High Current Arc Discharge Phenomena
with Particular Reference to the Plasma
Torch.

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Summary.

The purpose of this investigation was to study high current arc discharge phenomena with particular reference to the plasma torch. The principle object was to provide basic information where required to enable the factors affecting the operation of a plasma torch used for industrial process heating to be evaluated. This has been achieved.

An extensive literature survey of

(i) Arc discharge processes relevant to the operation of a plasma torch.

(ii) Existing arc devices used for heating gases

has been made. A plasma torch operated from both direct current and alternating current has been used to establish the areas where further research was required.

The preliminary investigations indicated that further fundamental information on the behaviour of arcs rotated at high velocities between co-axial electrodes in an axial magnetic field was necessary. In particular the conditions required for the apparently diffuse nature of the arc that had been observed at high rotational velocities and the variation of the erosion rate of the arc electrodes with arc velocity were required. These were investigated experimentally and the results employed in an a.c. plasma torch operating at 415V 50 Hz at power inputs up to 60 kW and with conversion efficiencies greater than 60%, measured in terms of electrical power input to the arc and the useful heat output.

The results from the literature survey, basic investigations and the final version of the plasma torch have been used to establish the design criteria for a d.c. or a.c. plasma torch suitable for industrial process heating.

In addition results of a wider application have been obtained including the development of a synchronous switch suitable for supplying accurately controlled high current pulses, improved methods of arc ignition and a new definition of arc stability that enables quantitative measurements of arc stability to be made.

ACKNOWLEDGMENTS.

I would like to acknowledge the far sightedness of the late Professor E. May for initiating this work and his encouragement. I am grateful to Dr. A. E. Guile of Leeds University for willingly taking over as supervisor after the unfortunate death of Professor May, and thank Professor J. E. Flood, and Professor W. K. Roots for their support and encouragement.

I would like to acknowledge assistance from Mr. P. J. W. Rayner in the design of the electronic circuit of the control unit of the synchronous switch described in Chapter 5.

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Symbols and Units Used.

Rationalised M. K. S. units have been used for all calculations involving electrical quantities. The C. G. S. system has been used where it is customary for quantities not primarily of an electrical nature.

Symbol	Description and Units.
a	area of arc root (cm^2)
a_o	bore radius (m)
a_p	fraction of total cathode current carried by positive ions
a'	cross sectional area of throat of nozzle (m^2)
c	fraction of period during which heating occurs
c_p	specific heat (J/g^oc)
d	diameter (cm) electrode separation (m)
e	electron charge
f	frequency (Hz)
f_c	critical frequency (Hz) (see also 250)
f, g, h	also used to denote functional relationship.
g_{min}	see page 247.
g_{max}	see page 247.
h	heat transfer coefficient ($W/cm^{2o}c$)
i	instantaneous current (A)
i_{ions}	current in constricted section of nozzle (A)
i_{conv}	current in convergent section of nozzle (A)
k	thermal conductivity ($W\ cm/cm^2\ {}^oK$)
k_R	Bolzman constant (page 14)

Symbol	Description and Units.
l	arc length (m)
m	mass (g) or e xponential index (see page 42)
n	exponential index (see page 42)
p	exponential index (see page 55)
q	exponential index (see page 55)
r	exponential index (see page 57)
s	exponential index (see page 57)
s_s	shape factor (cm/ohm)
t	time (s)
t_r	residence time in nozzle (s)
u	instantaneous velocity (m/s)
v	instantaneous voltage (V)
v_n	output voltage from Hall probe (V)
w	instantaneous power (W)
x	axial distance measured from cathode (cm)
A_o	Richardson constant ($A/m^2\ {}^oK^2$)
A	area (cm^2)
B	magnetic flux density (Wb/m^2)
C	charge (C), capacitance (Fd)
Cp	specific heat of gas at constant pressure (J/g^oc)
D	diameter of arc column (cm), diameter of arc electrode (cm)
D_e	hydrodynamic diameter
E	voltage gradient (V/cm)
F	force acting on arc column (N_w)
F_c	circumfrential force (N_W)
F_R	radial force (N_W)
G	geometry factor (Fabry factor)
I	rms current (A)
$\hat{I}$	peak current (A)
J	current density (A/cm^2)

Symbol	Description and Units.
L	flow rate (ml/s), (L/s)
M	mass (g)
N	arbitrary number
N_u	Nusseldt number
P	gas pressure (Atm)
P_R	Prandtl number
Q	magnitude of heat pulse (W)
R	resistance (Ω)
R_e	Reynolds number
S	arc stability
T	temperature (^{o}c)
T_c	temperature at cathode root (^{o}c)
T_1	temperature at electrode-water interface (^{o}c)
T_o	initial temperature (^{o}c)
T'	temperature (^{o}K)
ΔT	rise in temperature of electrode surface(^{o}c)
U	velocity (m/s)
U_c	critical arc velocity (see also page 250)
V	r.m.s. volts (V)
V_h	voltage output from Hall probe (V)
V_A	arc voltage (V)
V_a	anode fall voltage (V)
V_c	cathode fall voltage (V)
V_s	supply voltage (V)
V_e	equivalent evaporation energy (V)
V_g	equivalent energy transfer from gas (V)
V_i	equivalent potential energy (V)
V_j	equivalent conduction loss (V)
V_k	equivalent kinetic energy (V)
V_r	equivalent radiation energy (V)

Symbol	Description and units.
W	power (W)
W_c	power dissipated by conduction (W)
W_e	power dissipated by evaporation (W)
α	thermal diffusivity (cm. s), normalised outer radius of coil.
β	normalised half length of coil.
δ	diffusion depth (cm).
ε	fractional error.
ω	angular velocity (rad. s.)
Ω	resistance (ohms)
η	efficiency
θ	angular deflection (rad)
λ	filling factor
ρ	resistivity (ohm. m), density (g/m and g/ml)
ϕ	power factor, arbitary arc parameter.
ϕ'	work function (eV)
τ	period of revolution(s)

CHAPTER 1.

