that precursor ionization and excitation must be considered when attempting to explain the processes taking place before a luminous front advancing into a gas.
Therefore, at this point it was decided to investigate more fully the precursor radiation. The ionization ahead of the front was believed to be due to the photon flux from behind the front. The shock tube with co-planar electrodes was chosen for this study because its discharge is more intense. It was hoped that the high impurity level found in the plasma behind the luminous front in this tube does not play a significant role in the precursor ionization.

From previous work it has been established that the co-planar electrode configuration gives reproducible results so readings were made with only one monochromator. The oscilloscope channel with the differential amplifier fed from the two collimated photomultipliers was used to display the time of passage of the luminous front through 5 cm. In order to measure Hα or Hβ profiles in the precursor radiation it was necessary to add approximately 2% hydrogen to the rest gas being used as fresh gas was used in the tube for each firing; in the electrodeless tube the same gas was used for many shots and small amounts of hydrogen and other impurities accumulated.

Observations with argon were made at two stations in the tube, 12 cm and 17 cm from the driver, with an initial pressure, \( p_0 \), of 0.6mmHg. Some additional readings were taken at 17 cm with \( p_0 = 1\text{mmHg} \). Observations made with helium were all at the 17 cm station and were taken at two pressures, 0.1mmHg and 0.3mmHg. Helium was
chosen for closer study as its atomic parameters are better known.

(a) Argon

(1) Twelve Centimeters From The Discharge

At 12 cm from the discharge the speed of the luminous front was 1.67 cm per microsecond with \( p_0 = 0.6 \text{mmHg} \). The time variations of intensity of typical Al, AlII, and AlIII lines are shown in Figure 9. These traces include the line intensities after the luminous front for comparison with the precursor intensities. In Figure 9, on the trace for AlII 4806 Å it will be noticed that the time before the luminous front arrival has been roughly divided into two periods, corresponding to two regions before the luminous front in the shock tube. There is a break in the slope of the intensity trace of AlII and AlIII lines at the division. These regions have been labelled early and late precursor and will be referred to in the discussion. Two traces on the \( H\alpha \) profile in the precursor are shown in Figure 10, one on the line centre (measured at 6563.25 Å) and the other, 1 Å off the centre. The \( H\alpha \) broadening cannot be measured before 5.5 microseconds after the beginning of the discharge. After this time it is broadened sufficiently to get an estimate of the electron density. Table 2 gives the values of electron density and temperature in the precursor immediately before, and 0.5 microseconds before the luminous
Figure 9 - Intensity histories of Al, AlII and AlIII lines in tube with Co-planar driver @ 12 cm from driver $p_0 = 0.6$ mmHg.

Al $8115^\circ$

precursor signal

AlII $4806^\circ$

late precursor region
early precursor region

AlIII $3286^\circ$

precursor signal
front as well as the electron density and average temperature immediately after the front. The temperature after the front was obtained by averaging the values calculated from pairing the intensities of 5 Al lines (8006Å°, 8014Å°, 8103Å°, 8115Å°, and 8408Å°) and 6AlII lines (4348Å°, 4579Å°, 4589Å°, 4764Å°, 4806Å°, and 4933Å°). The temperature before the front was calculated from averaging results from one pair of Al and AlII lines (Al 8115Å° and AlII 4806Å°), and from one pair of AlII and AlIII lines (AlII 4806Å° and AlIII 3286Å°), and assuming equilibrium between the electron and the atomic excitation temperatures. Though the existence of such equilibrium is open to doubt in the region of relatively low electron density before the front, this assumption was made in the absence of better knowledge of the mechanisms of excitation.
As the sensitivity of the monochromator could not be determined in the ultra-violet, the calculation involving AIII 3286Å necessitated taking as known the temperature after the luminous front and calculating only the change in the last term in the denominator of Equation 6 of Chapter II. Knowing the change in this term across the luminous front we can calculate the temperature ahead of the front. The percentage variations written after the temperature are the maximum spread of the observed values from which the average is calculated.

