The aim of this study was to establish reliable temperature distributions, within an argon plasma jet in both the cases of an unconstrained jet discharging to the atmosphere and a jet impinging on a cooled metal surface under various input conditions.

An optical technique, the Two Line Relative Intensity Method was employed with both Ionic/Atomic and Atomic/Atomic Line Combinations.

Results are presented in Chapter 5 and are compared with published data in Chapter 6 and have been published.

Noise measurements have been made and represent an initial investigation into turbulent fluctuations within the jet.

A novel technique of collimation and scanning of the plasma jet is described in Appendix 3.

"Temperature and Noise Profiles in an Argon Plasma Jet".

CONTENTS

(1) INTRODUCTION
(1.1) Plasma jet definition
(1.2) Area of Interest
(1.3) Theoretical Analysis

(2) PHYSICS OF THE PLASMA JET
(2.1) Volt-Ampere Characteristics
(2.2) Temperature concept and LTE
(2.3) Radiation and Collision Processes

(3) EFFECTIVE METHODS OF TEMPERATURE ESTIMATION IN A PLASMA JET
(3.1) Non-spectroscopic Methods
   (i) Probe Measurements
   (ii) Laser Measurements
(3.2) Spectroscopic Methods
   (i) Line Width Measurements
   (ii) Absolute Line Intensity
   (iii) Boltzmann Plot
   (iv) The Two Line Ratio Method
   (v) Continuum Measurements

(4) APPARATUS
(4.1) The Monochromator
(4.2) The Grating
(4.3) Detection Equipment

(5) TEMPERATURE PROFILES
(5.1) Scanning Technique
(5.2) Steady State
(5.3) Profiles obtained in a Free Jet
   (i) Profiles using Atomic/Ionic Line Combination
   (ii) Profiles using Atomic/Atomic Line Combination

(5.4) Profiles obtained in a jet impinging on a cooled metal surface.
   (i) The Copper Tube and Thermocouple Results
   (ii) Temperature Profiles

(6) ERRORS, COMPARISON WITH PUBLISHED DATA, AREAS FOR FURTHER WORK
    AND CONCLUSIONS

(6.1) Error Analysis
   (i) Sources of Error
   (ii) Errors in Line Intensity Measurements

(6.2) Comparison with Published Data

(6.3) Areas for Further Work

(6.4) Conclusions

(7) REFERENCES

(8) ACKNOWLEDGEMENTS

(9) APPENDICES
Nomenclature

Symbols not defined in the text have the following meanings:-

\( h \) = Planck Constant
\( k \) = Boltzmann Constant
\( u_\lambda \) = Radiation density
\( \nu \) = Frequency
\( \lambda \) = Wavelength
\( E \) = Energy Level (with suffixes \( m, n, j \) or \( i \) to distinguish levels)
  or Electric Field Strength
\( g \) = Degeneracy (with suffixes \( m, n, j \) or \( i \) to distinguish levels)
\( Q \) = Partition Function
\( A \) = Einstein Transition Probability (with suffixes \( m, n, j \) or \( i \) to distinguish levels)
\( n \) = Particle concentration (with suffixes \( m, n, j \) or \( i \) to distinguish levels)
\( n_0 \) = Ground Level particle concentration
\( \epsilon \) = Degree of Ionization or Electrical Conductivity
\( \sigma \) = Thermal Conductivity
\( \dot{m} \) = Gas flow rate
\( C_p \) = Specific Heat at Constant Pressure
\( e \) = Electronic Charge
\( P \) = Pressure
\( \theta \) = Characteristic Temperature
\( b_e \) = Electron Mobility
\( \tau \) = Reciprocal Frequency
Chapter 1

Introduction

Section (1.1) defines a plasma jet and indicates current applications. Section (1.2) defines an area of interest for the present study. Section (1.3) outlines the approach to plasma jet analysis from a theoretical point of view.

(1.1) The Plasma Jet

The important distinction between a neutral gas and a plasma is that the latter contains a sufficient number of charged particles for its dynamical behaviour to be dominated by electromagnetic forces. Tournier defines a plasma as a gas which is at least partially ionized. More formal definitions stipulate that a plasma must be macroscopically neutral (i.e. electron and ion concentrations are roughly equal) and that any particle interacts at any moment with a large number of neighbouring particles. These conditions can be expressed mathematically in terms of the Debye length, $\lambda_D$. This is the distance from any charged particle at which its effect on the surrounding field becomes negligible. The conditions are

$$n_0 \lambda_D^3 > 1$$

($n_0$ = particle density)

and

$$\lambda_D \ll L$$

($L$ = characteristic length of plasma).

This definition covers a whole range of naturally occurring plasmas such as star interiors, interstellar gas, the ionosphere, the Van Allan Belts and transient plasmas caused by lightning. Man-made plasmas
include those of thermonuclear fusion experiments, MHD devices, ion propulsion devices, plasmas created by re-entering space vehicles and in the positive columns of arcs.

This study is concerned with the analysis of the plasma produced in the positive column of a D.C. arc and then blown out through a nozzle by a superimposed co-axial gas flow. The construction of a typical plasma torch used to produce such a plasma jet is shown in Figure 2 (p.6). Constriction of the arc produces high temperatures (as explained in section(2.1))and it is as a high temperature source in industrial processes such as welding, metal cutting and cleaning and chemical/metallurgical applications that the plasma jet owes much of its importance.

(1.2.) Area of Interest

British Rail's interest in improved adhesion between train wheels and railway lines cleaned by a plasma jet initiated this enquiry. A grant was provided to the Engineering Department at the University of Leicester under the supervision of Dr. R.W. Maxwell to finance research into elucidating the mechanisms of heat and mass transfer processes at a plasma jet/moving metal interface. This study represents an integral part of the work done and being done by others^3^,^4^,^5^ to achieve some insight into this situation. In particular the main aim of this piece of work has been to evaluate the reliability of spectroscopically determined temperature measurements using a novel technique of collimation and scanning. The concept of temperature is taken up in section(2.2) and in particular, the meaning of a high temperature is discussed.

Chapter 3 is concerned with different methods of temperature measurement at the elevated temperatures expected in a plasma jet and gives reasons for deciding that spectroscopically determined temperatures are the most meaningful.

Plasma jet temperature profiles are important, in order that temperature
dependent transport properties may be estimated. The processes may then be modelled and solutions to the conservation laws sought to validate estimated transport properties.

(1.3.) **Theoretical Analysis**

The basic description of a plasma lies in the kinetic theory. A distribution function, \( f(\mathbf{r}, \mathbf{v}, t) \), is defined such that \( f d\mathbf{r} d\mathbf{v} \) is the probability of finding particles within the 6-dimensional volume element \( d\mathbf{r} d\mathbf{v} \), centred at the point \( (\mathbf{r}, \mathbf{v}) \). Observable properties of the plasma can then be obtained from this function. The equation that determines the distribution function is obtained by considering the time rate of change of the number of particles in a given volume element in \((\mathbf{r}, \mathbf{v})\) space\(^2\). This leads to an equation of the form

\[
\frac{\partial f}{\partial t} + \mathbf{v} \cdot \frac{\partial f}{\partial \mathbf{r}} + \frac{\mathbf{v}}{m} \cdot \frac{\partial f}{\partial \mathbf{v}} = \left( \frac{\partial f}{\partial t/c} \right)
\]

where the R.H.S. represents the time rate of change due to collisions. The form the R.H.S. takes depends on the assumptions made about collisions. This term is in general a non-linear function of \( f \) and is a source of most of the mathematical difficulty in kinetic theory.

If the form of \( f(\mathbf{r}, \mathbf{v}, t) \) can be established then temperature and other plasma properties can be determined by taking velocity moments of \( f \).
Chapter 2

Physics of the Plasma Jet

Section (2.1) considers the form of Volt-Ampere characteristics of the plasma jet. Section (2.2) takes up the concepts of temperature and equilibrium in the jet and section (2.3) considers radiation and collision processes in the jet.

(2.1.) Volt-Ampere Characteristics

A previous report investigated volt-ampere characteristics of atmospheric argon and nitrogen plasma jets using a B.O.C. stabilized arc furnace rectifier unit as power supply. This power supply is shown schematically in Figure 1 (P.5). The high frequency unit was used at ignition to break down the gas from its insulated state after which large D.C. currents (up to 400 Amps) and low supply potentials (of the order of 50 volts) constituted power to the arc. A choice of three "no load" supply potentials was available as shown.

The plasma torch used in this earlier investigation was a British Rail Mark II model which has been superseded by a later more compact model used in the present study. The latter is shown in Figure 2.

The variation of Volt-Ampere characteristics with argon flow rate is shown in Figure 3. These curves are shown superimposed onto the "drooping" characteristics of the supply. Points where the two sets of characteristics intersect are stable operating points for plasma torch operation.

Interpretation of arc volt-ampere characteristics and stability criteria are both developed by Hoyaux and Cobine with reference to the high pressure arc. The general form of the volt-ampere characteristics does not significantly change when the plasma jet (essentially a constricted high pressure arc) is considered and it is therefore permitted to interpret volt-ampere characteristics and arc stability with reference to the
FIG. 1. SCHEMATIC OF POWER SUPPLY

Three 50 volt D.C. outputs that can be connected in series to give 100 volts or 150 volts output.
high pressure arc and then logically extend the argument to consider the effect of a superimposed axial gas flow.

The "drooping" characteristics of the power supply are a consequence of the need for arc stability. Consider diagrams 1 and 2.

Diagram 1 illustrates the case of an ideal constant potential source characteristic and a typical arc characteristic. The condition for equilibrium is \( V_s = e \) where \( e \) is the burning potential of the arc. This condition is only met at point A. At points such as B, there is an imbalance between the potential supplied and the arc potential of \( (V_s - e) \) and this serves to increase the current in the circuit. Thus, if the arc characteristic remains below the supply characteristic as current increases, there is a condition of \( I \rightarrow \infty \). At point A, any slight disturbance will either cause \( I \rightarrow \infty \) or \( I \rightarrow 0 \).

Diagram 2 illustrates the same typical arc characteristic but in this case the supply incorporates sufficient impedance to control the arc current. At any current demand setting, the output potential falls rapidly when the load is applied. Point C is a stable operating point and this can be seen as follows: Assume that some transient condition reduces the
current so that the arc is operating at point B momentarily. Again, there is an imbalance between the potential supplied and the arc potential of \((V_g - e)\) which causes an increased current and returns the arc to point C. Similarly, operation at Point D means that there is an imbalance of \((e - V_g)\) which would reduce the current and return the arc to point C.

The shape of the volt-ampere characteristics can be explained by considering the transition from an abnormal glow discharge to an arc discharge.

\[ \text{Diagram 3} \]

Diagram 3 shows how at a critical threshold value of \(I\) (somewhere between 0.1A and 1.0A and a very large upper limit) there is a sudden drop in arc burning voltage. Beyond point A the thermionic emission of the cathode becomes important. The emitted electrons ionize the gas in front of the cathode hence supplying additional heat to the latter. When the thermionic current \(I_t > I\) an electron space charge is formed in front of the cathode which locally cancels the electric field. This explains the drop in \(V\) in the region AB of diagram 3. At some point C, \(I_t = I\) i.e. the entire arc current can be supplied by thermionic emission, at which point the discharge is a true arc. This transition is accompanied by an increase in current density and an increase in temperature. It is possible for the volt-ampere characteristic slope to become positive at high currents.
Diagram 4 (reproduced from Cobine) illustrates this. Curve A is the static characteristic and is obeyed provided that the arc operating conditions are changed slowly enough for pressure and temperature equilibrium to be established. (This could be anything from several mins to 2 hrs.). Curves B represent dynamic characteristics - the current is varied rapidly with no change in pressure.

Hysteresis effects were observed in the volt-ampere characteristics (Figure 3) i.e. different values of supply potential were obtained according to current decreasing or increasing. These have also been observed by Holmes and Freeston working with an atmospheric argon plasma jet.

There are also larger variations in supply voltage which are thought to be due to anode root motion. If the anode root moves to a less efficiently cooled part of the anode there is a likelihood of copper vapour contamination. Copper has a first ionization potential of 7.7 eV as opposed to 15.7 eV for argon and the effect of contamination would be to reduce the burning voltage and the temperature. Also, the cathode may be losing material and altering the effective electrode separation.

The effect of a superimposed axial gas flow on the high pressure arc
and the consequent change in the volt-ampere characteristics can best be seen by applying a simplified energy balance to the plasma jet.

Neglecting energy that is lost through radiation, convection and electrode conduction, the power into the arc is balanced by the sum of the power radially conducted and the power carried away by the gas.

This can be written in polar cylindrical co-ordinates as:

\[ E^2 = - \left( \frac{1}{r} \frac{d}{dr} \left( r \sigma \frac{dT}{dr} \right) \right) + \int_o^R C_p dT \quad (4) \]

This is the Elenbaas-Heller equation\(^7\) which is based on Poisson's equation applied to the arc positive column. The inclusion of the last term is responsible for a "constriction" of the high pressure arc. The effect of the gas stream is to withdraw carriers from the conducting plasma. To maintain the current constant requires a higher burning voltage. The surplus energy is needed to produce new carriers inside the constriction to maintain the current. The carrier production is related to a higher temperature within the central part of the constricted arc. Therefore there occurs an apparent paradox that the more an arc is cooled from without, the more the temperature within the central core is increased. This phenomenon was first discovered by Gerdin\(^10\) in the years 1922-1924. Several of the effects that are present that are thought to cause a contraction of the conducting channel are listed by Phelps\(^11\). Thus it is possible to achieve temperatures of the order of 20,000\(^0\)K within a plasma jet as opposed to temperatures of the order of 5,000\(^0\)K within a non-constricted high pressure arc\(^8\).

(2.2.) Temperature and Equilibrium

(1) Temperature. Temperature is defined classically in terms of equilibrium states but its meaning is nebulous when applied to systems that are not in equilibrium such as occurs in the case of high potential,
low current discharges where the electrons and ions are not in thermal equilibrium. In the cases of shock tube and exploding wire phenomena where high transient temperatures are quoted detailed study of the times taken for thermal equilibrium to be established is necessary for temperature to have meaning in the classical thermodynamical sense.