Introduction.

An introduction to the investigations described in the following chapters and a brief summary of the state of knowledge at the time this work was commenced and the reasons for its instigation are given.

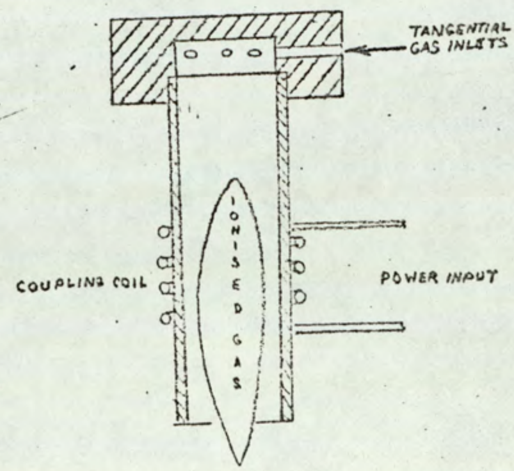
1. INTRODUCTION.

The plasma torch is an electrically heated source of hot gas. Various types of plasma torches exist for different applications. In some cases heated gas is directed in a jet out of the plasma torch so that it is in a field free region away from the electrodes and is referred to as a plasma jet. In this sense it may be considered as a plasma source but a more useful description might be an arc gas heater.

The energy input to the plasma torch may be

1. Indirectly coupled.
2. Directly coupled.

An indirectly coupled plasma torch is shown in Fig. 1.1.+



The Indirectly Coupled Plasma Torch.

Figure 1.1.

The energy input to the indirectly coupled plasma torch is obtained by inducing a current in a stream of pre-ionised gas. This is coupled to a high frequency power source in the same way as the output of an induction heater used for R.F. heating is coupled to its load. The discharge may then be made self sustaining so

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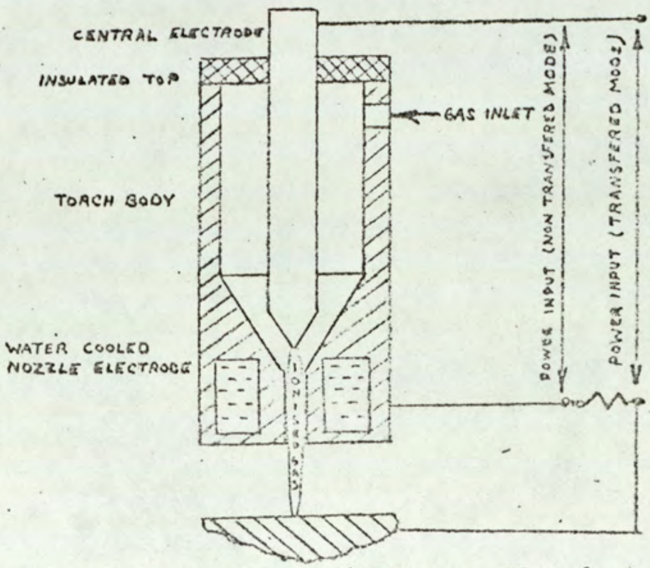
\+ Figures are referred to by the chapter number followed by the order in which they appear in the chapter.

so that it is no longer necessary to preionise the gas. The frequency of operation is necessarily high to take advantage of the skin effect in the heated gas which controls the minimum power input required to sustain the discharge. Operating frequencies are typically from 400 kHz to 12 MHz at which capital cost of frequency conversion equipment and operating costs are high. As a result the process has up to now been confined to laboratory applications and the manufacture of high cost products which have been reviewed elsewhere (Stern, 1968).[#]

The directly coupled plasma torch may use a transferred or non-transferred power supply and a simple form of plasma torch is shown schematically for both methods of operation in Fig. 1.2.



The Directly Coupled Plasma Torch.

Figure 1. 2.

An electric arc is initiated by some external means between the central or rod electrode and the outer electrode which also acts as a nozzle. Gas is blown through the nozzle blowing the arc

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[#] References are keyed to the alphabetical list on page 330.

into the nozzle and constricting it due to forced convection and by the proximity of the cooled nozzle walls. As a result the voltage gradient and temperature of the arc column in the nozzle is higher than that in a free burning arc. A jet of highly ionised gas issues from the nozzle in which temperatures of up to 26,000^{o}c have been measured spectroscopically (King & Jordan, 1964). Such a plasma torch is referred to as non-transferred. If the jet of ionised gas strikes a third electrode which may be made the material to be heated, connected to the power supply through a lower impedance than the connection to the nozzle, the arc root is transferred from the nozzle to the third electrode. When operated in this way the torch is known as a transferred arc plasma torch.

The plasma torch can provide a method of transferring the heat from an arc discharge to the material to be heated, unlike conventional arc processes such as direct arc furnaces and the manufacture of acetylene in which the arc is contained within the reaction vessel. The unique combination of extremely high temperature, ethalpy,. rapid response, and the low level of contamination of the heated gas obtainable, typically less than 0.1% by weight of gas throughput are also advantageous in certain applications and both combustible or non combustible and inert gases may be used.