Table 2

$kT_e$ and $N_e$ for $v_s = 1.67 \text{cm/µ sec} @ 12 \text{ cm from Arc in Argon assuming thermal equilibrium}$

<table>
<thead>
<tr>
<th></th>
<th>In Precursor at shock</th>
<th>In Precursor, .5 sec before shock</th>
<th>After shock</th>
</tr>
</thead>
<tbody>
<tr>
<td>$kT_e$</td>
<td>1.66 ev (±4%)</td>
<td>1.61 ev (±4%)</td>
<td>2.3 ev (±7%)</td>
</tr>
<tr>
<td>$N_e$</td>
<td>$1 \times 10^{16}$ cm$^{-3}$</td>
<td>$3 \times 10^{15}$ cm$^{-3}$</td>
<td>$0.97 \times 10^{18}$ cm$^{-3}$</td>
</tr>
</tbody>
</table>

(2) Seventeen Centimeters From Discharge

At the 17 cm station the velocity of the luminous front was 1.31 cm per microsecond at a pressure of 0.600 mmHg and 0.83/ cm per microsecond at a pressure of 1 mmHg. Here no AI signal can be picked up from the precursor radiation. The AII and AIII traces in the precursor are shown in Figure 11 for the two pressures. Table 3 gives the spectroscopic values
Figure 11 - Precursor Intensity histories of AII and AIII lines in tube with Co-planar driver @ 17 cm from driver, \( p_0 = 0.6 \) and 1 mmHg.

Note - the intensity scales on these two graphs are each in arbitrary units and are unrelated as the calibration procedure could not be carried out in the ultraviolet.
of $kT_e$ and $N_e$ immediately before the front and after the front for a front velocity of 1.3 cm per microsecond. The value of $kT_e$ in the precursor was calculated from the change in intensity ratio across the luminous front, of the same AII and AIII lines used in Table 2. This ratio increased by a factor of 19. The time history of points on the H$^\alpha$ line appear the same as in the case of the 12 cm readings except the line is narrower. Again the broadening can not be measured more than 1 microsecond before the shock.

**Table 3**

$kT_e$ and $N_e$ for $v_s = 1.31$ cm/μsec at 17 cm from Arc in Argon assuming thermal equilibrium

<table>
<thead>
<tr>
<th></th>
<th>Precursor</th>
<th>After Shock</th>
</tr>
</thead>
<tbody>
<tr>
<td>$kT_e$</td>
<td>1.48 ev</td>
<td>2.06 ev</td>
</tr>
<tr>
<td>$N_e$</td>
<td>6x10$^{15}$ cm$^{-3}$</td>
<td>9x10$^{18}$ cm$^{-3}$</td>
</tr>
</tbody>
</table>

(b) **Helium**

Line intensity time variations at the 17 cm station are displayed in Figures 12 and 13 for the two pressures 0.1 mmHg and 0.3 mmHg. The intensity scales in these figures are all in the same relative units. Table 4 shows the electron temperatures and densities after the luminous front and in the precursor immediately before the front for the above two pressures. These values were calculated from the intensity of HeI 5876Å and HeII 4686Å lines. Calculations of the
Figure 12 - Precursor Radiation Intensity Histories for HeI5876Å°, 4471Å° and 3888Å° @17 cm from driver

HeI5876Å° 
2^3P-3^3D
luminous front
to peak at 3.6
p_o=0.3 mmHg
p_o= 0.1 mmHg

HeI4471Å° 
2^3P-4^3D
to peak at 0.089
luminous front

time

HeI3888Å° 
2^3S-3^3P
luminous front
to peak at 0.27

time
Figure 13 - Precursor Radiation Intensity Histories
for HeI5016A°, 4922A° and HeII4686A°
@17 cm from driver

HeI5016A°
2^1S - 3^1P

HeII4922A°
2^1P - 4^1D

HeII4686A°
3^2D - 4^2F etc.
ratios of the numbers of He atoms in the upper excited states of the HeI lines observed were made from Equation (3) of Chapter II at three separate times in the precursor and at the peak of intensity after the passage of the luminous front. These are displayed in Table 5 with the ratio which could be expected with the excited states in equilibrium. Four of these ratios are insensitive to temperature, the others vary slowly with temperature. It is seen the states with principal quantum number 4 are very much under-populated compared with equilibrium conditions. If the intensity of the $2^3P - 4^3D$ line is inserted in Equation (6) of Chapter II with that of the HeII 4686Å line the temperatures in Table 4 will be increased by approximately 0.7 ev.