When particle collisions are examined it is possible to write an expression for temperature that evolves from kinetic theory.

The Boltzmann constant can be construed as the Universal Gas constant per particle and the equation of state for an ideal gas can be rewritten in the form:

\[ p = nkT \quad (5) \]

The pressure can be written in terms of the r.m.s. value of a velocity distribution

\[ p = mn \int \frac{u^2}{n} \, \, \, dn = nmu^2 \quad (6) \]

where \( u \) is the x-direction component of isotropic velocity distribution

\[ \overline{u^2} = \overline{v^2} = \overline{w^2} \quad (7) \]

and if

\[ \overline{u^2} + \overline{v^2} + \overline{w^2} = C^2 \quad (8) \]

then

\[ \overline{u^2} = \frac{C^2}{3} \quad (9) \]

Substituting into (6) and equating pressures:

\[ kT = \frac{m C^2}{3} \quad (10) \]

Thus temperature can be defined kinematically in terms of the average kinetic energy of the gas particle. Basically, classical thermodynamic concepts are independent of the atomistic nature of matter and the definition of temperature given by (10) is consistent with the thermodynamic temperature in equilibrium situations. In non-equilibrium situations (10)
may be thought of as an interpretation of temperature.

One third of this energy per molecule \( \frac{K T}{2} \) may be associated with each translational degree of freedom and by the Equipartition of Energy Theorem this degree of freedom concept may be extended to internal modes of energy storage with each having an average energy of \( \frac{K T}{2} \).

However, some internal modes of energy are ignored and the presence of radiation cannot be explained by this approach. Planck's Theory of Radiation, replacing the Equipartition of Energy Theorem with the notion of an oscillator having discrete allowable energy levels laid the foundations for a Quantum Mechanical account of energy distribution within a heated gas. Quantum Mechanics also shows that the excitation of each degree of freedom occurs in a series of very small steps such that the average energy of each mode approaches \( \frac{K T}{2} \) asymptotically.

Within each degree of freedom of a gas in equilibrium the energy distribution can be described by a statistical distribution corresponding to the most probable macrostate. For translational modes this is the Maxwell-Boltzmann Distribution (equation (11))

\[
f(v) = n \left( \frac{m}{2\pi kT} \right)^{\frac{3}{2}} \frac{1}{\sqrt{2\pi}} \exp \left( -\frac{mv^2}{2kT} \right)
\]

For radiation it is the Planck Distribution (equation (12)).

\[
u = \frac{8\pi hv}{[\exp(hv/kT) - 1]} \quad (12)
\]

Equation (12) is derived by treating radiation as a collection of degenerate particles that obey Bose-Einstein Statistics. For Internal Modes the most likely distribution of particle energies is given by Boltzmann's Equation (equation (13)).

\[
n_n = n \frac{g_n}{Q} \exp \left( -\frac{E_n}{kT} \right)
\]

[where \( Q = \sum_i g_i \exp( -\frac{E_i}{kT}) \)].
Since the system is in thermodynamic equilibrium the parameter \( T \) in the several distributions is assumed to have a common numerical value said to be the thermodynamic temperature. At sufficiently high temperatures some of the thermal energy enters the excitation and ionization processes. If thermodynamic equilibrium prevails then the numbers of excited and ionized atoms each satisfy a Boltzmann Distribution with the same parameter \( T \) in it. Throughout the system the rate of production of excited atoms by impact equals the rate of the number of collisions of the second kind and similarly, the rate of ionization equals the rate of recombination through three body collisions. Furthermore, absorption and emission of radiation occurs at equal rates in all parts of the spectrum. Here temperature appears to have a perfectly good physical meaning.

However, the plasma jet situation is not one of thermodynamic equilibrium, but, so long as radiation losses are small each small region may be considered in quasistatic equilibrium at a characteristic temperature.

If radiation is non-negligible and does not satisfy the Planck Distribution (optically thin radiation) then the temperature deduced from spectroscopic line intensity measurements is designated an excitation temperature. Lochte-Holtgreven\(^{12}\) maintains that this temperature is very close to the electron temperature in high pressure arcs and the electron temperature is in turn very close to the atom temperature. [See p.19]

It is thus permitted to say that the excitation temperature measured spectroscopically is equal to the thermodynamic temperature.

Having established that spectroscopically measured temperatures are meaningful it remains to show the relationship between temperature and the measured intensity of radiation. This is taken up in Appendix 2.
(ii) Local Thermodynamic Equilibrium. LTE assumes that at each point of the plasma a unique temperature (and other thermodynamic parameters depending on temperature) can be defined. The equilibrium is purely local so that significant temperature gradients may exist.

Available literature seems to suggest divided opinion as to whether the assumption of LTE is valid in an atmospheric plasma jet. If it is valid then analysis is straightforward once reliable temperature distributions are established. If the assumption is not valid then analysis is much more complicated, needing detailed knowledge about collision cross-sections and radiative coefficients. In LTE equilibrium relations are independent of these quantities because all processes are balanced by their inverses.

Hoyaux7 maintains that the dispute amongst specialists as to the existence of LTE in positive columns is a matter of words. He argues that two points are indisputable

(a) In most cases the positive column does not meet all LTE requirements.

(b) Despite this it is unquestionable that conclusions drawn on LTE assumptions are reasonably valid in most cases.

Point (a) arises because most arcs radiate in a non-negligible manner and the photons released do not obey a Planck distribution. (This is equivalent to a Maxwell distribution for particles at the same temperature) Consideration of electron-atom collisions (discussed in the next section) gives a difference between $T_e$, the electron temperature and $T_a$, the atom temperature which becomes more pronounced in the constricted high pressure arc than in the free-burning arc. Also, inelastic collisions are only possible for fast electrons in the Maxwellian tail and their effect is to deplete this tail causing a non-Maxwellian distribution to be established.
Point (b) answers these objections on the grounds that the spectra of most high pressure arcs are made up of optically thick radiation i.e. photon mean free paths are small relative to the radius of the arc and photons are in local equilibrium with the plasma. In most cases optically thin radiation, where the photon leaves the plasma without collision and does not contribute to any equilibrium, is confined to a small range of frequencies. Hoyaux also states that even if a Bremsstrahlung exists, the influence upon the velocity distributions in the plasma is insignificant. Also, electrons are extremely resourceful in finding mechanisms for re-establishing a Maxwellian Velocity Distribution when it is perturbed. Such mechanisms tend to salvage the situation and render the consequences of LTE acceptable in practice.

The effect of a severe temperature gradient, as is present in the plasma jet, can be to disrupt LTE. The local elements of volume of the plasma jet are not quite independent. Particles are transported from one element to another by diffusion and convection. A particle freshly introduced into an element of different temperature will require a certain relaxation time to become adjusted to the new surroundings and may cause measured temperatures to be in error.

The importance of LTE is obvious when it is realized that many spectroscopic techniques and the application of the Saha equation depend upon it for meaningful results.

Diagnostic tools for reliably determining the particle velocity distributions in atmospheric plasma jets are not available and non-equilibrium theories are not well developed so it is appealing to accept LTE as applying until it is proved otherwise. Lochte-Holtgreven states that atmospheric and higher pressure arcs possess Boltzmann distributions provided that energy loss due to radiation is small and that emission from the plasma may be treated as an equilibrium radiation corresponding to the temperature of the plasma.
(2.3.) **Radiation and Collision Processes**

A more complete understanding of the emission spectrum from the plasma jet and the establishment of equilibrium can be gained by a discussion of the detailed microscopic physical processes occurring in the plasma jet.

Again, the plasma jet is basically a constricted high pressure arc and analysis of the latter can be extended to the former.

The potential gradient in an arc has the form shown in diagram 6.

![Diagram 6](image)

This can be divided into three distinct regions.

The cathode fall region is one of very high positive ion space charge and its magnitude is of the order of the first ionization potential of the gas. Thermionic emission is the obvious mechanism maintaining the large electron currents that occur in the cathode region and the necessary high temperature is produced by impacting ions. These ions are most probably produced in the cathode fall region but may come from the positive column.

Because the probability of an electron crossing the cathode fall region without an ionizing collision is high, a high electron current density relative to the ion current density is necessary to ensure enough ions are produced to maintain the cathode temperature. The space charge arises because the electrons travel much more rapidly than the ions.

The anode fall region is characterized by a high electron space charge...
at the anode end. At high pressure electrons are emitted from the anode due to its high temperature and contribute to the space charge until driven back into the anode. Positive ions produced in the anode drop region by collisions move towards the cathode, the concentration of ions increasing in the direction of the cathode. At the cathode end of the anode-drop region the density of positive ions is high enough nearly to neutralize the electron space charge, thus forming the plasma constituting the positive column. Thus it is at the anode that the essential positive ion current is established.

The positive column is an example of a plasma i.e. an ionized region in which the concentrations of electrons and ions are approximately equal and are relatively high. It is a highly conducting region and exhibits a relatively low average potential gradient. In general the negative carriers in a plasma are electrons (negative ions would quickly recombine with positive ions). The positive ions, the electrons and the neutral gas atoms of a plasma may or may not be in thermal equilibrium. Since a plasma is usually established in an applied electric field the temperature of the positive ions is usually greater than the gas temperature and the electron temperature may be high.

When an electric field is applied to a plasma the drift current density is usually much smaller than the random current density of the ions and electrons, so that the applied field does not necessarily produce a departure from Maxwellian velocity distribution, though it does increase the ion and electron temperatures. This increase in temperature derived from the field is greater for the electrons because of their higher mobility. The electrons, because of their small mass give up little energy to the neutral particles but the positive ions will increase the gas temperature since ion and atom masses are comparable.

Following Lochte-Holtgreven, in the steady state the electrons give up a fraction of their surplus energy to the atoms which is equal to the
energy gain from the field

i.e.,

\[
\frac{3}{2} k (T_e - T_g) \frac{2m}{M} = eE^2 b_e \tau \tag{14}
\]

Also

\[
b_e = \frac{r_e}{m} \tag{15}
\]

From (9) and writing \( \tau \) as \( \frac{\lambda}{c} \) it follows that

\[
\frac{T_e - T_g}{T_e} = \left( \frac{\lambda eE}{\frac{3}{2} kT_e} \right)^2 \frac{M}{\text{I.m}} \tag{16}
\]

(where \( T_e \) and \( T_g \) are electron and gas temperatures, \( \lambda \) is m.f.p., \( b_e \) is electron mobility). In free burning atmospheric arcs the axial value of the left hand side is of the order of 1% but increases with constricted arcs because of the higher \( E \).

For argon at atmospheric pressure, a temperature of 10,000°K, a field strength of \( E = 2 \times 10^3 \text{ V/m} \) and a typical value of \( \lambda \) taken as \( 7 \times 10^{-5} \text{ cm} \) (from a \( \lambda_D \) given by Boyd and Sanderson\(^2\) for an arc) the left hand side is approximately 2%.

Thus it is from the electric field that electrons gain the energy necessary to excite and ionize the gas in an electric arc and it is this which compensates the losses due to radiation, conduction etc. The electric field is therefore much higher in molecular gases than in atomic gases since the former absorb more energy by dissociation and the excitation of vibrations and rotations. This was illustrated in an earlier report where volt-ampere characteristics of nitrogen and argon plasma jets were compared\(^6\).

The connection between gas radiation and gas temperature can be understood in terms of the degrees of freedom which give rise to the various types of spectra observed. It has been seen in section 2.2 that the equilibrium state of each degree of freedom is characterized by a distribution described either by equation (11) or by equation (13). Hence
each degree of freedom that produces observable radiation provides a parameter to measure temperature. Diagram 7 is a simplified schematic diagram showing the internal energy levels of an atom or ion with a single orbital electron.

The energy of an atom or ion is continually being changed by radiation and by collisions. When an atom emits radiation its orbital electron makes a transition to a lower energy level and vice versa for radiation absorption. If sufficient energy is imparted to the atom by a collision or by radiation absorption causing the total energy to exceed the ionization potential of the atom, the electron is ejected from the atom leaving behind an ion. The ionized atoms have a different set of energy levels and hence a different line spectrum from the neutral atom. The spectrum corresponding to bound-free transitions is a continuum. When a free electron passes through an atom or ion micro field it will in general be deflected with a consequent acceleration. This gives rise to free-free (Bremsstrahlung) transitions in a continuum.
Chapter 3

Methods of Temperature Measurement

This chapter gives brief outlines of the most commonly used methods of measuring temperature, or species concentration (and hence temperature from Saha's Equation), that are suitable for an atmospheric argon plasma jet.

Section (3.1) deals with probe and laser techniques, perhaps the two most important techniques that do not use a spectroscopy method.

Section (3.2) deals briefly with spectroscopic techniques and this is followed in section (3.3) by a description of The Abel Inversion which is necessary to transform laterally observed line intensities into radial emission coefficients.

(3.1.1) Non Spectroscopic Techniques

(i) Probe Measurements. The most useful type of probe measurement in an atmospheric argon plasma jet is due to Langmuir. From the probe characteristic (obtained by biasing the probe relative to the local plasma potential and measuring current flow) it is possible to calculate electron densities and temperature. This has been done for an atmospheric argon plasma jet by Holmes and Freeston, although the list of assumptions that are made in interpretation of the characteristic is daunting.

The theory for a cylindrical probe in a weakly ionized gas is not fully developed and rapid degradation of the material and disturbance of the plasma region in which the probe is immersed make probe measurements hazardous.

Advantages of probe measurements are an ability to determine whether or not a Maxwellian Distribution holds for the electrons and also, a local measurement is obtained (as opposed to a measurement along a line of
sight obtained with spectroscopic methods).

(ii) **Laser Measurements.** A laser delivers an intense beam of monochromatic and coherent light in the form of a pulse (or, with less average power, a continuous wave). When such a beam falls upon a very dense plasma \(10^{18} \text{ carrier pairs/cm}^2\) a certain amount of Rayleigh Scattering takes place. The intensity of the scattered light is proportional to plasma density.