The advantages of the electrical circuit being independent of the material to be heated and at the same time a potentially efficient method of heat transfer makes the non-transferred plasma torch an attractive alternative process for the manufacture of high quality steel from pig-iron and steel scrap conventionally carried out in arc furnaces. At the time of the conception of this project by the late Professor May in 1963 it appeared that one of the main limitations to increasing arc furnace size and power ratings was the effect of fluctuations in load that occurred at high arc currents. This fluctuation or instability is discussed in more detail in 2.3. but two causes of interest here are the movement of the furnace charge during the breakdown period causing short circuiting of the arc electrodes and random fluctuations in arc voltage and current due to arc movement during melting and refining of the steel. If the arc circuit is made independent of the furnace charge the fluctuations due to the movement of the charge could be eliminated and the random movement of the arc reduced. For such an application the process would need to be economically viable with existing processes and a high efficiency of transfer of energy would be required. Typical efficiencies of arc furnaces during the melting period defined as

$$\frac{\text{energy input} - \text{losses}}{\text{energy input}} \times 100\% \qquad (1.1.)$$

are of the order of 67% measured in terms of the energy input and known heat losses (Robiette, 1955).

Many other possible industrial applications of a mains frequency plasma torch exist in the metallurgical and chemical industries, and some of these applications are discussed in Chapter 3 and are listed in Appendix 3, but the application to steel melting has perhaps the most stringent requirements.

The minimum requirements of a plasma torch for any large scale industrial process are

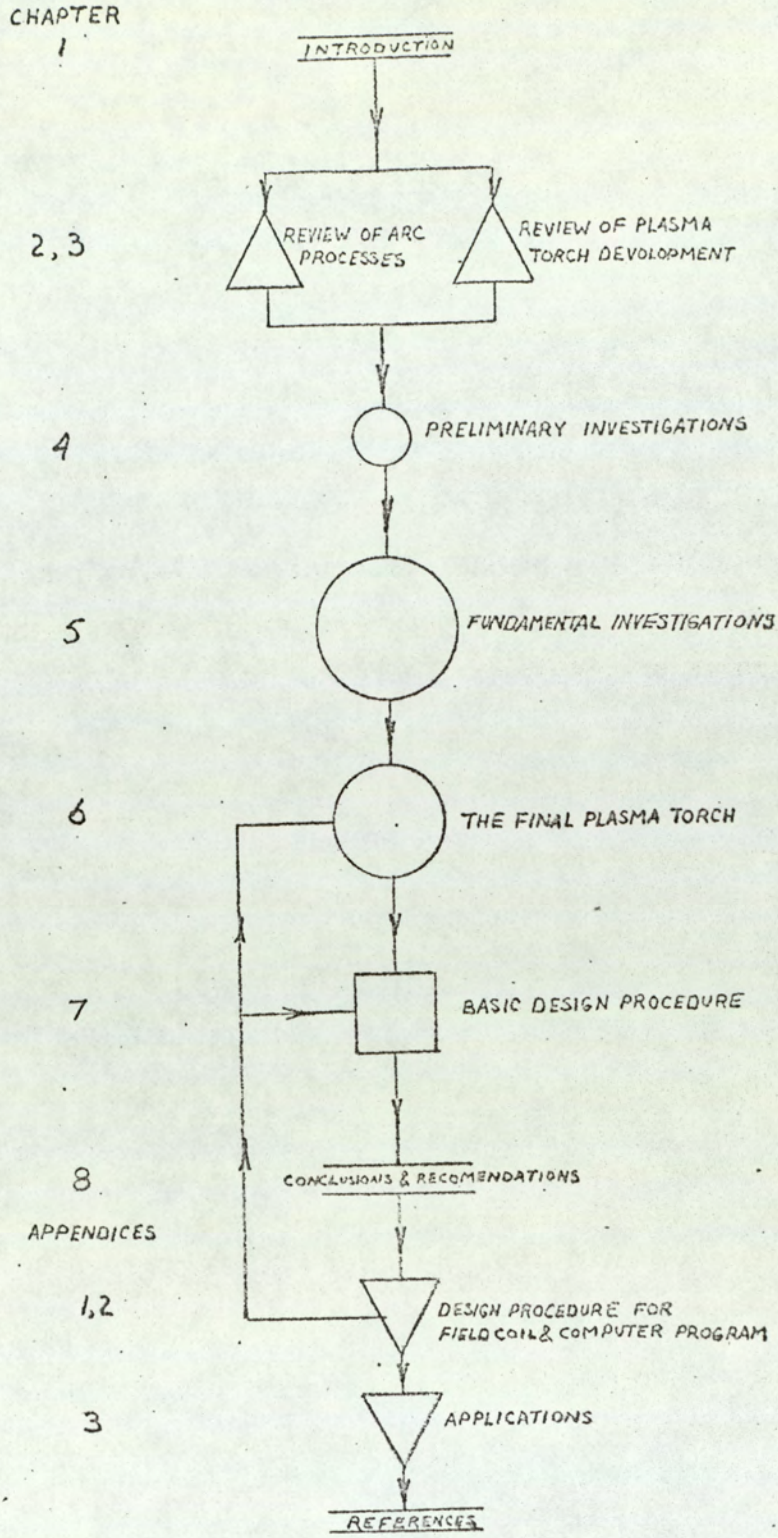
1. A high overall efficiency of utilization of the input energy.
2. Reliable continuous operation.

A secondary requirement which will vary with the application is the optimum gas temperature at the outlet of the torch.