Table 4

$kT_e$ and $N_e$ for $p_0 = 0.1 \text{mmHg}$ and $p = 0.3 \text{mmHg}$ at 17 cm from Arc in Helium assuming thermal equilibrium

<table>
<thead>
<tr>
<th></th>
<th>Precursor</th>
<th>After Shock</th>
</tr>
</thead>
<tbody>
<tr>
<td>$kT_e$</td>
<td>2.32 ev</td>
<td>3.63 ev</td>
</tr>
<tr>
<td>$N_e$</td>
<td>$2 \times 10^{15} \text{cm}^{-3}$</td>
<td>$2 \times 10^{17} \text{cm}^{-3}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Precursor</th>
<th>After Shock</th>
</tr>
</thead>
<tbody>
<tr>
<td>$kT_e$</td>
<td>2.43 ev</td>
<td>3.6 ev</td>
</tr>
<tr>
<td>$N_e$</td>
<td>$2 \times 10^{15} \text{cm}^{-3}$</td>
<td>$4.2 \times 10^{17} \text{cm}^{-3}$</td>
</tr>
<tr>
<td>Time from start of Discharge</td>
<td>1.0 μsec.</td>
<td>2.4 μsec.</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>-----------</td>
<td>-----------</td>
</tr>
<tr>
<td>( \frac{N_03D}{N_03P} )</td>
<td>2.2</td>
<td>3.92</td>
</tr>
<tr>
<td>( \frac{N_{043D}}{N_{041D}} )</td>
<td>1.73</td>
<td>3.52</td>
</tr>
<tr>
<td>( \frac{N_033D}{N_033P} )</td>
<td>1.96</td>
<td>2.41</td>
</tr>
<tr>
<td>( \frac{N_033P}{N_031P} )</td>
<td>1.12</td>
<td>1.63</td>
</tr>
<tr>
<td>( \frac{N_033D}{N_041D} )</td>
<td>12.8</td>
<td>63.2</td>
</tr>
<tr>
<td>( \frac{N_{041D}}{N_{031P}} )</td>
<td>0.172</td>
<td>0.062</td>
</tr>
<tr>
<td>( \frac{N_{033D}}{N_{043D}} )</td>
<td>7.4</td>
<td>18</td>
</tr>
<tr>
<td>( \frac{N_{043D}}{N_{033P}} )</td>
<td>0.265</td>
<td>0.13</td>
</tr>
</tbody>
</table>
Table 5B

Ratios of $N_{om}$ at Various Times in Helium, $p_o=0.3$mmHg

<table>
<thead>
<tr>
<th>Time from start of Discharge</th>
<th>1.5 $\mu$sec.</th>
<th>3.25 $\mu$sec.</th>
<th>3.5 $\mu$sec. (luminous front)</th>
<th>4.2 $\mu$sec.</th>
<th>equilibrium</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\frac{N_{O_3^3D}}{N_{O_3^3P}}$</td>
<td>2.2</td>
<td>6.9</td>
<td>6.2</td>
<td>12.8</td>
<td>5</td>
</tr>
<tr>
<td>$\frac{N_{O_4^3D}}{N_{O_4^3D}}$</td>
<td>0.646</td>
<td>0.96</td>
<td>1.04</td>
<td>2.22</td>
<td>3</td>
</tr>
<tr>
<td>$\frac{N_{O_3^3D}}{N_{O_3^3P}}$</td>
<td>2.15</td>
<td>1.97</td>
<td>2.01</td>
<td>1.85</td>
<td>1.667</td>
</tr>
<tr>
<td>$\frac{N_{O_3^3P}}{N_{O_3^1P}}$</td>
<td>1.02</td>
<td>3.5</td>
<td>3.1</td>
<td>6.95</td>
<td>3</td>
</tr>
<tr>
<td>$\frac{N_{O_3^3D}}{N_{O_4^1D}}$</td>
<td>7.85</td>
<td>25.2</td>
<td>24.8</td>
<td>35.9</td>
<td>4.17 before 3.6 after</td>
</tr>
<tr>
<td>$\frac{N_{O_4^1D}}{N_{O_3^1P}}$</td>
<td>0.28</td>
<td>0.274</td>
<td>0.25</td>
<td>0.357</td>
<td>1.21 before 1.4 after</td>
</tr>
<tr>
<td>$\frac{N_{O_3^3D}}{N_{O_4^3D}}$</td>
<td>12.2</td>
<td>26.2</td>
<td>23.8</td>
<td>16.1</td>
<td>1.4 before 1.2 after</td>
</tr>
<tr>
<td>$\frac{N_{O_4^3D}}{N_{O_3^3P}}$</td>
<td>0.176</td>
<td>0.075</td>
<td>0.084</td>
<td>0.115</td>
<td>2 before 2.33 after</td>
</tr>
</tbody>
</table>
CHAPTER V

DISCUSSION AND CONCLUSIONS

Nature of Luminous Plasma

From the work done on shock tubes with different configurations of driver electrodes the impurity concentration in the luminous slug would appear to be less a function of electrode configuration than of some other parameter. Other workers such as Cormack (1962), and Starr and Naff (1960) reach the conclusion that the impurity concentration is proportional to \( \int I^2 dt \) which varies inversely with the ringing frequency of the capacitor bank. The banks available in this laboratory did not permit the investigation of the effect of very high voltage, low inductance, high frequency capacitor banks on impurity concentration.