Laser interferometry provides a method of calculating plasma jet species concentrations and is currently being used as such at the University of Leicester Engineering Department by Sturrock\textsuperscript{15}.

Difficulties arise because the refractive index is a function not only of electron density (as it is in the microwave region) but also, ion and negative ion densities and neutral density. An account of plasma diagnostics based on refractivity has been given by Ascoli-Bartoli\textsuperscript{16}.

(3.2.) **Spectroscopic Methods**

Spectrographic analysis of the optical radiation from the plasma jet provides an attractive, non-perturbing diagnostic technique.

Tourin\textsuperscript{1} divides spectrographic techniques into two classes, viz. Radiometric and Spectrometric. The former apply generally to optically thick gases (e.g. large flames; exhaust gases) and rely upon the principles of thermodynamics of radiation for interpretation whilst the latter are generally applied to optically thin gases and rely upon quantum mechanisms of radiation.

Excluding radiometric methods for the moment, spectroscopic methods rely upon measurements of spectral line intensity, width or shift or measurements of continuum intensity.

(1) **Line Broadening and Line Shift Methods.** The various broadening and shift mechanisms are given by Hoyaux\textsuperscript{7}, and Mitchner and Kruger\textsuperscript{17} and
are treated briefly below. These may be encountered singly or in combination.

(a) Natural Broadening is a wave mechanics phenomenon, related to Heisenberg's Uncertainty Principle according to which the excitation energy of a level is only known with a precision depending upon its lifetime.

The order of magnitude does not exceed $10^{-2}$ Å and the resulting profile is Lorentzian (i.e. decreasing as $\left(1 - \frac{\delta v}{\delta v_0}\right)^2$).

(b) Isotopic Broadening - most chemical elements are mixtures of isotopes. This gives in principle a decomposition of the spectral lines with a separation not exceeding $10^{-3}$ Å.

(c) Doppler Broadening and Shift. The Doppler shift due to macroscopic motion is usually only a minor effect with respect to Doppler Broadening which arises from emitter random velocities. If the latter obey a Maxwellian Distribution a Gaussian Profile that is varying as $\exp\left(-\frac{\delta v}{\delta v_0}^2\right)$ is obtained.

In high pressure arcs Doppler Broadening is generally negligible compared to other mechanisms. If it is not, its influence is only sensed in the vicinity of the nominal frequency and the wings are dominated by other mechanisms implying functions of $\Delta v$ which decrease less rapidly.

Its importance as a diagnostic tool is in magnetically confined plasmas at temperatures of around $10^6$ K.

(d) Stark Broadening and Shift. When an atom is in a significant Electric Field electron orbits (Bohr Model) become deformed and as a result the energy levels and characteristic frequencies are modified.

A Stark Shift is sometimes observable in strong electric fields but the dominant effect in arcs is usually Stark Broadening. This arises from the interaction of the atomic field with slowly varying ionic fields and more rapidly fluctuating electronic fields.
Two distinct mechanisms are operating and a satisfactory theory accounting for both is given by Griem\textsuperscript{18} using impact broadening theory.

(e) Resonance Broadening. The mechanism is similar to the ionic field mechanisms of Stark Broadening. The perturbing agent is an atom in the lower level of the particular transition. An exchange of virtual photons may occur between two atoms which become coupled. Only the ground level achieves a population such that the phenomenon becomes significant; the profile is Lorentzian.

(f) Van Der Waals Broadening. This is a similar mechanism to the previous one and represents short range interactions between atoms. The profile is Lorentzian.

With the exception of Stark Broadening and more exceptionally Doppler Broadening, the observation of line profiles and widths will not provide information about arc plasma parameters.

Calculation of electron densities have been made by Holmes and Freeston\textsuperscript{9} in an atmospheric argon plasma jet using Stark Broadening data but the results are not conclusive because of the difficulty of precise measurement of line half-width.

The theory of Stark Broadening is best developed for the Balmer Lines of Hydrogen\textsuperscript{18} indicating an accuracy of 10\% in electron density measurements of seeded plasmas. Wiese\textsuperscript{19} and Jahn and Butler\textsuperscript{20} have made measurements of the H\textsubscript{p} line in seeded argon plasmas.

A disadvantage with optically thin plasmas is that the electron temperature must be known to calculate electron densities. Conversely, the electron density must be known if the method were to be used for temperature measurement. This latter method of temperature measurement is not attractive because in many cases the electron density changes very little over a broad temperature range.
(ii) Absolute Line Intensity. An account of the relationship between
temperature and intensity of radiation is given in Appendix 2.

The relevant equation is:

\[ I = A_{\text{nu}} n_{\text{nu}} h\nu = A_{\text{nu}} \frac{e^m}{Q} n_{\text{nu}} h\nu \exp \left( -\frac{E_m}{kT} \right) \]  

(17)

The requirements of line intensity measurements are optical thinness
and LTE. The direct measurement of absolute intensity of a spectral line
involves a comparison between the intensity of the line from the source
under investigation with the radiation emitted at the same wavelength from
a standard source. (Black body or calibrated tungsten ribbon lamp).

Corrections must be made for losses in the optical system so that the
energy distribution can be deduced from measurements of the emergent
energy distribution.

This method has been used by Olsen and Chapelle and Cabannes for
an atmospheric argon plasma jet and is discussed by Tourin.

An extension of the single line method, called the Fowler-Milne
Method relies on the fact that a spectral line passes through a peak value
as temperature is increased. This occurs when the effect of increasing
temperature on the population of excited states is counterbalanced (this
about temperature is 15,500 K for the 4158 Å line), by reduction in radiating
species due to ionization.

This method has been used by Adcock and Plumtree and McGregor and
Dooley for plasma jets and is discussed by Tourin.

A disadvantage of the method is that the intensity plot has quite a flat
peak which introduces uncertainty into temperatures measured in this way.

(iii) The Boltzmann Plot. From equation (17):

\[ \log \frac{I}{e^A} \text{ is plotted as a function of } V, \text{ a decreasing exponential is obtained with a sub-tangent } \left( \frac{kt}{e} \right). \]  

(18)
The advantage of using more than one or two lines is that errors due to overlapping or self absorption tend to average out.

A Boltzmann Plot is shown in Fig.1 for an argon plasma jet but is considered inaccurate because of coarse intensity measurements. A feature of the Boltzmann Plot, relevant to the Two Line Intensity Method which is considered next, is that spectral lines that lie over the plotted line have a better chance of being optically thin than lines that are below it.

(iv) The Two Line Intensity Ratio Method. Details of the relevant equations and symbols used can be found in Appendix 2.

\[
\left( \frac{E_{n_2} - E_{n_1}}{kT} \right) = \ln \left( \frac{I_1}{I_2} \right) + \ln \left( \frac{g_{A_1}A_2}{g_{A_2}A_1} \right)
\]  

(19)

If an ionic line and atomic line are considered an additional term accounting for ionic and atomic ground state densities and partition functions is needed.

The two line intensity ratio method has advantages over the single line intensity method in that absolute measurements do not have to be made, loss factors cancel, number densities do not have to be known and relative transition probabilities can be used.

A disadvantage is that calculated temperatures are critically dependent upon line ratio measurement if the difference in upper state energies is small.

This situation is improved if an atomic line and an ionic line are considered. The effective energy difference is now enhanced by the ionization energy which is much larger than the thermal energy.

Fig.1 of Appendix 2 shows equation (19) plotted for the 4198 Å and 4200 Å Argon 'blue' lines with error bands defining a 10% error in intensity ratio and a 25% error in transition probabilities. The upper state energy differences in the blue region are of the same order and a curve for two different atomic lines would not be significantly different to Fig.1 of Appendix 2.
The straight line is the result of a least squares fit and is equivalent to a temperature of 7000 °K.

Power input = 7.5 kW
Gas flow rate = 25 l/min
Collimator centred on axis near nozzle

FIG. 4. Boltzmann Plot
Fig. 2 of Appendix 2 illustrates the improvement when the ratio of an atomic and ionic line is considered.

The curved spectral response of the photomultiplier and availability of observable ionic lines limits this method to the adjacent $4345^\circ\text{AI}/4340^\circ\text{AII}$ pair.

Another advantage of this method is that the lines can be scanned quickly which is important as the arc tends to fluctuate.

Pearce favours this method mainly because Saha's Equation and Dalton's Law of Partial pressures do not have to be solved.

(v) Continua Intensity. The continua in the plasma jet are due to transitions of free electrons to bound states (recombination) or to different free states (Bremsstrahlung).

The theory is established only for a few simple cases and the two kinds of radiation are difficult to separate experimentally.

McGregor and Dooley and Demyantsevich have used continua measurements to obtain temperatures in an atmospheric argon plasma jet.

The two line intensity ratio method seems to offer the most attractive means of measuring temperature for an unsteady source like the plasma jet especially when an atomic/ionic pair such as the $4345^\circ\text{AI}$ and $4348^\circ\text{AII}$ lines are used.

A lower limit on temperature measurement is introduced because of the disappearance of the ionic line at about 10,000°K.

(3.3.) Abel Transformation

The Abel Transformation provides a means of estimating radial emission coefficients from laterally observed collimated intensities along parallel chords.

A summary and comparison of viable numerical methods for this transformation has been made by Tourin and a previous report lists and com-
pares two programmes based upon different numerical methods.

Appendix 4 shows the development of one of these methods and a listing of a simple BASIC programme suitable for use on a small computer such as a PDP-11 is given.
Chapter 4

Apparatus

Section 4.1 describes the Monochromator and some of its characteristics, section 4.2 describes the grating and section 4.3 describes the evolution of the detection system used.

4.1. The Monochromator

The Monochromator used is a Monospek 600 available from Hilger and Watts Ltd. It employs a Bausch and Lomb plane reflection grating ruled with 1200 lines/mm, blazed at 0.3μ, and in a Czerny-Turner mounting. It is shown schematically in diagram 1.

![Diagram 1](image)

**DIAGRAM 1**

**SCHEMATIC OF MONOSPEK 600**

The focal length of both mirrors is 600mm, the available area of the grating is 64mm x 64mm, and the slits used are 20mm x 1.5mm. Symmetrical adjustable curved slits. The grating can be rotated either manually or by means of a servo-controlled motor. A digital indicator shows the emitted wavelength in Angstrom Units and scan speeds from 0.5 Å/min. to
The Monochromator fundamentally separates the wavelengths present in incident radiation and allows measurement of the relative amounts of radiation at each wavelength. It can be characterized by several properties.

The resolving power characterizes the property of recording as distinct two monochromatic input radiations of the same intensity and of nearly the same wavelength. An arbitrary criterion is established for this separation and when it is satisfied the resolving power, \( R \), is given by:

\[
R = \frac{\lambda}{\delta \lambda}
\]

(20)

Another property is the dispersion. Incident light is deviated through an angle \( \theta \) which depends on wavelength. The dispersion, \( D \), is given by:

\[
D = \frac{d\theta}{d\lambda}
\]

(21)

It is more common to use the reciprocal dispersion, or plate factor, \( \left( \frac{d\lambda}{dz} \right) \) where,

\[
\frac{d\lambda}{dz} = \frac{1}{fD}
\]

(22)

where \( f \) is the focal length of the camera mirror. With the grating and focal length involved \( \left( \frac{d\lambda}{dz} \right) \) varies from 12.7 Å/mm at the long wavelength end to 13.6 Å/mm at the short wavelength end of the wavelength range of the grating. The reciprocal dispersion diminishes as the number of grating rulings/mm increases and as the focal length increases.

The free spectral range is the interval of the spectrum that can be observed without interference or overlapping from other wavelengths in the incident radiation.

The throughput is a measure of the detector response for a given light source. The measurement is a relative one comparing the responses of two instruments when the same light source and detector are used.
The Monochromator contains two kinds of optics. The first forms images of the source. The second disperses the light. A schematic of the image forming optics is shown in diagram 2.

![Diagram 2](image)

**DIAGRAM 2**

The source is a narrow entrance slit. Assuming it is of infinitesimal width then its image at the receptor is a diffraction pattern whose width depends upon the size, \( W \), of the aperture. The intensity at angle \( \theta \) is given by \(^{30}\):

\[
I(\theta) = I_o \frac{\sin^2 \beta}{\beta^2} \quad (23)
\]

where \( \beta = \frac{\pi W \sin \theta}{\lambda} \)

This function is shown in diagram 3.

![Diagram 3](image)

**DIAGRAM 3**

SINGLE SLIT DIFFRACTION PATTERN
If a grating is placed at the aperture, single slit diffraction patterns are formed at various angles, θ, with each image corresponding to a particular wavelength. The intensity at angle θ is given by a function of the form,

\[ I(θ) = \text{const.} \times W^2 \left( \frac{a_o}{a} \right)^2 \left( \frac{\sin θ}{\beta} \right)^2 \left( \frac{\sin NY}{N \sin θ} \right) \]  

(2L)

where \( β = \frac{πa_o \sin θ}{λ} \), \( γ = \frac{πa_o \sin θ}{λ} \), \( W \) = width of grating, \( a_o \) = width of apertures, \( a \) = centre to centre spacing of apertures, \( N \) = total number of apertures and \( γ = \frac{πa_o \sin θ}{λ} \).

This function is shown in diagram 4 for \( N = 10 \) and \( a = 3a_o \).

The maximum intensity is proportional to \( W^2 \). One factor of \( W \) arises because a larger grating accepts a larger solid angle of light. The second arises because the image width gets smaller as the aperture width gets larger. The factor \( \left( \frac{\sin NY}{N \sin θ} \right) \) is the N-slit interference pattern from which is derived the grating equation \( mλ = a \sin θ \) which gives the locations of the principal maxima of the function. These maxima define the orders of the spectrum. There are secondary maxima which can theoretically have up to 1/2% of the intensity of the principal maxima but in practice, because of actual line shapes being broader than theory indicates, non-monochromatic
sources, insufficient dispersion or the slit width being too large, these are not seen.