Since the object of this investigation was to produce a useful mains frequency plasma torch the control and efficiency were considered only relative to the torch itself rather than the overall process which is discussed in Chapter 8. It was therefore desirable that the efficiency should be at least as high and preferably greater than values obtained for existing processes. At the same time new processes may be made possible by some of the unique characteristics of the plasma torch that might lead to increased values of the overall process efficiency. An example of this is the application of a plasma torch to the manufacture of tool steel, which by using nitrogen or other oxygen free gases might eliminate the need for induction heating under vacuum, in order to remove the absorbed oxygen obtained in conventional processes.

At the time when work was commenced at the University some qualitative information was available on d.c. plasma torches used for spraying but very little information was available on the high power a.c. arc-heaters used for re-entry simulation and none on mains frequency torches for industrial applications. During the course of this investigation more information became available on the high power a.c. arc-heaters used for re-entry simulation. Consequently whilst the first plasma torch was based on those used for metallurgical applications, later versions were influenced by the techniques used in arc heaters used for re-entry simulation.

The overall structure of the thesis is shown in Fig. 1.3. Two review sections are presented in this thesis. The first in Chapter 2 deals with the arc theory relevant to the plasma



STRUCTURE OF THESIS

FIGURE 1.3.

torch, Chapter 3 review the development of the plasma torch and its applications up to the most recently available information.

Chapter 4 describes the initial experimental work carried out on a d. c. plasma torch and the progression from the conventional nozzles used for spraying and cutting processes to nozzles more suitable for general industrial heating processes, through the investigation of the effect of each part of the nozzle. The development of the a. c. torch from the d. c. torch and the tests carried out on it are described. During the investigations the range of operation was increased as larger power supplies and additional measuring equipment were made available and the tests became more comprehensive.

Chapter 5 describes the supporting investigations carried out as a result of the initial work which indicated where further basic data on arc behaviour was required. These results which comprise a major part of the experimental work were used in the design of the second a. c. torch described in Chapter 6. The basic criteria for the design of a plasma torch for industrial process heating has been obtained using the literature survey and experimental results and is described in Chapter 7.

Chapter 8 summarises the results of the investigation and indicates fruitful areas of further research. The design of the field coil described in Chapter 6 and the computer program used is given in Appendices 1 and 2. Existing and potential applications of the plasma torch are given in Appendix 3.

CHAPTER 2.

Review of Basic Arc Processes.

The behaviour of the electric arc under conditions likely to be encountered in a plasma torch is discussed.

2. REVIEW OF BASIC ARC PROCESSES.

Several reviews of arc behaviour have been written (Cobine, 1958, Somerville, 1959, von Engel, 1965), extending over a wide range of operating conditions. This Chapter deals only with the behaviour of the arc over the range of operating conditions likely to be encountered in a plasma torch and in this respect it is believed to be unique. A background of information is provided from which the behaviour of an arc in a plasma torch under a variety of complex conditions can be considered in terms of available data obtained for arcs under less complex and more accurately known operating conditions.

The range of interest has been limited to

1. High pressure arcs (Atmospheric pressure and above).
2. Arc currents greater than 1A.
3. Arc voltages such that the total arc voltage is considerably greater than the sum of the anode and cathode fall voltages and the arc length is long compared with the electrode fall regions and transition regions.

It has been found necessary to consider the behaviour of arcs outside these ranges where there is a lack of information available over the region of interest. In many cases due to lack of reliable data it has not been possible to be conclusive. Where this occurs the available information is presented over as wide a range as possible in order that a generalised picture of the arc behaviour can be obtained. Inevitably it has not been possible to always quote the precise conditions under which measurements have been made although where they are believed to be significant they are included.

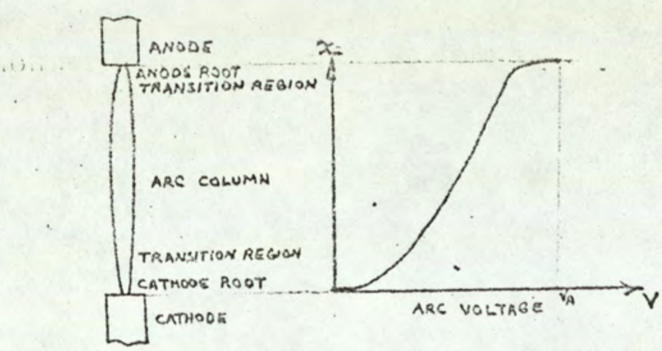
2.1. Electrode Processes.

The processes that occur at arc electrodes although localised to only a small region greatly influence the behaviour of the arc. The energy losses and erosion at the arc electrodes and therefore the choice of electrode materials are affected and as a result the electrode processes have an important influence on the operation of a plasma torch.

The main electrode processes of interest are

1. The electrode fall voltages.
2. The current density at the arc roots.
3. The extent of the electrode fall region.
4. Energy input and erosion at the electrodes.

The electrode fall voltages, current density at the arc roots, and measurements of energy input and erosion, are required forthe analysis of the power density and energy input and erosion at the arc electrodes. The electrode fall voltage and extent of the electrode fall region are needed for the analysis of arc column behaviour so that the electrode effects can be accounted for separately.

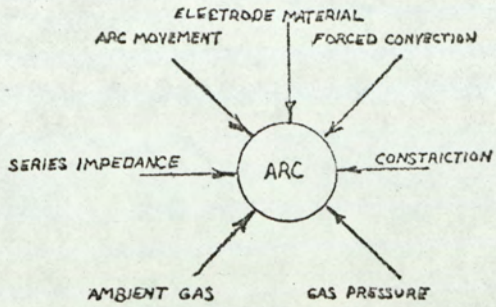


The Main Regions of an Electric Arc.