From the observation of a more or less irregular luminous front followed by gas which strongly emits impurity spectra it was concluded that in all the shock tubes with electrodes used in this laboratory no real shock plasma has been found.

In these experiments, the impurity concentration in the discharge heated plasma was considerably reduced by the use of an electrodeless driver on the shock tube. With the electrodeless driver, a shock wave appears to be formed in argon when the driving discharge is terminated after two pulses of current within the tube. The spectroscopically measured
electron temperature of the region behind the shock wave was approximately 20% higher than the theoretical values obtained from the Rankine-Hugoniot equations for a shock wave propagating into a cold gas. However, it was possible to measure approximately the electron temperature and density ahead of the shock wave. When the spectroscopically observed conditions ahead of the shock are inserted in the Rankine-Hugoniot equations the agreement between theory and experiment for the region behind the apparent shock wave become closer than 10%, the approximate experimental error. From this close agreement and from the evidence that wall impurities were not found in the central one half inch diameter core of the plane-fronted luminous region preceding the more luminous remains of the discharge we conclude that a shock wave separates from the advancing discharge.

The attempt to create the above conditions in helium was not successful. The luminous fronts were more irregular than in the case of argon and moved at approximately twice the speed. Other workers (Jeanmaire et al 1963, Chang 1961) have found that discharges advancing above a certain critical speed, dependent on the given experimental parameters, do not establish shock fronts. The shock speed in argon in the electrodeless tube was 0.6 cm per microsecond as compared with typical shock speeds of 1.3 to 2 cm per microsecond in the other electromagnetic shock tubes. This shock speed of 0.6 cm per microsecond is as slow as that of fast mechanically driven shock waves.
Precursor Ionization

The studies of the precursor radiation from argon in the shock tube with co-planar electrodes permit only a qualitative discussion in the absence of data on the excitation cross sections for the relevant energy levels. The intensity measurements made at 17 cm from the driver show that an increase in the initial pressure drastically reduces all spectral intensities except those just after the initial discharge. This is most marked in the case of AIII where the intensity at 2 microseconds after the initiation of the discharge is unchanged by the pressure increase and it is also substantially unchanged by moving the observation point from 12 cm to 17 cm from the driver. This behavior would seem to indicate that ionization of argon atoms and ions at points remote from the luminous front is caused by radiation from the discharge itself, and that this radiation has a long mean free path. With $p_0=0.6\text{mmHg}$ the precursor excitation of AII and AIII lines begins a steep rise at 0.6 to 0.75 microseconds before the arrival of the luminous front thus defining the beginning of the late precursor region (see Figure 9, Chapter IV). This region is always about 1 cm thick. Because the late precursor region always extends the same distance before the front we conclude that it is caused by light which is strongly absorbed by the gas ahead of the front or through electrons which diffuse out from the front. The theory that the above behavior is caused by photo-excitation is favoured
here over the electron diffusion theory. From the observed spectroscopic temperature before the luminous front we can calculate a degree of ionization, \( \alpha \), of 1.29; the corresponding electron density of \( 2.62 \times 10^{16} \text{cm}^{-3} \) is much greater than the observed electron density of \( 6 \times 10^{15} \text{cm}^{-3} \). This apparent deficiency of electrons before the front could be caused by photo-excitation enhancing the populations of the excited states of AII and AIII ions and thus making the gas appear hotter and more ionized than it actually is.

In the case of helium the behavior of the precursor radiation intensity line variation is somewhat similar to that in argon, having the sharply defined early and late precursor regions in advance of the luminous front. The major effect of the reduction of \( p_0 \) from 0.3 mmHg to 0.1 mmHg was to more than double the thickness of the late precursor region. Another effect of the decreased pressure was to considerably reduce the intensity of the HeII line in the precursor radiation. Again as in the case of argon we have a seeming deficiency of electrons in the region before the luminous front. At the observed spectroscopic temperature and electron density the gas should be completely ionized, yielding an electron density of at least \( 1 \times 10^{16} \text{cm}^{-3} \) for \( p_0 = 0.3 \text{mmHg} \) and \( 0.33 \times 10^{16} \text{cm}^{-3} \) for \( p_0 = 0.1 \text{mmHg} \). The electron density observed, \( 0.2 \times 10^{16} \text{cm}^{-3} \), is much too low and does not change appreciably with \( p_0 \). This last characteristic would seem to suggest that the electrons come from photo-ionization of wall
impurities. The more than linear decrease of HeII line intensity with $p_0$ is compatible with photo-excitation as electronic excitation should be linear because the electron density remains fairly constant with changing $p_0$.