The Monochromator is a stigmatic instrument i.e. a point in the entrance slit is imaged as a corresponding point in the exit slit. Distortion is present and this results in a curved image of the slit being formed. If vertical spectral lines are to be obtained then it is usually sufficient to make the entrance slit circular with its radius of curvature equal to that at the vertex of a spectral line near the middle of the range over which the instrument is to be used. The same result is obtained, and this is the case with the Monospek 600, by giving both the entrance and exit slits half this curvature.

The choice of slit width depends upon the particular use to which a monochromator is put and no universal rules exist\textsuperscript{31}. If the entrance slit is so wide that diffraction effects are negligible, the spectrum consists of a series of monochromatic images of the slit. With a narrow slit, diffraction effects spread the slit image. The pattern depends on the width of the slit and on the aperture and focal length of the collimator.

The slit width limits the resolution as can be seen from the following analysis using a plane reflection grating.

\begin{center}
\textbf{DIAGRAM 5}
\end{center}
The grating equation is:

\[ m \lambda = a [\cos (\alpha_1 - \theta) + \cos (\alpha_o + \theta)] \]  \hspace{1cm} (25)

If \( \alpha_1 \) and \( \alpha_o \) vary by \( \delta_1 \) and \( \delta_o \), which represent the non-zero slit widths, then:

\[ m \frac{\delta \lambda}{\alpha} = - \sin (\alpha_1 - \theta) \delta_1 - \sin (\alpha_o + \theta) \delta_o \]  \hspace{1cm} (26)

If \( \delta_1 = 0 \) and \( \delta_o \) changes from +\( \delta \) to -\( \delta \) where 2\( \delta \) is the angular width of the exit slit, then the spectral spread of energy emerging from the exit slit and deriving from the central strip of the entrance slit is deduced. This is shown in diagram 6(a).

Similarly if \( \delta_1 = \delta \) and \( \delta_o \) ranges from +\( \delta \) to -\( \delta \) then the energy spread deriving from the outer strip of the entrance slit is deduced. The result of doing this for all strips in the entrance slit results in diagram 6(b) which gives a spectral distribution for the energy emerging from the exit slit and deriving from the whole of the entrance slit. This trapezoidal "slit function" has a full width 2B = 4\( \delta \) cos \( \alpha \) sin \( \theta \), and a width at the top 2\( \delta \) = 4\( \delta \) sin \( \alpha \) cos \( \theta \). The spectral resolution, \( \delta \lambda \), can be defined as the width of the slit function at half height, i.e.
The accurate determination of the slit function is necessary for any line width measurements.\(^9\)

Criteria for choosing optimum slit widths for different types of sources and methods of slit irradiation can be found in Sawyer\(^{31}\).

(4.2.) The Grating

Almost no transmission gratings are used in research instruments, even though practically obtainable blazes may throw up to 90% of the light into a single order for a specified wavelength. Some of the reasons are that the dispersion of the grating material introduces complexities, ultraviolet absorption and the difficulty of making transmission optics achromatic over a wide wavelength range.

All research quality gratings are of the reflection type. The grooves are specially shaped so as to reflect the light into the desired order of interference.

\[
\frac{\delta \lambda}{\lambda} = A + B = 2 \delta \sin (\alpha + \theta) \tag{27}
\]

(for \(m = 1\)).

![Diagram of a reflection grating](https://example.com/diagram7.png)

**DIAGRAM 7**

**PROFILE OF A REFLECTION GRATING**
When the grooves are sharply defined, as shown in diagram 7, the grating is said to be strongly blazed. Gratings most often have one steep and one shallow face, with an angle between faces of about 90°. The light is arranged to strike the grating at an angle $\phi_0$, parallel to the shallow face, of width, $t$, and perpendicular to the steep face of width, $S$. The diffracted light is observed at an angle $\phi$ nearly equal to the angle of incidence. This condition of use is known as autocollimation. The grating equation is

$$m \lambda = a \left( \sin \theta + \sin \phi_0 \right)$$

The single slit diffraction pattern is centred about the angle $\theta_0 = \phi_0$ from the normal to the grating and has an angular width dependent upon the distance, $S$.

The interference maxima have positions and spacings dependent on the distance $a(\sin \theta + \sin \phi_0) = 2t$. If $2t$ is an integral number of wavelengths, then the pattern appears similar to that shown in diagram 8.

Most of the light is thrown into the single order $m = 2t/\lambda$. The $m^{th}$ order interference maximum falls at the central maximum of the single
slit diffraction pattern, while all others fall at zero minima of the
diffraction pattern. At a different wavelength only two orders have much
intensity, and all the rest are weak. A grating is blazed over a wave­
length range $\Delta \lambda = \pm \lambda/2m$, according to the following considerations.
Let $\theta$ and $\phi$ be the same and equal to $\theta_0$, and let $m \lambda = 2a \sin \theta_0$. Light
of appreciable intensity is diffracted only up to about one half an angle
$\delta$ each side of $\theta_0$ given by the width of the central maximum of a single
slit, $\sin \delta = \pm \frac{\lambda}{S}$. The wavelength at the edge of the diffraction pattern
is given by

$$m \lambda' = a \sin[(\theta + \delta) + \sin \theta_0] \quad (29)$$

Now:

$$m \lambda' = 2a \sin \theta + a \cos \theta_0 \sin \delta$$

$$m \lambda' = m \lambda + a \left( \frac{S}{a} \right) \frac{1}{\sin \delta}$$

$$\lambda' - \lambda = \frac{\lambda}{m}.$$ 

Taking one half this value gives

$$\Delta \lambda' = \pm \frac{\lambda}{2m} \quad (30)$$

Thus the blaze wavelength range of the grating used in this study is
$0.15\mu$ to $0.45\mu$.

(4.3) Detection Equipment

Devices for measuring radiant energy fall into two broad classes
depending on whether the response is selective or not with respect to the
frequencies present. The latter class generally depends on the heating
effect of radiation, so they respond equally well to a given amount of
radiant energy regardless of its wavelength and is exemplified by thermo­
piles and bolometers. Among the selective detectors are the human retina,
the photographic plate and the photomultiplier.

The sensitivity of selective receivers may vary with wavelength and
therefore, if absolute intensity measurements are required, have to be
calibrated against a source whose radiation characteristics are known. This is usually either a black body or a tungsten strip filament lamp which has been calibrated against a black body source.

Three different receivers were used for the experiments starting with a Hilger-Schwarz thermopile (FT20). This was replaced with a Mullard 150 AVP photomultiplier loaned by British Rail which was finally replaced by an EMI 6094S photomultiplier.

The initial detection system is shown schematically in diagram 9(a). Diagram 9(b) shows the thermopile schematically.

Figure 5 shows the spectral response of the thermopile and some of its characteristics. The principle of operation is based on the Seebeck or thermo-electric effect whereby an e.m.f. is generated when heat is applied to the junction of two dissimilar metals. Two cone shaped semi-
Fig. 5. Thermopile spectral response curve

Relative intensity

window material CaF$_2$
conductors are spot welded to the underside of the receiver to form the hot junction and the cold junction is made between the semi-conductors and their platinum electrodes embedded in a metal block. This block has a high thermal capacity compared to the receiver to give a greater temperature between hot and cold junctions and hence greater sensitivity. The envelope (glass) is also evacuated for greater sensitivity. The output from the thermopile is often sufficiently high to be measured directly with a galvonometer or potentiometer but if the radiation is weak, as it was for the $4345\AA$ AI and $4348\AA$ AI lines, amplification is necessary. A.C. amplification was preferred to prevent the need for a compensating element to eliminate the D.C. voltage created by a change in ambient temperature. The radiation falling onto the receiver was interrupted by a chopper (16.5 Hz) and the output of the thermopile was transmitted via a tuned transformer to a Grubb-Parsons Amplifier (type TA FA 680). The amplifier output was monitored by a potentiometer type pen-recorder (TOA Electronics polyrecorder).

Unfortunately this system did not work very well and considerable time was spent in trying to rectify the situation. A Mullard 150 AVP photomultiplier and power supply were made by British Rail and in view of the low light levels anticipated and the trouble encountered from stray radiation with the thermopile it was decided to abandon the latter in favour of a photomultiplier detection system.

This system is shown schematically in Figure 6 and the photomultiplier spectral response curve is shown in Figure 7(a). The photomultiplier is of the end-on type with an S11 cathode giving a peak spectral response at 0.42\mu and was biased at 1kV by a D.C. power supply. It was thought that this arrangement would be satisfactory for investigating relative intensities of the $4345\AA$ AI and $4348\AA$ AI lines. The Boltzmann plot, P.27, was obtained using this arrangement. Trouble was experienced with this
Fig 6a. Apparatus in diagrammatic form

Fig 6b. Collimating arrangement
Fig. 7 Spectral response curves of photomultipliers
system too. Spurious signals were picked up whenever electrical equipment was switched on and off in the laboratory or in the workshop next door. It was also eventually found that one valve in the first stage of the Grubb Parsons Amplifier was microphonic which gave rise to similar signals. A further complication arose when the amplifier tended to be unstable and oscillate at high amplification. The pick up was reduced to a tolerable level by shortening and screening leads and the stage containing microphonic valve was replaced by a transistorised two stage preamplifier. There was also a problem with impedance matching. The thermopile was of low output impedance and was matched to the amplifier by the transformer. The photomultiplier has a high output impedance and the transformer was therefore dispensed with. After these modifications, the signal to noise ratio was still low and it was felt that the measured maximum intensities of the $\lambda 3d5\alpha$ Al lines and $\lambda 3d6\alpha$ AlI and the resolution realized could be improved with a special purpose photomultiplier such as an EMI 609S. This is a tube for low level photometry with a small exposed area of photocathode to reduce dark current. The spectral response is shown in Figure 7(b). Improvements in intensity measurements were also achieved at this stage by introducing a new torch model (P.6) with a larger nozzle diameter of 5mm. The results of Chapters 5 and 6 were obtained with the EMI 609S photomultiplier.
Chapter 5
Temperature Profiles

This chapter tabulates, and presents graphically, the results obtained from a free burning plasma jet (i.e. discharging to the atmosphere) and a jet impinging on a cooled metal surface under a variety of input conditions.

Section (5.1) deals with the scanning technique; Section (5.2) discusses the steady state characteristics of the jet; Section (5.3) presents temperature distributions obtained with the Ionic/Atomic Line Ratio Method and shows how the Atomic/Atomic Line Ratio Method can be used to extend these temperature distributions into cooler regions of the jet for the free burning jet; Section (5.4) presents temperature profiles obtained in a similar fashion for the case of a jet impinging on a cooled metal surface. Thermocouple measurements were made to establish a surface temperature distribution and these are presented for one particular set of operating conditions.

A discussion of these results, a detailed error analysis and comparison with published data is taken up in Chapter 6.

(5.1) Scanning Technique

A method whereby the jet is scanned laterally in a step-wise fashion is described in Appendix 3.

The problem is that the collimator aperture has to be large enough to collect sufficient radiation to make measurements of line intensity reliable and to enable sufficient reduction of the entrance slit width to provide acceptable resolution; whilst not so large as to make any calculated temperatures averages, weighted towards the hotter part of a relatively large region of the plasma jet.

(5.2) Steady State Characteristics

It was considered desirable to know what sort of fluctuations to
expect in intensity measurements and when the steady state was reached under different input conditions.

Figures 8, 9, 10(a) and 10(b) show the variation of the $\lambda 4361$ AII peak intensity with time for different input conditions. In the first case, (Figure 8), the intensity of the continuum at $\lambda 4361$ was also monitored (not at the same time as the ionic peak: it was established that a fluctuation in one was accompanied by a fluctuation in the other). In Figure 10 the results on two separate occasions are shown. All these results were obtained with the collimator locations as indicated for the free burning jet.

A preliminary observation indicates that the 200 Ampere jet with 50 litres/min. of argon (Figure 8) achieves a steady state after about 15 minutes and thereafter is subject to fluctuations, probably caused by re-rooting of the arc, occurring in a fairly regular fashion ($1/f \approx 5$ to 10 mins.). These fluctuations are about 5% of the signal level for both line and background radiation.

Figure 9 shows that the 370 Ampere jet with 50 litres/min. of argon does not reach a steady state in the monitoring interval. Again, anode fluctuations occur in a fairly regular fashion ($1/f \approx 5$ mins.) and they are about 10% of the signal level. The large drop in intensity after about an hour is probably due to a loss of anode material. It was observed occasionally that this larger fluctuation was accompanied by an audible noise change and a green flare in the jet, characteristic of copper vapour. In the monitoring interval the signal changed by about 50%.

Figure 10 shows the 370 ampere jet with 90 litres/min. of argon. The anode fluctuations again occur in a regular fashion ($\approx 1$ min.) and represent about 10% of the signal level. The signal has changed during the monitoring time interval by about 25%.

The results of Figure 8 were obtained with an integrating time constant (R.H.S. meter) of 10 seconds and those of Figures 9 and 10 were obtained with time constants of 3 secs. and 1 sec. respectively.
Fig. 8. Variation of 4348 Å AII Line peak intensity and 4356 Å continuum intensity with time (200 Amps; 50 Litres/min).

Fig. 9. Variation of 4348 Å AII Line peak intensity with time (370 Amps; 50 Litres/min)

Fig. 10a. Variation of 4348 Å AII Line peak intensity with time (370 Amps; 90 Litres/min)
The sensitivity of the \( \text{H}_\alpha \) peak intensity to temperature changes can be calculated as follows:

The relationship between intensity and temperature is of the form:

\[
I = \text{const.} \exp \left(-\frac{E}{kT^*}\right)
\]

(cf. equation (4) Appendix 2).

Now,

\[
E = 30.705 \times 10^{-3} \text{ J} \quad \text{and} \quad k = 1.38 \times 10^{-23} \text{ Joules/deg K}
\]

Thus,

\[
I = \text{const.} \exp \left(-22.25 \times 10^4 / T\right)
\]

This can be re-written:

\[
\ln \left(\frac{I_1}{I_2}\right) = 22.25 \times 10^4 \left(\frac{1}{T_2} - \frac{1}{T_1}\right)
\]

Table 1, (P.49) shows \( T_2 \) values for assumed values of \( T_1 \) and \( I_1/I_2 \).