Figure 2.1.

The various regions of an electric arc are shown in Fig. 2.1.

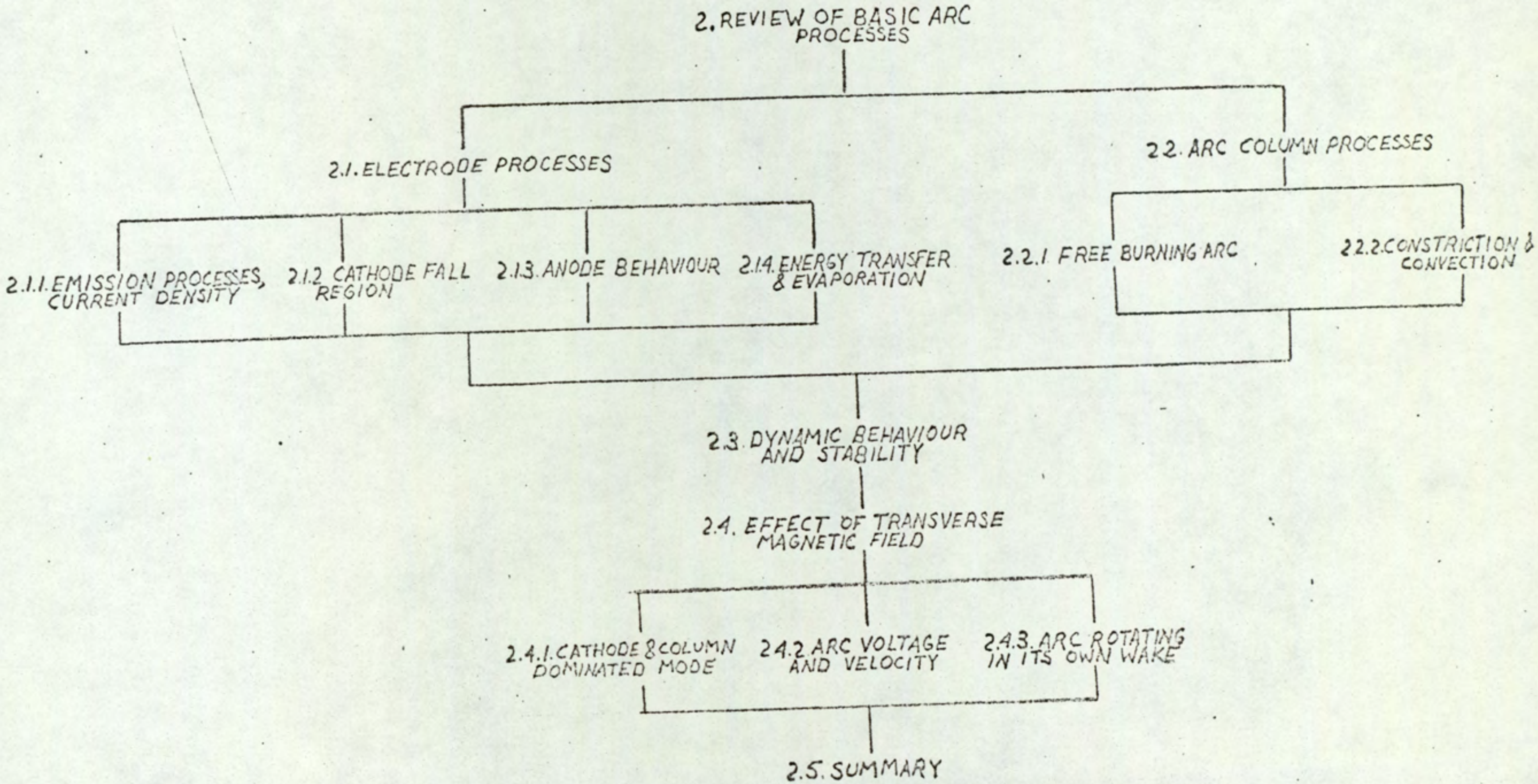
Each region is considered individually except the transition zones which are included in the other regions. The effect of the variation in external conditions illustrated in Fig. 2. 2 are discussed separately



External Conditions Affecting the Arc Behaviour.

Figure 2. 2.

where possible so that the complex conditions in a plasma torch can be considered in terms of the separate effects. The structure of the chapter is shown in Fig. 2. 3.



STRUCTURE OF CHAPTER 2

FIGURE 2.3

2.1.1. Cathode Emission Processes and Current Density at the Cathode Root.

The variation in the cathode emission process with electrode material and the effect on the current density are considered. The cathode materials used for electric arcs can be described as either thermionic or cold-cathode materials (von Engel & Robson, 1957), and are characterised by the difference in current densities at the cathode root and the boiling point of the electrode material. Both thermionic and cold cathode materials have been used as electrodes in plasma torches.

Thermionic cathodes are made of refractory materials whose temperature at the boiling point is sufficient to enable the current at the cathode to be maintained by thermionic emission alone, according to the Richardson equation

$$J = A_0 T^2 \exp\left(\frac{e\phi'}{k_B T}\right) \qquad (2.1)$$

where J = the current density (A/m^2)

A_0 = the Richardson constant ($A/m^2\ {}^oK^2$)

e = the electron charge (Coulombs)

ϕ' = the work function (eV)

T = the temperature at the emitting region (^oK)

k_B = Boltzman constant.