From Table 5 it is seen that all the ratios of neutral helium excited state populations depart from those which would be expected at equilibrium. Far ahead of the luminous front the triplet states are all underpopulated with respect to singlet states of corresponding principal quantum number. As the front approaches and passes, the relative populations of the triplet states increase and the above ratios approach or pass the equilibrium ratios. The ratios of populations of states of quantum number 4 to those of quantum number 3 are always smaller than would be expected under equilibrium conditions.

**Attainment of Equilibrium in Plasma Investigated**

Following the work of H. R. Griem (1963) the criteria for "local thermal equilibrium" in time independent and homogeneous laboratory plasmas is that collisional processes be more important than radiative decay and recombination and that the velocity distributions of the colliding particles be thermal. Since most collisional excitations and ionizations and their inverses involve electrons, the electron velocity distribution must be thermal. This condition should be satisfied here as even at electron densities as low
as \(10^{13}\) cm\(^{-3}\) at a temperature of 1 ev the time for electronic relaxation is of the order of \(10^{-1}\) sec. (Spitzer (1956)). The criterion adopted by Griem to determine if collisional processes dominate over radiative processes is that the rate for a given collisional process be ten times that for competing radiative processes.

The rates for collisional excitation and ionization and hence the time to achieve a given distribution of atoms and ions among the excited states may be calculated knowing the cross sections for electronic collisions and the temperature and density of the electrons. Radiative rates are easily obtained knowing the transition probabilities between the energy levels concerned. Calculations can easily be made for helium as values of cross sections for excitation and ionization from the ground state are available for neutral helium (Gabriel and Heddle (1960) and Francis (1960)) and may be easily calculated for hydrogenic, ionized helium and for transitions between excited levels in neutral helium (Seaton (1962)).

Inserting the appropriate cross-section, \(\sigma_{ij}(E_e)\), where \(E_e\) is the electron energy, in the equation

\[
R_{i,j}^{\text{coll}} = 2 N_e \left(\frac{2}{\pi}\right)^{1/2} \frac{kT_e}{m_e} \int E_j - E_i \sigma_{ij}(E_e) \left(\frac{E_e}{kT_e}\right) \frac{dE_e}{E_e} \exp\left(-\frac{E_e}{kT_e}\right)
\]

we obtain the rate of collisional transfer per atom from energy state \(E_i\) to \(E_j\). Considering the neutral helium
energy level $2^1P$ at an electron density of $10^{15}\text{cm}^{-3}$ and electron temperature of 2eV, we obtain a rate, $R_{2^1P-3^1D}^{\text{coll}}$ of $570 \times 10^6 \text{sec}^{-1}$ or a time between collisions of $1.75 \times 10^{-3}$ microsecond for this level, assuming the radiation $2^1P-1^1S$ (resonance line) is trapped. The assumption of trapping is valid at the values of $N_0 (\sim 10^{16}\text{cm}^{-3})$ used in this work (see Phelps (1958)). The above calculation yields even higher collisional rates for the higher excited levels of helium because of the closer grouping of energy levels as the principal quantum number increases. The populations of the excited states could therefore be expected to always assume an equilibrium distribution among themselves at the above electron temperature and density under steady state conditions.

The theoretical time of relaxation to collisional equilibrium for the conditions observed before and after the luminous front will now be calculated. As almost all of the helium atoms must be ionized an approximate time for the plasma to reach equilibrium between neutral and ionic helium can be found by inverting the rate,

$$R_{\text{I,II}}^{\text{coll}} \approx R_{1,2}^{\text{coll}} + R_{1,\text{ion}}^{\text{coll}}$$