Thus it can be seen that a 50% change in the \( \text{H}_\alpha \) AII peak represents about 1,200°K at 25,000°K (=5%) and about 250°K at 7,500°K (=3%). A 10% change in the \( \text{H}_\alpha \) AII peak represents about 200°K at 25,000°K (=1%) and about 100°K at 7,500°K (=1%).

Of the results shown in Figures 8, 9 and 10 the worst possible case (Fig.1, 50% variation in mean signal level) would mean a variation in temperature of about 5%. As a single scan (to obtain an intensity distribution) takes 20 mins. to 30 mins. (see next section), and the 50% reduction in the peak took approximately one hour, it would appear probable that the temperature variation will not be so high as 5% during the time interval of one scan.

(5.3) (1) Temperature Profiles - Free Burning Jet - Atomic/Ionic Combination

The results obtained with the two line method using the \( \text{H}_\alpha \) AII line and the \( \text{H}_\alpha \) AII and the optical arrangement of Fig.6 page 42 (with
the EMI 6094S photomultiplier) are presented in this section. One set of readings, Fig.26, was obtained with the Mullard 150 AVP and because of the relatively poor resolution is considered less reliable than the other results of this section.

For clarity the section is subdivided according to the current input as follows:-

(a) 370 Amps.
(b) 300 Amps.
(c) 200 Amps.

Thus the dependence of temperature upon flow rate and position is treated at constant power input in each sub-section. One of the sets of results in sub-section (a) is studied in detail to show how a temperature profile is obtained.

<table>
<thead>
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<th>$T_1$ ($^\circ K \times 10^{-3}$)</th>
<th>$T_2$ ($^\circ K \times 10^{-3}$)</th>
<th>$(I_1/I_2)$</th>
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</tr>
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<td></td>
<td>7.25</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>7.20</td>
<td>2.0</td>
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<tr>
<td></td>
<td>7.10</td>
<td>3.0</td>
</tr>
<tr>
<td></td>
<td>6.85</td>
<td>10.0</td>
</tr>
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</table>

**TABLE 1**
Lateral scans in 0.2mm steps at three different axial positions \( x_1 = 0.6 \text{mm} \), \( x_2 = 5.7 \text{mm} \), \( x_3 = 10.8 \text{mm} \) of the 4348 Å AI and 4345 Å Al peak line intensities and background intensity (current and flow rate constant).
Lateral scans of 4348 Å Al, 4345 Å Al II peak line intensities and background continuum intensity at two different axial positions
($x_1 = 0.6$ mm; $x_2 = 5.7$ mm)
(a) 370 Amperes

Figures 11, 12 and 13 show the result of laterally scanning the jet in steps of 0.2 mm. for the 370 Amps, 90 litres/min. argon jet at three different axial positions.

Figures 14 and 15 show scans for the 370 Amps, 25 litres/min. jet at two different indicated axial positions.

A smoothed intensity distribution has been drawn in by eye in Figures 11 to 15 and the calculation of Appendix 3 has been performed on these weighted average distributions to obtain a curve approaching the actual lateral intensity distribution. This is then followed, in each case, by the calculation of Appendix 4 to obtain a radial emission coefficient distribution. It is then a simple matter to deduce temperature distributions.

The actual points plotted for the weighted distributions include corrections for overlapping and corrections for the nonlinear response of the R.M.S. meter where necessary.

As an example, and to indicate sources of error, the procedure outlined above for processing the data is carried out for the date of Figure 11. Figure 16 shows the weighted average distribution of the 434 Å AI emission intensity along with the actual distribution, obtained by the calculation of Appendix 3, for both the smoothed and the unsmoothed cases. From Figure 16 it can be seen that a small change in the weighted distribution can give rise to quite a substantial change in the actual distribution.

The region of the weighted average curves bounded by AB in Figure 16 is especially important because it is the slope here that determines the central maximum of the actual distribution. It can be seen that the different gradients in the AB region give rise to a value of $\frac{I(\text{unsmoothed})_{\text{max.}}}{I(\text{smoothed})_{\text{max.}}}$, i.e. 1.2 which from Table 1 of section (5.2) amounts to about 1,000 K at 25,000 K ($\approx 4\%$) and about 200 K at 10,000 K ($\approx 2\%$).

A noteworthy point is that if $d$, the scan increment, is made small enough, then provided a reliable weighted average curve is drawn, an exact
Fig. 16. The calculation of appendix 3 carried out on the data of Fig. 11 for both smooth and unsmoothed.
Fig 17. The output of the pen recorder showing the 4345 Å Al and 4348 Å Al II lines at three different lateral positions (not to scale).

This figure corresponds to the data of Fig 11.
knowledge of collimator location is not necessary because the actual distribution is fixed with respect to $y$ by the calculation of Appendix 3. It appears from the smoothed and unsmoothed data of Figure 16 that the uncertainty in central location is about 0.1mm. For this reason and in order to minimise the scan time (and thus minimise the risk of a large scale jet fluctuation) a practical scan increment was taken as 0.2mm. This is a compromise between the need to obtain the scan results quickly and the need to keep $d$ as small as possible in order to get an accurate estimate of the weighted average distribution. With $d = 0.2\text{mm}$, the average number of points in a single lateral scan is about eight with each point taking about three minutes to plot.

Figure 17 shows the output of the pen recorder for the scan of the $13\lambda 8\lambda$ AII/$13\lambda 5\lambda$ A II peak intensities at three positions and indicates how the correction for overlapping was made. This figure corresponds to the data of Figure 11.

Figure 18 shows the actual intensity distributions of Figure 16 for $13\lambda 8\lambda$ AII re-plotted with their maximum centralised at $x = 0$.

Figure 19 shows the radial emission coefficients obtained by the calculation outlined in Appendix 4 for both the smoothed and unsmoothed distributions of Figure 18.

This whole procedure is repeated for the $13\lambda 5\lambda$ Al line data of Figure 11. In this case the scatter allows the intensity distribution of Figure 11 to be taken as constant and $= 0.13\lambda$. Conversion to an actual distribution (Appendix 3) leaves this value unchanged over the region of interest. The radial emission coefficient distribution corresponding to this constant input is shown in Figure 20. The ratio of radial emission coefficients at any $r$ will give the temperature at that point in the manner outlined in Appendix 2. A temperature distribution is shown in Figure 21 for the data of Figure 11. Notice that the intensity level of the ionic line falls off so rapidly that the atomic/ionic combination is not useful below temperature of about 15,000$^\circ\text{K}$. 
Fig 18. Intensity distributions of Fig. 16, re-plotted with maxima centralised at \( y=0 \).
Volts / mm

Radial emissivity of 4348 Å II line from smoothed data of Fig. 18.

Distance (mm)

Input ○ Output

Volts/mm

Radial emissivity of 4348 Å II line from unsmoothed data of Fig. 18.

Distance (mm)

Fig. 19: Radial emission coefficients obtained from the data of Fig. 18.
Fig. 20. Radial emission coefficient distribution for the 4345 Å AI line obtained from the data of Fig. 11.
Fig. 21. Temperature profiles obtained from the data of Figs. 11, 12, 13 and 14.

Fig. 22. Temperature profiles obtained from the data of Figs. 24 and 25.

Fig. 23. Temperature profiles obtained from the data of Figs. 26 and 27.
The next section (5.3)(ii) indicates how an atomic/atomic line combination can be usefully employed to give information about jet temperatures in the cooler regions.

The temperature profiles obtained from the data of Figures 12 and 13 are also shown in Figure 21. The effect of flow rate is indicated in the lowest curve (from the data of Figure 14). The data of Figure 15 is not sufficiently accurate to calculate temperature profiles.

The effect of errors of \( \pm 25\% \) in transition probability and \( \pm 10\% \) in \( \epsilon \), the degree of ionization, can be seen in Figure 2 of Appendix 2. If the maximum error in radial emission coefficient from all sources is assumed to be \( \pm 10\% \) (giving rise to an error of about \( \pm 25\% \) in the ratio in the worst case) then this could mean a variation from a large upper limit to 17,000\( ^0\) K (the high upper limit caused by the effect of \( \pm 10\% \) in \( \epsilon \)) and 15,750\( ^0\) K to 14,250\( ^0\) K at 15,000\( ^0\) K. The relative insensitivity to errors of this method can be compared with the atomic/atomic method in the next section.

(b) 300 Amperes

Results for this power input were obtained from the data of Figures 24 and 25.

The temperature profiles are shown in Figure 22.

(c) 200 Amperes

Results for this power input were obtained from the data of Figures 26 and 27. The temperature profiles are shown in Figure 23.

(5.3)(ii) Temperature Profiles - Free Burning Jet - Atomic/Atomic Combination

Results obtained using the two atomic lines, 4198\( ^0\) AI and 4200\( ^0\) AI, are presented in this section.

As an example, the atomic/atomic combination data obtained under the same conditions as those of Figure 11 will be studied in detail.
Fig. 24

Fig. 25

4348 Å  4345 Å  □ Background  4348 Å  △ 4345 Å  △ Background

Fig. 26

Fig. 27
Intensity (volts) - relative to the background level

Current = 370 Amps
Flow rate = 90 litres / min
Position $x_1$
$d = \infty$

$4198$ Å AI
$4200$ Å AI

Fig. 28. Weighted distributions of the $4198$ Å AI and $4200$ Å AI line intensities under the same operating conditions as those of Fig. 11.
Figure 28 shows the weighted distributions of the 4198A Al and 4200A Al line intensities. These are converted into actual distributions and then into radial emission coefficients in the manner outlined in the last section. The radial emission coefficient ratios as a function of radius in this case are shown in Table 2.

<table>
<thead>
<tr>
<th>Radius (mm)</th>
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<tr>
<td>0.8</td>
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<td>0.9</td>
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<td>13</td>
</tr>
<tr>
<td>1.8</td>
<td>very large</td>
</tr>
</tbody>
</table>

**TABLE 2**

It can be established from Figure 21 that the temperature at \( r = 0.8 \text{mm} \) is 16,000°K. At \( r < 0.8 \text{mm} \), pressure broadening of the lines impairs the resolution and it is impossible to accurately measure intensities. Comparing the emission coefficient ratio of Table 2 with the emission coefficient ratio versus temperature curve of Fig.1, Appendix 2 shows that the ratio only changes significantly at temperatures below 5,000°K. Between 5,000°K and 2,000°K there is, roughly, a 25% change in ratio. This sort of change should be obvious in any emission coefficient ratio distribution obtained from experimental data, such as that shown in Table 2, and provides a convenient method of establishing the radial distance at which the temperature becomes 5,000°K. In this case it would appear that the temperature is around 5,000°K at \( r = 1.5 \text{mm} \).

Figure 29 shows how temperature profiles have been extended into cooler regions of the jet using the atomic/atomic line ratio method.

(5.1.4) **Temperature Profiles - Impinging Jet**

The experimental arrangement is shown schematically in Figure 30 along
Fig. 29. Temperature profiles are extended into the cooler regions of the jet using an atomic/atomic line combination.
Fig. 30. Experimental arrangement

Fig. 31. Thermocouple
Fig. 32. Temperature distribution in the copper tube wall.

Boiling point of copper = 2582 °C
Melting point of copper = 1084 °C

plasma torch

copper tube

d = 2.2 cm

90 litre/min
370 Amps
Observed weighted distributions at three different axial positions

Intensity (volts)

370 Amps
90 Litres / min
Position $x_1$ ($d=2.2\text{cm}$)
$=0.6\text{mm}$

Intensity (volts)

370 Amps
90 Litres / min
Position $x_2$ ($d=2.2\text{cm}$)
$=5.7\text{mm}$

Intensity (volts)

370 Amps
90 Litres / min
Position $x_3$ ($d=2.2\text{cm}$)
$=10.8\text{mm}$
Fig. 36: Temperature profiles calculated from the observed distributions of Figs. 33, 34, 35, 37 and 38.
Fig. 37

370 Amps
25 Litres / min
Position $x_1 (d=22\text{cm}) = 0.6\text{mm}$

Fig. 38

370 Amps
90 Litres / min
Position $x_1 (d=11\text{cm}) = 5.7\text{mm}$

$\times 4348\text{ Å} \quad \bigcirc 4345\text{ Å} \quad \square \text{Background}$

$\times = 0.6\text{mm}$

Fig. 39

200 Amps
90 Litres / min
Position $x_1 (d=22\text{cm}) = 0.6\text{mm}$

Observed weighted distributions

Fig. 40

200 Amps
50 Litres / min
Position $x_1 (d=2.2\text{cm}) = 0.6\text{mm}$
with the copper tube dimensions.

A Chromel-Alumel thermocouple was mounted in the tube wall as shown in Figure 31. The copper tube could be moved in the y-direction and a wall temperature was obtained. Figure 32 shows this wall temperature distribution for \( d = 2.2 \text{cm} \), a flow rate of 90 litres/min. and 370 Amperes arc current.

Results are presented in subsections according to electrical power input to the torch.

(a) 370 Amperes

(b) 200 Amperes

The value of \( d \) was 2.2 cm, throughout except for some of the results in subsection (a) where \( d \) was 1.1 cm.

(a) 370 Amperes

Figures 33, 34 and 35 are observed weighted intensity distributions for a flow rate of 90 litres/min. at three different axial distances. Figure 37 relates to a flow rate of 25 litres/min. Figure 36 shows the temperature profiles relating to Figures 33, 34, 35 and 37. Also included is the effect of \( d = 1.1 \text{ cm} \), (obtained from the data of Figure 38).

Temperatures in cooler regions of the jet are indicated and were obtained using the \( 4198\text{Å}, 4200\text{Å} \) line intensity ratios (atomic/atomic).