Values of ϕ' and A_0 for different materials have been tabulated for a wide range of materials. (Fomenko, 1964). Current densities varying from 100-1,000 A/cm^2 on graphite electrodes in air at 1 Atm have been variously reported.

Cold cathode materials have boiling points that are too low to enable the conduction process at the cathode to be by thermionic emission only. The current density at the cathode root of a cold cathode arc is considerably higher than a thermionic arc and is difficult to measure.

Some measured values of the current density at the cathode root are shown in table 2.1 on the next page. Measurement of the arc tracks is likely to give values of current density lower than the actual value due to the effect of heating of the adjacent region. Photographic measurements of the cathode root show the bright region beyond the dark space about 10^{-3} cm above the cathode surface (Smith, 1946) and not the cathode root. The measurements by Froome (1949) indicate that current densities of from 2×10^{6} A/cm^2 to 1×10^{7} A/cm^2 are obtained in this way. In addition the current density is likely to be non-uniform and may be higher at the centre of the arc spot. Measurement of the current density from arc tracks after arc ignition before gross melting occurs and of moving arcs at low pressure indicates current densities of up to 10^{8} A/cm^2. (Hutchins & Newton, 1962). Froome (1946) has suggested that when an arc becomes normal a few microseconds after initiation of the arc no further change in the current density occurs.

Subdivision of the cathode root occurs as the arc current is increased. Observation of arcs on Mercury cathodes at low pressures (Froome, 1946, Kesaev, 1957), and at 1 Atm in air on Cu, Al and W cathodes (Cobine and Gallagher, 1948), indicate that the cathode root tends to divide above currents of about 10A. A simplified treatment of the conditions at a cold cathode (Robson, 1955), indicates that the total current carried by a single cathode emission site is dependent mainly on the temperature at the cathode surface. Since this cannot increase indefinitely the cathode root may split.

Table 2.1.

Summary of Measured Values of Current Density at Cathode Root.

Cathode Material	Gas & Gas Pressure	Arc Current (A)	Arc Duration	Method of Measurement	Current Density A/cm^2	Reference
Hg	Hg vap 10-50torr	2.6	-	(a)	$50\times10^3 - 22\times10^5$	Cobine & Gallagher, 1948
W	Air 1 Atm	2.6	-	(a)	74×10^3	" "
Cu	Air 1 Atm	2.6	-	(a)	124×10^3	" "
Al	Air 1 Atm	2.6	-	(a)	30.10^3	" "
Hg	Hg Vap L.P.	50	120μs	(b)	2×10^5	Froome, 1948
Na	Hg Vap L.P.	12	120μs	(c)	2×10^5	" "
Cu	Hg Vap L.P.	9	150μs	(c)	2×10^5	" "
Hg	Hg Vap L.P.	50	160μs	(c)	$2\times10^6 - 1\times10^7$	" 1949
	"	200	40μs	(c)		" "
	"	450	15μs	(c)		" "
Al	Air 1 Atm	200	50μs	(c)	40×10^3	" "
Cu	Air 1 Atm	200	200μs	(c)	35×10^3	Somerville & Blevin, 1949
Mg	Air 1 Atm	200	200μs	(c)	35×10^3	" "
Ni	Air 1 Atm	200	200μs	(c)	18×103	" "

Cathode Material	Gas & Gas Pressure	Arc Current (A)	Arc Duration	Method of Measurement	Current Density A/cm^2	Reference
Sn	Air 1 Atm	200	200μs	(c)	9×10^3	Somerville & Blevin, 1949
W	Air 1 Atm	200	50μs	(c)	22×10^3	" "
W	Air 1 Atm	30	20μs	(b)	45×10^3	Dunkerley & Schaefer, 1955
W	Air 1 Torr	150	30ms	(a)	$1\times10^7 - 1\times10^8$	Wroe, 1958
Ti	Air 0.1 Torr	1-10	0.5μs-10μs	(a)	1.6×10^8	Hutchins & Newton, 1962

Method of measurement (a) area of tracks, (b) area of arc tracks left by arc in a tranverse magnetic field (c) diameter of arc root measured photographically.

The emission process at a cathode of a refractory material may under various conditions such as at arc ignition or when moved at a high velocity become similar to that at a cold cathode. Current densities have been measured under these conditions of 10^7 A/m^2 to 10^8 A/cm^2 of the same order as at a refractory electrode (Wroe, 1958). This has an important effect on the choice of electrode materials used in a plasma torch where the arc is moved rapidly over the electrode surface with a transverse magnetic field when the cathode root behaviour on a refractory electrode may be similar to that on a cold cathode electrode.

A large number of theories have been advanced to account for the emission process at a cold cathode electrode. Some of these have been discussed elsewhere (von Engel & Robson, 1957, Ecker, 1961). It is not relevant to discuss the merits of the various theories here but since so many theories are at least plausible it is likely that several different mechanisms contribute to the emission process at the cathode root. In order to assist the explanation of some of the cathode phenomena that occur some of the theories and accompanying processes are mentioned briefly.

Theories depending solely on thermionic emission from a cold cathode have been disproved since non-refractory materials are incapable of maintaining high enough temperatures. (Cobine & Burgher, 1955).

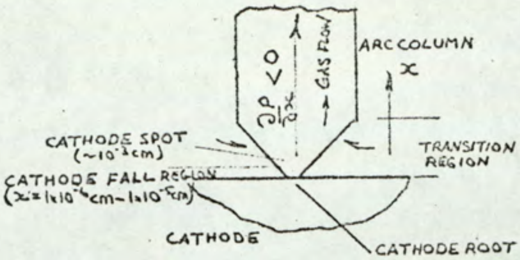
Field emission alone at the cathode root is not sufficient (von Engel & Robson, 1957), since current densities at the cathode root greatly in excess of those observed are needed, and a large proportion of the total current is required to be carried by positive ions in the cathode fall region with cathode fall voltages greater than occur in practice.