of collisional transfer from the ground state to the states of principal quantum number 2 and to the ionized state. The
rate $R_{1,2}^{\text{coll}}$ is the critical rate as the energy gap between the $n = 1$ and $n = 2$ levels is much greater than that between higher levels and so the upper levels are depopulated rapidly towards ionization. The rate $R_{1,\text{ion}}^{\text{coll}}$ is roughly 6% of $R_{1,2}^{\text{coll}}$ at an electron temperature of 2 ev and 20% of $R_{1,2}^{\text{coll}}$ at 4 ev. For $N_e = 10^{15} \text{cm}^{-3}$ at the two temperatures, 2 ev and 4 ev, this calculation yields times of 3600 microseconds and 14 microseconds respectively. As even the time for the higher temperature is long compared with the time for the luminous front to travel from the driver to the point of observation, it would appear that the plasma observed in the tube ahead of the luminous front is not in equilibrium. Considering the gas behind the front, where the electron density is of the order of $10^{17} \text{cm}^{-3}$ and the temperature about 4 ev, we have a relaxation time of 0.14 microsecond for equilibrium between helium atoms and ions. Thus the gas flowing into the luminous front can be ionized by electron impact in a time of this order which is short when compared with the rise times and fall times of the intensity histories seen here (typical rise time = 0.6 microseconds, fall time to 1/2 intensity = 1 microsecond). It must therefore be concluded that other complex processes are responsible for the departure from equilibrium values of the population ratios behind the luminous front (see Table 5, Chapter IV).
Concluding Remarks

In plasmas formed in electromagnetic shock tubes many complex mechanisms are active. Only a limited amount of insight into these mechanisms has been gained in the work reported here and there is much scope for future research. One possible line of research would be to determine more accurately the electron density in the region ahead of the advancing luminous front. The work in this field which has been done with microwave probing of the region far in advance of the front could be complemented and extended towards the front with spectroscopic equipment of higher resolution than has been available for the present experiments. Another more complex problem would be to further study the mechanisms responsible for excitation of rest gas atoms and ions in the precursor region. As it is fairly certain that photo-excitation and ionization are the dominant processes, such a study would have to begin with an accurate determination of the spectral distribution of radiation falling on the gas from the discharge and the advancing luminous front.
THEORETICAL LINE STRENGTHS

The theoretical line strengths to be used in calculations for argon and helium plasmas will be taken directly from published values where available.

Argon Line Strengths

The argon line strengths used in this work were for the most part calculated from the transition probabilities for Argon I and Argon II published by Olsen (1963). The transition probability, $A$, for emission of a line of wavelength $\lambda$ is related to the line strength, $S$, by

$$A = \frac{1}{g_m} \frac{64\pi^4}{3h \lambda^3} S \tag{1}$$

where all symbols are as previously defined. As our calculations of temperature etc. involve only the ratios of line strengths we will rewrite the above equation in arbitrary units:

$$S^1 = g_m \lambda^3 A \tag{2}$$

The values of $A$, $g_m$, and $S^1$ for the Argon I and II lines studied in these experiments are tabulated below, $\lambda$ in Angstrom units is inserted in Equation (2) to obtain these values.
No published values were available for Argon III lines so the strength of the line used, AIII 3286A°, was calculated using the Coulomb approximation method of Bates and Damgaard (1950). The result of this calculation is shown below, with that from the same calculation for the line AII4806A°.

Also shown for AIII4806 is the value of $S_1$ which from Equations (1) and (2) can be obtained by multiplying $S$ by $\frac{64 \pi^4}{3h} = 2.02 \times 10^{18}$ for $S$ in units of $(a_o^2 \cdot e^2) (a_o = \text{Bohr radius})$. This last determination of $S_1$ for AII4806A° can be compared with that in the table for AI and AII lines.
Carbon Line Strength

The strength of the carbon line, CII4267A°, used in the impurity determination was calculated from the absorption oscillator strength as quoted by Allen (1963). The values $g_m A_{CII4267}$ and hence $S_{CII4267}^1$ were found from the relation of $g_n f = 1.499 \times 10^{-8} g_m A$. $S_{CII4267A°}^1$ was found to equal 15.3, in the same arbitrary units as are the values of $S^1$ for AI and AII.

Helium Line Strengths

The line strengths of neutral and ionized helium lines used in temperature determinations were also calculated from the absorption oscillator strengths quoted by Allen (1963). The strengths of the neutral helium lines which were used to determine ratios of the numbers of atoms in various excited stages are calculated from the self consistent set of values of $A$ found in Gabriel and Heddle (1960). The strengths for the lines used are as follows:

<table>
<thead>
<tr>
<th>Line</th>
<th>Strength</th>
<th>$S^1 = g_m \lambda^3 A$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HeI5875A°</td>
<td>32.9</td>
<td>2.18x10^{20}</td>
</tr>
<tr>
<td>HeII4686A°</td>
<td>126</td>
<td></td>
</tr>
<tr>
<td>HeI4471A°</td>
<td></td>
<td>0.327x10^{20}</td>
</tr>
<tr>
<td>HeI3888A°</td>
<td></td>
<td>0.049x10^{20}</td>
</tr>
<tr>
<td>HeI5016A°</td>
<td></td>
<td>0.051x10^{20}</td>
</tr>
<tr>
<td>HeI4922A°</td>
<td></td>
<td>0.115x10^{20}</td>
</tr>
</tbody>
</table>
APPENDIX II

DETERMINATION OF MONOCHROMATOR SPECTRAL SENSITIVITY

The experimental arrangement by which the spectral sensitivity was determined is shown in Figure 14. The temperature of the tungsten source had been determined in a previous experiment by Robinson (1962).