An axial scan was carried out with \( d = 2.2 \text{cm} \), a current of 370 Amperes and a flow rate of 90 litres/min. This was done using both the atomic/ionic and atomic/atomic line ratios without carrying out the conversions of Appendix (3) or (4). The observed intensity distributions are shown in Figures 11 and 12 and the temperature distribution is shown in Figure 13.

(ii) 200 Amperes

Temperature profiles obtained with \( d = 2.2 \text{cm} \), at one axial position but with different flow rates are shown in Figure 14. These profiles were obtained from the data of Figures 39 and 40.
Fig. 41. Observed weighted intensity distributions along axis using ionic/atomic combination

Fig. 42. Observed weighted intensity distributions along axis using atomic/atomic combination
Temperature (°K x 10^-3)

- Using atomic/ionic ratio
- Using atomic/atomic ratio
- From thermocouple measurements

Fig. 43. Axial temperature profile obtained from the data of Figs. 41 and 42

Fig. 44. Temperature profiles obtained from the data of Figs. 39 and 40
Chapter 6

Conclusions

This chapter presents an error analysis in (6.1), compares the results with published data in (6.2), mentions areas for further study in (6.3) and gives conclusions in (6.4).

(6.1)

(1) Sources of Error

The form of the basic equation of the two line intensity ratio of temperature measurement is given by equation (9) of Appendix 2.

viz.

\[ \frac{X}{T} = \ln(gA\ln Q) \]  

(33)

Partial differentiation gives:

\[ \frac{\delta T}{T} = \frac{\delta X}{X} - \frac{1}{\ln(gA\ln Q)} \left\{ \frac{\delta g}{g} + \frac{\delta A}{A} + \frac{\delta I}{I} + \frac{\delta n}{n} + \frac{\delta Q}{Q} + \frac{\delta v}{v} \right\} \]  

(34)

Assuming \( \frac{\delta X}{X} \) is negligible (which is reasonable as energy levels are accurately established) and substituting from (33):

\[ \frac{\delta T}{T} = - \frac{T}{X} \left\{ \frac{\delta g}{g} + \frac{\delta A}{A} + \frac{\delta I}{I} + \frac{\delta n}{n} + \frac{\delta Q}{Q} + \frac{\delta v}{v} \right\} \]  

(35)

The compound error in temperature due to the errors in independent variables is the sum of individual errors multiplied by a factor \( T/X \).

In the case of the \( \text{H}198^\circ \text{A}1/\text{H}200^\circ \text{A}1 \) pair and the \( \text{H}345^\circ \text{A}I/\text{H}348^\circ \text{A}II \) pair the values of \( X \) are 892.1 \( (^\circ \text{K})^{-1} \) and 55,860 \( (^\circ \text{K})^{-1} \) respectively.

The value of \( T/X \) is approximately 2 at 2,000\(^\circ\)K (20 at 20,000\(^\circ\)K) in the atomic/atomic case and approximately 0.04 at 2,000\(^\circ\)K (0.4 at 20,000\(^\circ\)K) in the atomic/ionic case.

Thus \( T/X \) is substantially greater than one in the atomic/atomic case over the temperature range of interest (up to 20,000\(^\circ\)K) and is less than one in the atomic/ionic case. This means that if equation (35) is assumed to
\[ \frac{5T}{T} = -\left( \frac{1}{1} \right) \left( \frac{5A}{A} + \frac{5T}{T} \right) \]  

(i.e. the only sources of error taken into account are in transition probabilities and intensity measurement) and errors of 25\% and 10\% in transition probability and intensity measurement are taken to be realistic (i.e. errors in transition probability ratio and intensity ratio could be about 33\% and 20\% respectively, then at 20,000\,^\circ\text{K}, \left( \frac{5T}{T} \right) = 1000\% for the atomic/atomic case and \left( \frac{5T}{T} \right) = 20\% for the atomic/ionic case. The advantage of using an atomic/ionic combination over the use of an atomic/atomic combination from the point of view of error reduction is obvious.

The ± 25\% error in transition probabilities is taken from Wiese\textsuperscript{26} and it remains to establish the error in intensity measurements. Most authors seem to take a maximum error of 10\% as realistic. Another source of error could be \left( \frac{5T}{n} \right), however if this were large then serious doubts about the viability of the method would be raised on grounds of non-equilibrium. The effect of a ± 10\% error in degree of ionization is shown in Figure 2 of Appendix 2. For the present \left( \frac{5T}{n} \right) is assumed to be negligible. Non-equilibrium of the plasma jet is to be taken up as an experimental project (see (6.2)) using laser holography. Comparing experimentally determined neutral and electron densities in the plasma jet with theoretical particle densities at equilibrium (Figure 3, Appendix 2) will afford a check on the validity of this assumption.

(ii) Errors in Line Intensity Ratio Measurement

The procedure by which a radial emission coefficient distribution is obtained has been outlined in section 5.3. The same set of data is used here to illustrate the cumulative effect of errors and the curves of Figure 11, Page 50, are reproduced in Figure 45(a) with error bands shown. The limits on each plotted point represent measurement uncertainty. These
Fig. 45. Effect of errors on the data of Fig. 11
include dial gauge errors and the errors associated with accurately centering
the jet (abscissa) and voltmeter errors, the errors associated with lines
overlapping and with the line radiation being the result of subtracting the
continuum radiation from the overall radiation (ordinate).

The broken curves forming envelopes to the shaded areas include the
effects of jet fluctuations. From the data in Figure 10, Page 47, it can
be seen that the fluctuations in intensity on the axis are about 10% on
average with an occasional longer variation of about 30%. The broken curves
are drawn at approximately ± 10% to the smoothed curves in the ordinate di­
rection and in the region of high gradient the uncertainty in radius (≈ ± 0.1 mm)
is taken into account. Thus it is possible that the experimental curves
could lie anywhere within the shaded areas.

Figures 45(b) and 45(c) show various possible distributions for the
4348Å AII and 4345Å AI lines respectively. The curves of Figure 45(b) are
labelled A to E to illustrate upper and lower error limits and the effect of
changing slope on the distribution. The result of performing the calculation
of Appendix 3 is shown in Figure 46.

The curves of Figure 45(c) are labelled A to D. These were drawn with
the knowledge of Figure 49(c) (Appendix (3) and Appendix (4) calculations
performed) and many distribution curves that could be associated with a neg­
ative value of emission coefficient have been excluded.

The next step is to perform the calculation of Appendix 3, converting
the observed weighted distributions into lateral intensity distributions.
The basic equation is of the form, (see equation (4), Appendix 3),

\[ I = L (\Delta l) \]  

(37)

Partial differentiation gives:

\[ \frac{\delta I}{I} = \frac{\delta (\Delta l)}{\Delta l} + \frac{\delta L}{L} \]  

(38)

Using the nomenclature of Appendix 3
Fig. 46. The result of the calculation of Appendix 3 on the curves of Fig. 45b.
Fig. 47. Effect of variation in \( \ell/d \).

\[ \begin{align*}
&\text{Intensity (volts)} \\
&\circ \ell/d = 6 \\
&\triangle \ell/d = 7 \\
&\square \ell/d = 5
\end{align*} \]

Fig. 48a. The curves of Fig. 46 re-plotted with maxima centralised.

- \( x \) Curve A, \( \circ \) Curve B, \( \triangle \) Curve C, \( \square \) Curve D, \( \triangledown \) Curve E

Fig. 48b. Distributions from the data of Fig. 45c obtained using the calculation of Appendix 3.
\[
\frac{\delta I_n}{I_n} = \frac{\delta \left( \frac{i_n - i_{n-1}}{L} + \frac{I(n-L)}{L} \right)}{\left( \frac{i_n - i_{n-1}}{L} + \frac{I(n-L)}{L} \right)} + \frac{\delta L}{L}
\]  
(39)

(where \( I_{n-L} = 0 \) if \( n < L \)).

Now, \( L \) is taken as \((1.2/0.2) = 6 \) throughout where 1.2 mm. is the projected collimator diameter and 0.2 mm. is the scan increment. Now, 1.2 mm. is the projected diameter based upon nominal diameters of 1.0 mm. for the holes in the end caps of the collimator. Figure 47 shows the effect of \( L = 5 \) and \( L = 7 \) using the smoothed data curve. It can be seen that the resulting curves are virtually the same except at low values of \( y \). There is an uncertainty in axial position \( (x = 0) \) of approximately \( \pm 0.05 \) mm. and a variation in maximum intensity of approximately \( \pm 10\% \).

Figure 46 shows the output curves after performing the calculation of Appendix 3 on the curves A to E of Figure 45(b). Here the uncertainty in the position of maximum intensity is approximately \( \pm 0.1 \) mm. and the variation in magnitude (relative to the smoothed case, E) is about \( \pm 50\% \) in the case of curve C and \( \pm 25\% \) in the case of curve D. The peak variation is better for curves A and B and is approximately \( \pm 10\% \) in both cases. Thus, it is the gradient of the input curve that determines the magnitude of the output curve maximum.

Figure 48(a) shows the curves of Figure 46 redrawn after having been shifted in the \( y \)-direction so that peak values occur at \( y = 0 \).

Figure 48(b) shows the curves of Figure 45(c) after the calculation of Appendix 3 has been performed.

Figure 49(a) shows the emission coefficient distributions obtained from the curves of Figure 48(a) for the \( 4345\alpha \) AI line and Figure 49(b) and 49(c) represent the same procedure for the \( 4345\alpha \) AI line. The curves of Figure 48(b) (with the exception of curve A) are redrawn in Figure 49(c). Extra curves ((iii)(iv) and (vi)) have been drawn in to examine the sensitivity of the output curve to changes in the input curve. Corresponding
Emission coefficients obtained from the data of Fig. 48a.

Lateral distribution for the 4345 Å Al line intensity

Emission coefficients obtained from the curves in (b)
curves are denoted by roman numerals. Unfortunately in this particular case the \( \lambda 345 \AA \) AI line intensity profile is not measured very accurately. This is because using a more sensitive R.M.S. meter scale would have meant taking a longer time to obtain measurements with no guaranteed improvement in overall accuracy. The effect of the gradients of the input curves is quite marked. The falling off in gradient of curve (i) as compared to curve (ii) as radius decreases, results in a substantial central dip in the resulting output curve.

The scatter on the temperature profile due to errors in intensity measurement is established by taking highest and lowest value distributions of emission coefficient from Figure 49(a) (\( \lambda 345 \AA \) AII line) and Figure 49(c) (\( \lambda 345 \AA \) AI line) and finding the ratio at given values of radius. The temperature is then given by equation 4 of Appendix 2.

Thus, an upper error band is fixed by taking the highest value \( \lambda 345 \AA \) AII emission coefficient distribution of Figure 49(a) (curve (c)) and the lowest value-distribution of Figure 49(c). A complication arises with this particular case because of the appearance of negative values which are physically meaningless and arise from errors. For the purposes of evaluation of scatter in the temperature profile the \( \lambda 345 \AA \) AI lowest and highest value distributions are taken as curve (V) of Figure 49(c) ± 0.05 Volts/mm. A lower error band on the temperature profile is fixed by taking the higher value distribution for the \( \lambda 345 \AA \) AI case along with curve D of Figure 49(a) for the \( \lambda 345 \AA \) AII case.

The scatter on the temperature profile is shown in Figure 50. (Upper and lower boundaries to the cross-hatched region.) Also shown, for comparison, are the curves obtained if the line ratios are used to evaluate temperature profiles without carrying out the full procedures of Appendices 3 and 4. The data for each curve is that of Figure 11 on Page 50.

The curves of Figure 50 seem to indicate that the conversion of Appendix 3 is worth doing. If this conversion had not been carried out then the
Operations carried out on original data

- △ Calculation of app. 3 followed by calculation of app. 4
- ▽ Calculation of app. 3 only
- □ Calculation of app. 4 only
- × None

Fig. 50: Temperature profile scatter
Fig 51. Comparison with published data

Temperature (°K x 10^{-3})

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Temperature Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>A -</td>
<td>( x = 11 \text{mm} )</td>
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<tr>
<td>B -</td>
<td>( x = 10 \text{mm} )</td>
</tr>
<tr>
<td>C -</td>
<td>( x = 10 \text{mm} )</td>
</tr>
<tr>
<td>D -</td>
<td>( x = 6 \text{mm} )</td>
</tr>
</tbody>
</table>

Curve A - Demyantsevich, et al
Curve B - Jahn and Butler
Curve C - Chapelle
Curves D - McGregor and Dooley

\[ x_2 = 5.7 \text{mm} \]
temperature profile would be about 10% lower than indicated. This conversion also has a marked effect on the temperature gradient making it steeper than if the radial conversion only had been carried out. It can also be seen that the curve obtained when only the radial conversion is carried out is not within the fairly generous error bands, especially at the centre of the jet.

(6.2.) Comparison with Published Data

Comparison with published data is made difficult by the wide variety of torch chamber geometries and operating conditions. Also, because of the high temperature ranges established, the comparison is confined to torches operating with fairly high power inputs. The temperature profiles reproduced in Figure 51 are examples from the literature of temperature profiles established in argon plasma jets discharging freely to the atmosphere using some of the spectroscopic techniques outlined in Chapter 3. The torches used are all similar in geometry to the torch used in this study and all operate with water-cooled electrodes.

In the article by Demyantsevich et al.\textsuperscript{28} the temperatures were determined using the intensity of the recombination continuum in the $4400\,\text{K} - 4800\,\text{K}$ range. This was effected using a photographic plate as detector and the standard radiation source was the anode spot of a carbon arc. The quoted accuracy is $4\%$ in the $7000\,\text{K} - 12000\,\text{K}$ range.

The temperatures in the article by John and Butler\textsuperscript{20} were obtained by measuring the absolute intensity of either or both the $3949\,\text{Å}$ AI and $4046\,\text{Å}$ AI lines with a calibrated tungsten lamp as standard radiation source. The accuracy is quoted as better than $5\%$ in the $8500\,\text{K} - 15000\,\text{K}$ range.

The temperatures in the article by Chapelle and Cabannes\textsuperscript{22} were obtained by measuring the absolute intensity of the $4150\,\text{Å}$ AI line.