A combination of thermionic and field theories of emission has been suggested (Lee, 1959 & 1957) but the current density, field strength, surface temperature and percentage of the total current carried by positive ions lie barely within the ranges of observed values (von Engel & Robson, 1958). If the effect of variations of the electric field above the cathode surface rather than the mean field is used (Ecker & Muller, 1959), the effect of higher local electric field gradients is to increase the total emission. A more recently developed theory based on the presence of a semi-conducting layer on the cathode surface (Guile. et al, 1963), which is normally an oxide when the ambient gas is air, gives further support to theories based on field. emission.

The excited atom theory (von Engel & Robson, 1957) in which the potential energy of atoms in excited states is transferred to the crystal lattice of the cathode material (Knacke & Stranski, 1956), can to some extent account for emission from non refractory cathodes and for the cold cathode emission observed under certain conditions on refractory materials (von Engel & Arnold, 1962(b)).It also explains the loss of macroscopic particles of electrode material that have been observed by a stepwise ablation process (von Engel & Arnold, 1960), (Knacke & Stranski, 1956), which has an important influence on the minimum level of electrode erosion obtainable.

2.1.2. The Cathode Fall Region.

Plasma jets are caused by the contraction of the arc column in the transition region in front of the arc electrodes shown in Fig. 2.4 which increases the local current density and



The Cathode Fall Region.

Figure 2.4.

pressure in the arc due to the higher concentration of charged particles in this region (Maecker, 1955). A pressure gradient along the axis of the arc results causes high particle velocities which have been reported to be as high as 10^6 cm/s from copper electrodes at low pressures (Tanberg, 1930, Reece, 1947). It has been suggested however that these high apparent velocities are caused by large aggregates of electrode material which affected the measurements made and when these were excluded velocities of about 4×10^4 cm/s were obtained (von Engel & Arnold, 1962(a)).

These high velocity jets cause entrainment of the ambient gas in the transition regions (Reed, 1960), and may considerably affect the length and behaviour of the arc particularly if opposing jets from the cathode and anode impinge. The entrained cold gas causes a local increase in the voltage gradient and temperature with the formation of plasma jets which may cause the voltage gradient of the arc column to increase with increase in arc current (King, 1961).

The cathode fall voltage when the emission at the cathode is thermionic varies appreciably with the electrode geometry and cooling (Neurath & Gibbs, 1963). Values of from 4V (Dickson & von Engel, 1967) to 10V (Finkelnburg, 1948), for arcs on carbon electrodes in air have been measured. Minimum cathode fall voltages for arcs on cold cathode electrodes obtained for a wide variety of materials in air at atmospheric pressure and at low pressures at the threshold current for a cathode spot to form, (0.3A to 6A), are shown in table 2.2.

Cathode Fall Voltages at 1 Atm in Air in the Cold Cathode Mode. (Kesaev, 1965).

Material	Cu	Ag	Al	Sn	Ta	Mo	W	Fe
Voltage	16	15.3	14.4	12	13.5	16	16.1	15.1

Table 2.2.

Values obtained with moving electrodes for a wide range of cold cathode materials in argon and air at 1 Atm and at 10A indicate that the cathode fall voltage is between 11V and 16V (Dickson & von Engel, 1967).

The cathode fall distance is very difficult to estimate due to its small size. Measurements with carbon electrodes in air at 1 Atm at up to 80 A using a probe indicated that the cathode fall region was less than 1×10^{-2} cm and may be considerably less. (Finkelnburg & Segal, 1951). Measurements with moving electrodes (Dickson & von Engel, 1967), indicated that the cathode fall region was less than 4×10^{-6} cm. If a cathode fall voltage of 15V is assumed the voltage gradient in the cathode fall is therefore about 4×10^{7} V/cm. The cathode dark space has been measured optically for low pressure arcs on mercury as 1×10^{-3} cm. (Smith, 1946). At these high values of electric field gradient this region of the arc will not be in thermal equilibrium and the behaviour will be governed by field variations rather than thermal variations. Consequently the time required for the cathode fall region to be established or to decay is considerably less than in the arc column, and has been estimated at being of the order of $1x10^{-9}$s. for a mercury arc at low pressures, (Mierdel, 1936), and has an important effect on arc stability (see also 2.3).

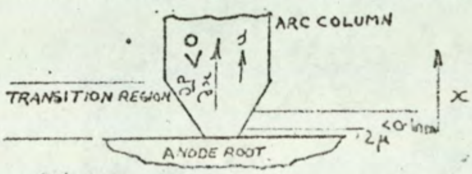
2.1.3. Anode Behaviour.

The principle featuresof interest at the anode root are the current and power densities and the anode fall voltage. The anode behaviour is controlled largely by the thermal properties of the anode material, cooling, and shape of the anode. As a result the anode fall voltage and current density at the anode root vary over wide ranges and it is not possible to accurately predict values. The anode does not emit positive ions except in the Beck arc (Finkelnburg, 1949), in which the electrodes contain compounds of low ionisation potential such as alkali metal salts. Such electrode materials which evaporate rapidly are not normally used except where a high light output or good electrical stability are required.