Figure 14 - Apparatus for Calibrating Monochromators

1000 watt tungsten @ T=2400°K, V=115Vdc

Red filter for use above 6200Å to remove second order spectra

Rotating mirror

All mirrors front silvered

Grating Monochromator

Photo-multiplier

To Oscilloscope

The exit and entrance slits on the monochromator were opened until the signal to the oscilloscope was of the same order as signals obtained from the light from the shock tubes. The slits were opened to obtain the above level of signal (with maximum allowable photomultiplier voltage) in the region of the spectrum where the response of the monochromator-photomultiplier to the pulses of light from the tungsten bulb
was the least. The photomultiplier voltage was reduced when necessary when responses were being measured in the other regions of the spectrum.

A semi logarithmic plot was made of the responses of the monochromator versus its wavelength setting. The photomultiplier voltage changes were reflected in discontinuous jumps in the response curve. Because of the glass envelope on the tungsten bulb, responses were plotted only for 3800 Å and above. This process was repeated for all the monochromator-photomultiplier combinations.

Next was plotted the radiation intensity curve for tungsten at a temperature of 2400° K,

\[ I(\lambda) = \frac{\varepsilon}{\lambda^5 \left( \exp \left( \frac{C_2}{\lambda T} \right) - 1 \right)} \]

where \( \varepsilon \) is the emissivity and \( C_2 = 1.428 \text{cm}^2 \text{K}^{-1} \). The emissivity values for the various wavelengths were taken from De Vos (1954). Taking the sensitivity to be related to the light intensity and response by:

\[ \text{Sensitivity} = \frac{\text{Response}}{\text{Intensity}} \]

a semi logarithmic plot of the sensitivity can easily be obtained by taking the difference between the response and intensity semi logarithmic plots. As only intensities
measured with the Jarrel-Ash monochromator were used in the calculations of these experiments, sensitivity curves for this instrument only are presented in Figures 15 and 16.

With radiation from the shock tube the variation of response and hence of sensitivity with photomultiplier voltage can be determined at various wavelengths. Changes of response at low photomultiplier voltages were determined by setting the monochromator on a strong line. This variation of sensitivity with both wavelength and photomultiplier supply voltage was found to be quite considerable in the case of the IP 28 tube where readings were taken with voltages from 500V to 1100V. The sensitivity variation for the IP 28 photomultiplier in the spectral region of interest is presented in Figure 17 in the form of a "Sensitivity Multiplier". In the case of the 150 CVP photomultiplier, voltages from 1500V to 1800V were used and the "Sensitivity Multiplier" can be taken as a factor of two for every 100V increment with little variation with wavelength.

In order to compare intensities of spectral lines in different wavelength regions the response at each wavelength was divided by the appropriate "Sensitivity Multiplier" and then further divided by the sensitivity for the wavelength.
Figure 15 - Sensitivity vs Wavelength for Jarrel-Ash Monochromator with Phillips 150 CVP Photomultiplier

Photomultiplier voltage = 1700V

Sensitivity (Arbitrary Units)

With red filter
Figure 16 - Sensitivity vs Wavelength for Jarrel-Ash Monochromator with RCA IP28 Photomultiplier

Photomultiplier volt. = 500V

With red filter
Figure 17-Sensitivity Multiplier vs Wavelength for IP28 Photomultiplier with various supply voltages

(Multiplier = unity for voltage = 500V)
APPENDIX III

Rough Spectroscopic Analysis of Carbon Content of Plasma In
Shock Tubes With and Without Electrodes

In each analysis a comparison is made between
the intensity of the AII 4806Å line and that of the CII 4267Å line. The intensity of the argon line AII 4266Å must be
estimated in order to correct the intensity observed at 4266Å and obtain a value for the intensity of the CII 4267Å line.
From equations (3) and (4) of Chapter II and using the line strengths from Appendix I, we obtain:

\[
\frac{I_{\text{AII 4266Å}}}{I_{\text{AII 4806Å}}} = \frac{21.9}{4266} \times \frac{4806}{47.2} \exp \left( \frac{19.14-19.46}{kT} \right)
\]

\[
= 0.409 \quad @ \quad kT = 1.3\text{eV}
\]

\[
= 0.452 \quad @ \quad kT = 2.2\text{eV}
\]