The temperatures in the article by McGregor and Dooley\textsuperscript{21} were obtained by using the peaking function method. The method was used separately
measuring the intensity of the H158 A Al line, the intensity of the recombination continuum and the intensity of the bremsstrahlung continuum. The results obtained are shown in curves, $D_2$, $D_1$ and $D_0$ respectively of Figure 51.

(6.3) Areas of Further Work

Areas of further work fall into two broad categories. The first of these includes areas that have nucleated in the present study and the second defines areas that would constitute the next step in attempting to establish more reliable temperature distributions and/or widen the scope of the study in order to make more accurate measurements of relatively low temperatures in the argon plasma jet.

(i) CN bands
(ii) Noise
(iii) Laser holography

The first two belong to the first category and the last one to the second category.

(1) CN Bands

In an earlier report\textsuperscript{32} it was noted that CN bands were produced near a plasma jet/metal (oil contaminated) interface. It was suggested that a chemical process was occurring whereby carbon and nitrogen ions produced in the hot jet were combining to form CN in the cooler regions of the jet. This could suggest entrainment of air into the jet which in turn could result in the observed falling off in temperature at the edge of the jet.

In this earlier work a prism spectrograph was used to disperse the energy and a photographic plate was used as detector. Due to lack of sufficient control over all the relevant parameters (instability in the jet, relatively long exposure times, oil flow rate to the metal surface) it was not possible to establish any quantitative results. It would be possible
Fig. 52 Normalized R.M.S. to mean intensity ratio at two axial distances from the nozzle for a free jet and an impinging jet
with the present apparatus to make a better and detailed study of this phenomenon which could lead to a fuller understanding of the nature of the obtained temperature profiles (i.e. whether entrainment is negligible or not) as well as an understanding of chemical processes in the plasma jet.

(ii) Noise

(The word "noise" is used loosely to describe all fluctuations in the jet). The problem of instabilities in the jet is briefly investigated in this study. The results are presented in Chapter 5, Figures 8, 9 and 10 and there is some discussion at the beginning of Chapter 5. The cyclical fluctuations (at approximately one minute intervals in Figure 10 and ten minute intervals in Figure 8) are thought to be due to re-rooting of the arc.

The high frequency component of the signal in all three Figures has been established as greater than 600Hz (the upper limit of the Prosser R.M.S. meter filters) and the large scale random fluctuations are accompanied by a greenish hue characteristic of copper vapour which seems to suggest a gross change in the electrodes. All these fluctuations are worthy of more detailed investigation into both cause and effect. The effect of these fluctuations off-axis is shown in Figure 52, a normalized R.M.S. fluctuation to mean intensity ratio distribution for the \( \lambda 195\AA \) continua. It shows that the noise increases with axial distance in both cases (\( d = \infty \) and \( d = 2.2\text{ cm} \)). Also, the noise level increases with lateral distance more rapidly in the case of \( d = \infty \) than it does in the case of \( d = 2.2\text{ cm} \).

In all these noise measurements no attempt has been made to perform the calculations of Appendices 3 or 4. It is felt that the whole subject of noise in the jet is worthy of further detailed study of both cause and effect and would give a fuller understanding of the physical processes in the jet.
(iii) Laser Holography

It is anticipated that scatter plate holography will be used to determine fluctuating electron densities in the plasma jet and thus estimate temperature gradients in the relatively cooler regions of the jet in both the impinging and unconstrained cases.

In order to obtain spatial and temporal resolution of electron densities in a turbulent plasma jet it is necessary to simultaneously record time resolved interferograms in several directions. This can be done using two doubly exposed holograms recorded in orthogonal directions. A scatter plate holographic system is proposed using a Q switched ruby laser as light source.

(6.4) Conclusions

The broad aim of the present study was to attempt to establish reliable temperature distributions within a plasma jet. In spite of the large magnitudes associated with possible errors (as outlined in (6.1)) the temperature profiles obtained in this study seem to be at least as reliable as those obtained by other experimenters using similar methods. It appears that the calculation of Appendix 3 produces a steeper temperature gradient at the centre of the jet and a profile that falls off fairly rapidly with radial distance when compared with other works although the evidence is not conclusive. The overlapping scanning technique outlined in Appendix 3 seems to work well and to be suitable in this case where a compromise was needed between sufficient intensity and resolution of the emission radiation from the plasma jet.

Comparing Figures 21, 22 and 23 (d = ∞) with Figure 36 (d = 1.1 or 2.2cm.) shows that the temperature profile may be less steep at the centre in the constrained case than in the d = 2.2cm. case although this is not conclusive. In the case of d = 1.1cm., the temperature profile falls off very rapidly when compared to the d = 2.2cm. case (T = 5000°K at r = 0.7mm.)
in the 1st case and at \( r = 1.4 \text{mm.} \) in the 2nd case. This may be due to entrainment or some other effect.

In all cases the temperature is an obvious function of argon flow rate and electrical power input - the dependence on the latter being more marked than the dependence on the former in the curves shown in Chapter 5. It is worth remarking that the observed trends are consistent (e.g. temperature increases with power input in all the cases observed) and that this would indicate a consistent error (or absence of error) as opposed to large random errors.

The raw data is reproducible (e.g. the curves of Figure 26, Page 61, each represent the average of three separate scans).

In high energy systems a central problem is determining transport coefficients in large temperature gradients. Viable temperature distributions have been established in both the case of a free burning jet and an impinging jet and an estimate of wall temperature distribution in the latter case. These temperatures provide boundary conditions for the solution of conservation laws.

Whilst some areas for further work have been pointed out as being possibly fruitful in terms of a better understanding of the processes within the jet; a knowledge of more reliable transition probabilities, certainty about the LTE assumption (thus electron density deviations from that predicted in equilibrium) and more accurately measured emission coefficient ratios would all serve to more reliably establish temperature profiles.
(7) References

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(9) **Appendices**

**Appendix 1**: The Equation of Transfer

**Appendix 2**: Establishing Temperatures from Emitted Line Radiation Measurements

**Appendix 3**: Estimation of Lateral Intensity Distributions from Observed Weighted Distributions

**Appendix 4**: Conversion of Lateral Distributions to Radial Distributions
Appendix 1

The Equation of Transfer

In Figure 1 following the nomenclature of Viskanta the cylindrical element, \( \delta V = \delta A \delta \omega \delta \nu \delta t \), absorbs (coefficient \( k_{\nu} \)) emits (\( \eta_{\nu} \)) and scatters (\( \sigma_{\nu} \)) monochromatic radiation and has specific intensity (\( I_{\nu} = I_{\nu} (x, t) \)) incident normally at one end.

\[
\delta e_{\text{in}} (1) = \text{energy in} = I_{\nu} \delta A \delta \omega \delta \nu \delta t.
\]

\[
\delta e_{\text{out}} (2) = \text{energy out} = \left( I_{\nu} + \frac{1}{\delta s} \right) \delta A \delta \omega \delta \nu \delta t.
\]

\[
\delta e_{\text{lost}} (3) = (k_{\nu} + \sigma_{\nu}) I_{\nu} \delta V \delta \omega \delta \nu \delta t.
\]

\[
\delta e_{\text{emitted}} (4) = \eta_{\nu} \delta V \delta \omega \delta \nu \delta t.
\]

\[
\delta e_{\text{gained}} (5) = \left[ \frac{\sigma_{\nu}}{4\pi} \int_{s'} \frac{p_{\nu}}{4\pi} (s' \rightarrow s) I_{\nu} (s') \delta \omega \delta \nu \delta t \right] \delta V \delta \omega \delta \nu \delta t = \sigma_{\nu} H_{\nu} \delta V \delta \omega \delta \nu \delta t.
\]

By executing an energy balance

\[
\delta e (2) = \delta e (1) + \delta e (3) + \delta e (4) + \delta e (5)
\]

\[
\frac{\delta I}{\delta s} = \eta_{\nu} + \sigma_{\nu} H_{\nu} - (k_{\nu} + \sigma_{\nu}) I
\]

then since

\[
\delta s = c. \delta t
\]

and by defining an effective emission coefficient (or spectral radiance)

\[
J_{\nu} = \eta_{\nu} + \sigma_{\nu} H_{\nu}
\]

neglecting \( \sigma_{\nu} \).
Fig. 1 Symbols for equation of transfer for a small cylindrical element of volume
and using the hydrodynamic operator

\[ \frac{D}{Dt} = \frac{\delta}{\delta t} + c \mathbf{s} \cdot \mathbf{v} \]

\[ \frac{1}{c} \frac{\delta I}{\delta t} + (\mathbf{\hat{s}} \cdot \mathbf{v}) I_{\nu} = J_{\nu} - k_{\nu} I_{\nu} \]

which reduces when \( x \) is the chosen direction to

\[ \frac{\delta I}{\delta x} = J_{\nu} - k_{\nu} I_{\nu} \]

This is an equation of transfer, neglecting scattering into the element, and considering monochromatic radiation, and may be simplified further by considering the emitting element to be optically thin.

\[ \frac{dI}{dx} = j - kI \quad \text{(dropping suffixes)} \]

\[ I' + kI = j \]

\[ e^{kx}(I' + kI) = je^{kx} \]

\[ \frac{d}{dx} e^{kx}I = je^{kx} \]

\[ I(L)e^{kL} - I(0) = \int_0^L je^{kx} dx. \]

\[ I(L) = I(0)e^{-kL} + j \int_0^L e^{-k(L-x)} dx \]

\[ = I(0)e^{-kL} + \frac{j}{k} (1 - e^{-kL}) \]

By defining the optical thickness \( \tau_{\nu} = \int k_{\nu} dk \)

as thick when \( kL >> 1 \)

and thin when \( kL << 1 \)

when thick \( I(L) = \frac{j}{k} \)

when thin \( I(L) = I_0 + jL \)

from which \( \frac{\delta I}{\delta x} = j \) (where \( j \) is the emission coefficient).

i.e. \( \delta I \delta A = j \delta A \delta x \)

\[ = j \delta \nu \]
Appendix 2

Establishing Temperatures from Emitted Line Radiation Measurements

When self-absorption is negligible the monochromatic intensity of an emission line is

\[ I_{ji} = n_j \frac{A_{ji}}{4\pi} \text{hv}_{ji} \]  

Typical units: ergs/sec/cm²/steradian.

If subscripts 1 and 2 are used to distinguish two lines and their associated atomic properties then the ratio of intensities of two lines is:

\[ \frac{I_1}{I_2} = \frac{n_1 A_{1i}}{n_2 A_{2i}} \]  

(2)

Using the Boltzmann relation, viz.

\[ n_{ji} = \frac{n_0 g_{ji}}{Q} \exp(\frac{\text{hv}_{ji}}{kT}) \]  

(3)

(2) can be rewritten:

\[ \frac{I_1}{I_2} = \frac{n_0 g_{1i}}{Q g_{2i} A_{1i} v_1} \exp\left\{ \frac{(E_{j2} - E_{j1})}{kT} \right\} \]  

(4)

Re-arranging:

\[ (E_{j1} - E_{j2})/kT = \ln\left( \frac{g_{1j} A_{1i} v_1 I_1}{g_{2j} A_{2i} v_2 I_2} \right) + \ln\left( \frac{n_0 Q_2}{n_0 Q_1} \right) \]  

(5)

In the case of two atomic lines the last term on the right is negligible.

(i) \( h198^{\circ} \) and \( h200^{\circ} \) atomic line pair

Values of the atomic properties in this case were obtained from Wiese and are reproduced in Table 1.
The values of $A_{ji}$ are both only considered to be accurate to within ±25%. Substituting these values into equation (5) gives:

$$\frac{I_2}{I_1} = \exp \left( \frac{892.4}{T} + 0.96 \right)$$

A graph of $(I_2/I_1)$ v. temperature for the $l200.6^0/l198.3^0$ pair plotted on semi-log paper is shown in Figure 1. Error bands are defined for ±25\% error in transition probabilities and ±10\% errors in intensity ratio.

(ii) $l3\lambda 5^0$ and $l3\lambda 8^0$ atomic/ionic line pair

Values of $E_j$, $g_j$ and $A_{ji}$ were again obtained from Wiese$^{26}$ and reproduced in Table 2.

<table>
<thead>
<tr>
<th></th>
<th>$l3\lambda 5.17^0$</th>
<th>$l3\lambda 8.06^0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_j$ (cm$^{-1}$)</td>
<td>118407</td>
<td>157234</td>
</tr>
<tr>
<td>$g_j$</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>$A_{ji}$ ($10^6$ sec$^{-1}$)</td>
<td>0.00313</td>
<td>1.24000</td>
</tr>
</tbody>
</table>

TABLE 2

In this case the last term on the RHS of equation (5) is not negligible and values of $n_0$ and $Q$ must be found.

If the subscripts 1 and 2 refer to the $l3\lambda 8^0$ AlII and $l3\lambda 5^0$ Al lines respectively, then $n_{0_1}$ and $n_{0_2}$ represent ion and atom number densities.