So, taking the intensity observed at 4806Å to be entirely
due to AII 4806Å, the intensity at 4267Å due to AII 4266Å can easily be estimated. The remainder of the intensity
observed at 4267Å is taken to be due to CII 4267Å. Subst-
ituting the values of \( I_{\text{CII 4267Å}} \) and \( I_{\text{AII 4806Å}} \) into
equation (3) of Chapter II, solving equations (3) and (4) for \( N_{\text{CII}} \) and \( N_{\text{AII}} \), and taking their ratio we obtain

\[
\frac{N_{\text{CII}}}{N_{\text{AII}}} \]

which can easily be converted into \( \frac{N_C}{N_A} \) by calculating
the relative population of the various stages of carbon and
argon ions from Saha's equation.

Tabulated in Table 6 are the measured intensities at $4806\,\text{A}^0$ and $4267\,\text{A}^0$, the estimated intensity of CII$4267\,\text{A}^0$ and the ratios $\frac{N_{\text{ClII}}}{N_{\text{AII}}}$ and $\frac{N_{\text{C}}}{N_{\text{A}}}$ for the two types of shock drivers.

Table 6

Ratios of carbon to argon in plasmas.

<table>
<thead>
<tr>
<th>Electrode</th>
<th>Electrodeless</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{4806,\text{A}^0} = 1.22$</td>
<td>$I_{4806,\text{A}^0} = 13.5$</td>
</tr>
<tr>
<td>$I_{4267,\text{A}^0} = 1.45$</td>
<td>$I_{4267,\text{A}^0} = 6.9$</td>
</tr>
<tr>
<td>$I_{\text{ClII}4267,\text{A}^0} = 0.90$</td>
<td>$I_{\text{ClII}4267,\text{A}^0} = 1.4$</td>
</tr>
<tr>
<td>$\frac{N_{\text{ClII}}}{N_{\text{AII}}} = 0.39$</td>
<td>$\frac{N_{\text{ClII}}}{N_{\text{AII}}} = 0.09$</td>
</tr>
<tr>
<td>$\frac{N_{\text{C}}}{N_{\text{A}}} = 0.36$</td>
<td>$\frac{N_{\text{C}}}{N_{\text{A}}} = 0.06$</td>
</tr>
</tbody>
</table>
APPENDIX IV

Correction of Measured Spectral Line Profiles for Instrumental Broadening

In order to obtain true profiles of lines having a whole half width of approximately 1 Å it is necessary to correct the measured profile for broadening due to the instrument being used.

In order to make the above correction it is necessary to solve the following equation involving a convolution integral:

\[ f(x) = \int_{-\infty}^{+\infty} f_1(x-y) f_{11}(y) \, dy \]

(from Unsold, 1955). In the case at hand we have the instrumental broadening which we will represent by the function \( f_1(\lambda) \) and the Stark broadening which will be represented by \( f_{11}(\lambda) \). The Voigt functions:

\[ f(x) = M \int_{-\infty}^{+\infty} \exp\left(-\frac{y^2}{\beta_2^2}\right) \, dy \frac{1}{\sqrt{1 + ((x-y)/\beta_1)^2}} \]

(Voigt (1912)) will satisfy equation (A) with the following relationship between the half widths:

\[ \beta_{11}^1 = \beta - \beta_1^1 \text{ and } \beta_{11}^2 = \beta_2^2 - \beta_2^1 \]

In order to use this procedure the observed profile and
the instrumental broadening function must be fitted to appropriate Voigt functions. The profile used as representative of the instrumental broadening was that from a low pressure, low temperature Hydrogen source (Geisler tube).

The fitting of the above two profiles to Voigt functions is facilitated by the use of Tables made by van de Hulst and Reesinck (1947). These tables are reproduced here (Table 7). The widths of the profile to be fitted are compared with those in the tables at the amplitudes listed and the best average Voigt profile obtained.
Table 7: Standard Voigt Profiles

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Ordinates in Terms of Central Ordinate</th>
<th>Widths in Terms of Half-width ($b_1/h$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b_1/h$</td>
<td>$b_1/b_2$</td>
<td>$b_2/h$</td>
</tr>
<tr>
<td>0.000</td>
<td>0.00</td>
<td>0.60</td>
</tr>
<tr>
<td>0.025</td>
<td>0.04</td>
<td>0.59</td>
</tr>
<tr>
<td>0.050</td>
<td>0.09</td>
<td>0.57</td>
</tr>
<tr>
<td>0.075</td>
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<td>0.55</td>
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