Saha's equation (7) may be applied to the plasma jet.

$$\frac{e^2}{1 - e^2} = C \frac{T^{5/2}}{p} \exp \left( -\frac{E}{T} \right)$$

where

$$C = 2 \left( \frac{2\pi m_e}{h^2} \right)^{5/2} k^{5/2} \frac{Q_1}{Q_2}$$
FIG. 1. Log plot of temp. v $I_2/I_1$ for $\{4200.7 \, \text{Å}\}$ Argon pair

Temperature [$^\circ K \times 10^{-3}$]

$[I_2/I_1]$
A programme suitable for use on a PDP-11 computer that will solve equations (7) and (8) to obtain values for $n_{o_1}$ and $n_{o_2}$ and then substitute these in equation (5) to obtain values for the intensity ratio at different temperatures is listed in Table 3.

```
1 PRINT"M.R. IEE 2"
10 DIMK(2,2),G(2,2)
20 LET K=0.95E0
100 LET LI=4.368.06
110 LET E(1,1)=1.342.42
120 LET E(1,2)=1.572.34
130 LET G(1,1)=6
140 LET G(1,2)=8
150 LET A1=1.24
200 LET L2=4.355.17
210 LET E(2,1)=95000
220 LET E(2,2)=118507
230 LET G(2,1)=3
240 LET G(2,2)=3
250 LET A2=0.9313
500 LET K1=1.38E-23E:LET P9=3.1415926
510 LET M1=9.109E-31:LET H1=6.626E-34
520 LET P1=1.013E5
1000 FOR T=5000 TO 20000 STEP 5000
1010 OOSUB 7000
1020 OOSUB 2000
1030 OOSUB 3000
NEXT T
1100 STOP
2000 LET Z1=E(1,2)-E(2,2)
2010 LET Z1=Z1/(S*T)
2020 LET Z2=G(1,2)*A1*L2/(G(2,2)*A2*L1))
2030 LET Z3=E(2,2)
2040 LET Z4=EXP(Z2)
2050 LET Z5=EXP(Z4)
2060 RETURN
3000 PRINT",Z5
3010 PRINT",A9,B9
3020 PRINT",I5,II
3030 PRINT",K9
3100 RETURN
3300 RETURN
7000 LET Y1=2*K1*T/P1
7010 LET Y2=1/((EXP(Y1)/(K1*T))))
7020 LET Y3=(2*P9*M1*K1*T/(H1*H1)+2)*(3/2)
7030 LET Y6=4.2*EXP(-2*F2/T)-2*EXP(-156560/T)
7040 LET Y5=1+50*EXP(-162500/T)
7050 LET Y8=Y1*X2*Y3*Y4/YS
7060 LET E1=(Y8/(1+Y8))*1/2
7070 LET A7=(1-E1)/(1+E1)
7080 LET B7=1/1+E1
7090 LET N1=P1/(K1*T)
7100 LET A9=A9+N1
7110 LET B9=B7+N1
7120 LET K9=B7*B7/A7
7130 RETURN
```

**TABLE 3**
Table 1 shows the programme read out for four temperatures.

Data for calculating partition functions was obtained from Sonntag and Van Wylen.34

A graph of \( (I_2/I_1) \) v. temperature for the \( 4345^0 \) Al/\( 4348^0 \) AlII pair plotted on semi-log paper is shown in Figure 2. Error bands due to ± 25% errors in transition probabilities and ± 10% errors in \( \epsilon \) the degree of ionization, are shown.

(iii) The effect of Energy Level Difference on the slope of \( T \) v. \( \ln(I_2/I_1) \)

Re-writing equation (5) with \( (g_{j_1}/g_{j_2}) = g; (A_{j_1}/A_{j_2}) = A; (v_{j_1}/v_{j_2}) = v; (I_2/I_1) = I; (n_{o_1}/n_{o_2}) = n; (Q_{j}/Q_{1}) = Q \) and \( (E_{j_1} - E_{j_2})/k = X. \)

\[
(X/T) = \ln (g A v I n Q) \tag{9}
\]

Differentiating,

\[
cT/(d(\ln I)) = - (T^2/X) \tag{10}
\]

It can be seen that the slope of \( T \) v. \( \ln(I) \) will be steep at high values of \( T \) and shallow at low values of \( T \). The difference between the atomic/atomic case (Fig.1) and the atomic/ionic case (Fig.2) lies in the value of \( X. \) For the \( 4198^0 \) Al/\( 4200^0 \) Al case the value of \( X \) is \( 892.1 (^0K)^{-1} \). This
Fig. 2. \( \frac{I_2/I_1}{T} \) v. temperature for the 4358 Å Al I / 4346 Å Al II line pair.
does not change significantly whichever two atomic lines are chosen. In
the 4345Å Al/4348Å AlII case the value of $X$ is 55,860 (°K)$^{-1}$. This is
because the upper state energy level difference is enhanced by the ioniza-
tion potential. The result is that temperature is less sensitive to inten-
sity ratio measurement in the atomic/ionic case than in the atomic/atomic
case.

(iv) The Equilibrium Composition of an Argon Plasma

Figure 3 shows the equilibrium composition of argon at a pressure of
one atmosphere. Values of neutral and ion particle densities were
obtained using the programme of Table 3.

The second ionization stage is taken into account and particle densi-
ties at equilibrium can be found by applying Saha's equation to the simul-
taneous reactions:

$$\text{Ar} \leftrightarrow \text{Ar}^+ + e^- \leftrightarrow \text{Ar}^{++} + e^- + e^-$$

(11)

Values for particle concentrations in argon at atmospheric pressure
at 1000°K intervals from 5,000°K to 30,000°K and up to and including the
third ionization stage are reproduced in King$^{35}$. 
Fig. 3. Equilibrium composition of argon at a pressure of 1 atmosphere
Appendix 3

Estimation of Lateral Intensity Distribution

from Observed Weighted Distribution

Figures 1 and 2 show the dimensions involved in the calculation. Figure 3 shows the situation as the jet is scanned across the collimator. It may be assumed that the locus of the projection of the collimator axis lies in a horizontal plane defined by \( y = 0 \) without introducing any appreciable error into the scan increment, \( d \).

Figure 4 shows an arbitrary observed distribution (\( i \) v. \( y \)) and related actual distribution (\( I \) v. \( y \)). The longer heavy horizontal lines define the observed intensity, \( i_n \), and the limits of the collimator projection (diameter, \( \delta \)) and the shorter horizontal lines define the average value of \( I \) within the scan increment \( d \).

It is possible, because the detector output is proportional to the amount of energy detected, to form a relationship between \( I \) and \( i \) as follows:-

Consider \( y_0 \) represents the distance at which the intensity \( i \) becomes negligible. When the jet is moved a distance, \( d \), in the positive \( y \)-direction, an intensity \( i_1 \) is recorded.

Now:

\[
\ell_1 = kdI \quad \text{(where} \quad 0 < k < 1) \quad (1)
\]

When the jet is moved another distance \( d \), an intensity \( i_2 \) is recorded where,

\[
\ell_2 = dkI_i + dI_2
\]

The effect of varying \( k \) is not very significant. \( I \) values at high \( y \) are slightly affected but the effect on central points is negligible.

i.e.

\[
I_2 = \frac{\delta}{d} (i_2 - i_1) \quad \text{(2)}
\]

and hence:

\[
I_n = \frac{\delta}{d} (i_n - i_{n-1}) \quad \text{(3)}
\]
Fig. 1. Collimator geometry

Fig. 2. Solid angle consideration

\[ s_1 = s_2 = 118 \text{ mm} \]

\[ \left( \frac{s_2 - s_1}{s_1} \right) < 0.6\% \]

Fig. 3. Scan geometry
Fig. 4. Observed distribution and the actual distribution derived from it using calculation of Appendix 3.
A refinement to equation (3) occurs when the jet has moved a distance of \((\ell + d)\), (i.e. when the trailing edge of the collimator projection intersects the \(I \text{ v. } y\) curve). Equation (3) becomes:

\[
I_n = \frac{\ell}{d} (i_n - i_{n-1}) + A \left( I_{n-\ell/d} \right) \tag{4}
\]

\[
\begin{cases} 
A = 0 \text{ if } n < \ell/d \\
A = 1 \text{ if } n > \ell/d
\end{cases}
\]

For practical reasons discussed in Chapter 5, \(d\) is 0.2 mm, but once a reliable smooth curve of \(I \text{ v. } y\) is established, \(d\) may be made smaller to achieve a greater number of points to plot the \(I \text{ v. } y\) curve.

It is obvious from Figure 4 that \(I_1\) is centred about a \(y\)-value of \(y_o - \frac{\ell}{2} - \frac{d}{2}\) and in the general case, \(I_n\) is centred about a \(y\)-value of \(y_o - \frac{\ell}{2} - (2n - 1) \frac{d}{2}\).

Table 1 lists a BASIC programme which will perform the calculation of equation (4) and gives the central value of \(y\) related to \(I_n\). (\(k\) in equation (1) has been given the value one).
1 PRINT"LOCAL VAL. DISTRIBUT. FROM AVE. VAL . DISTRIBUT."
5 DIM F(50),L(50)
10 PRINT"NO. OF DATA PTS.=";
15 INPUT M
20 FOR I=1 TO M
25 PRINT"L("I")=";
30 INPUT L(I)
35 NEXT I
40 PRINT"A,COLLIM. PROJECTED DIAM.=";
45 INPUT A
50 PRINT"D,INCREMENT SIZE=";
55 INPUT D
60 PRINT"X,DIST. WHERE I(AVE.)=Ø=";
65 INPUT X
70 FOR I = 1 TO M
71 PRINT
72 IF I=1 GOTO 120
75 IF I>(A/D) GOTO 95
80 LET F(I)=(A/D)*(L(I)-L(I-1))
85 PRINT"F("I")=";F(I)
90 GOTO 110
95 LET F(I)=(A/D)*(L(I)-L(I-1))+L(I-A/D)
100 GOTO 85
110 LET Y=(X-A/2-(2*I-1)*D/2)
115 PRINT"Y=";Y
116 NEXT I
117 GOTO 130
120 LET L(I-1)=Ø
125 GOTO 80
130 STOP

READY

**TABLE 1**
Appendix 4

Conversion of Lateral Distributions to Radial Distributions

In order to estimate radial distributions of temperature in a cylindrical gas column from collimated intensity measurements it is necessary to use a numerical method of the type described below. A summary and comparison of viable methods has been made by Tourin and two methods have been described, and results compared with published data, in an earlier report.

The geometry of the situation is shown in Figure 1 and the equation of transfer (see Appendix 1) applicable to the shaded volume element $\Delta x, \Delta y, \Delta z$ (where the z-axis is perpendicular to the paper) for a cylindrical, emitting, optically thin gas column may be written

$$6 I(y) \Delta A = j(r) \Delta V$$

from which

$$6 I(y) \Delta y \Delta z = j(r) \Delta x \Delta y \Delta z$$

and

$$I(y) = \sum_{x=x_0}^{x_0} j(r) \Delta x = 2 \sum_{x=x_0}^{x_0} j(r) \Delta x$$

In the limit as $\Delta x \to 0$ equation (3) becomes:

$$I(y) = 2 \int_{x=0}^{x=x_0} j(r) \, dx$$

(4)

(where $x_0 = (r_o^2 - y^2)^{\frac{3}{2}}$)

This can be re-written as:

$$I(y) = 2 \int_{r=y}^{r=R} j(r) \frac{r \, dr}{(r^2 - y^2)^{\frac{3}{2}}}$$

(5)

Equation (5) can be solved by assuming $j(r)$ to be a constant and equal to $j_k$ over a shell radius $r_k$ and width $\Delta$ (see Figure 2). Thus (5) can be written:

$$I(y) = 2 \sum_{n=k}^{n-1} \int_{r_n}^{r_{n+1}} \frac{r \, dr}{(r^2 - y_k^2)^{\frac{3}{2}}}$$

(6)
Fig. 1. Cross section of emitting cylindrical gas column

Fig. 2. Nomenclature for shells of constant $j(r)$
The integral is solved with the substitution \( r_n = n\Delta \) and \( y_k = k\Delta \)

where

\[
\frac{1}{\Delta} \int_{y_n}^{r_{n+1}} \frac{r \, dr}{(r^2 - y_k^2)^{3/2}} = \left\{ (n+1)^2 - k^2 \right\}^{1/2} - (n^2 - k^2)^{1/2} = C_{kn} \tag{7}
\]

Equation (6) becomes:

\[
I(y) = 2\Delta \sum_{n=k}^{m-1} \int C_{kn} \tag{8}
\]

A BASIC programme suitable for solving this system of \((m - 1)\) equations is listed in Table 1.
1 PRINT "AN ABEL TRANSFORMATION"
5 DIM E(20), F(20), L(20), C(20, 20)
6 PRINT "NO. OF DATA PTS.=";
7 INPUT M
8 PRINT
9 PRINT "FEED IN LAT. INTENSITIES- UPTO 20 PTS.- DESCENDING ORDER"
10 FOR I = 1 TO M
15 FOR J = 1 TO M
20 LET K = I - 1
25 LET N = J - 1
26 IF K = 0 GOTO 148
27 IF J > M GOTO l1
40 IF N > K GOTO 145
41 LET C(I, J) = 0
44 GOTO 150
50 IF N = K GOTO 1U5
50 LET C(I, J) = SQR((N+1)^2 - K^2) - SQR(N^2 - K^2)
52 GOTO 150
55 LET C(I, J) = SQR(2*N + 1)
60 NEXT J
61 NEXT I
65 FOR I = 1 TO M
68 LET F(I) = (L(I) / (2*D) / C(I, I))
70 NEXT I
75 PRINT "EMISSION COEFFICIENTS ARE- IN ASCENDING ORDER -"
77 LET E(M) = F(M)
78 PRINT "E("M")="); F(M)
79 PRINT
80 FOR I = (M-1) TO 1 STEP -1
83 LET S = 0
84 FOR J = 1 TO (M-1)
87 IF (I+J) > M GOTO 295
88 LET X = F(I) - E(I+J)*C(I, I+J) / C(I, I)
89 LET S = S + X
90 IF (I+J) > M GOTO 190
91 LET S = S - (J-1)*F(I)
94 NEXT J
97 LET E(I) = S
99 PRINT "E("I")="); S
100 PRINT
101 NEXT I
105 STOP

TABLE 1
Summary

The aim of this study was to establish reliable temperature distributions, within an argon plasma jet in both the cases of an unconstrained jet discharging to the atmosphere and a jet impinging on a cooled metal surface under various input conditions.

An optical technique, the Two Line Relative Intensity Method was employed with both Ionic/Atomic and Atomic/Atomic Line Combinations.

Results are presented in Chapter 5 and are compared with published data in Chapter 6 and have been published.*

Noise measurements have been made and represent an initial investigation into turbulent fluctuations within the jet.

A novel technique of collimation and scanning of the plasma jet is described in Appendix 3.

* "Temperature and Noise Profiles in an Argon Plasma Jet".