If the anode is unheated the arc column normally contracts in front of the anode so that the local power density is increased sufficiently to maintain the arc and the increased heat losses. The contraction is normally considerably less than that at the cathode and is dependent on the thermal properties of the electrode material. A negative space charge is produced in front of the anode due to the converging electrons travelling towards it.

The voltage gradient which is higher than that in the column results in an anode fall region in which positive ions are produced by electron collisions. The number of positive ions is small compared with the electrons emitted at the cathode. The anode fall voltage decreases with increase in arc current and depends on the electron space charge above the anode and the efficiency of the production of positive ions. This in turn depends on the ambient gas, anode material, temperature at the anode root, electrode geometry, and the effect of plasma jets. Values for the anode fall voltage for arc currents of 10A in air argon and nitrogen at 1 Atm lie between 2V and 11V have been measured (Dickson & von Engel, 1967). Typically for copper electrodes in nitrogen the anode fall voltage was 10V and for carbon in air was 11V.

The anode fall of a carbon arc in air at 1 Atm at up to 80A has been measured as extending less than 1×10^{-2} cm from the anode surface. (Finkelnburg & Segal, 1951) and this region consists of two layers shown in Fig. 2.5. The layer closest to the anode is



Anode Fall Region.

Figure 2.5.

about 2×10^{-4} cm thick in which positive ions are produced, the second layer above being a region of the arc column still affected by the electrodes.

Normally there is no cooling effect by evaporation of electrons at the anode surface. The arc column is usually less contracted than at the cathode root and since it is not required to take part in emission processes the power transfer to the anode surface may be greater than at the cathode. This has an important effect on the choice of materials for plasma torch electrodes.

The energy balance at the anode surface has been measured for various anode materials and gases and is discussed in section 2.1.4. A theoretical analysis of the energy balance indicates that the temperature at the anode root on an uncooled electrode is above the boiling point of most metals (Cobine & Burger, 1955). Under these conditions cooling of the anode occurs mainly by evaporation of electrode material and the region above the anode is filled with anode vapour. The anode vapour will normally have a lower ionisation potential than the ambient gas causing a higher current density and an axial pressure gradient in the anode fall region. A plasma jet is caused by the pressure gradient similar to that at the cathode (Reed, 1960). The anode jet may interact with the cathode jet disturbing the quasi-equilibrium conditions in the arc column but may be reduced by efficient cooling of the anode.

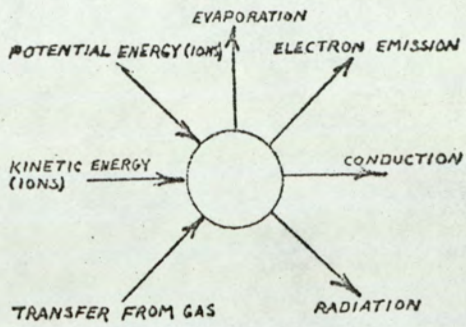
The current density at the ~~anode~~ cathode root is considerably larger than the ~~cathode~~ anode root and it has been possible to make measurements of the current distribution, current density, and the energy transfer at the anode root. The measurement of the energy transfer is discussed in the next section.

Measurements of current density have been mainly confined to water cooled copper anodes in argon at atmospheric pressure with a tungsten cathode. Current densities of the order of 300 A/cm^2 at arc currents of 50A to 150A were obtained for a separation of 6 mm (Schoek & Eckert, 1961), and maximum current densities at the centre of the anode spot of 500 A/cm^2 for approximately the same conditions (Nestor, 1962). Pulsed arcs of up to 1 millisecond duration on a wide variety of metal electrodes in air at 1 Atm and up to 80A, showed that the anode current density was independent of electrode spacing (Somerville et al,1952). A current density at a tin anode obtained photographically of 10^4 A/cm^2 was obtained. It was also found that the active area at the anode did not increase with arc duration the apparent growth of the area being due to thermal dissipation.

Division of the anode spot did not normally occur except for rapid rates of rise of arc current and variation of pressure from 0.01 Atm to 1 Atm had little apparent effect on the anode track. Photographic measurements of the anode spot on aluminium in air at 1 Atm with pulsed currents between $6\text{x}10^3$ A of up to 0.2 milli-seconds duration indicated current densities of from $6\text{x}10^4$ A/cm^2 to $12\text{x}10^4$ A/cm^2.

2.1.4. Energy Transfer & Evaporation at Arc Electrodes.

The energy transfer and evaporation at arc electrodes has an important effect on the efficiency and reliability of a plasma torch. The values of arc voltage and current density obtained in the preceeding sections are used here in the quantitative assessment of energy transfer and evaporation at the arc roots.



Energy Transfer at the Cathode Root.
Figure 2.6.

The energy transfer at the electrodes of an arc is closely associated with the arc root mechanisms and as a result is difficult to evaluate. The main processes are shown in Fig. 2.6. The energy flow processes may be represented by equivalent voltages (von Engel, 1965). If a positive ions per unit current are assumed to strike the cathode and (1-a) electrons are emitted. The energy flow equation becomes

$$a\left[(V_i + V_k - \phi') + V_g\right] - \left[(1-a)\phi' + V_e + V_r\right] = V_\lambda \qquad (2.2)$$

where V_i = potential energy

V_k = kinetic energy

ϕ' = work function

V_g = energy transfer from gas

V_e = energy for evaporation

V_r = radiated energy

V_λ = conduction loss.

In addition resistive heating at the arc root caused by the high current density should be included but is normally small for cathode materials with high electrical conductivities such as copper, silver, and aluminium at current densities of 10^6 A/cm^2 but may contribute up to 10% -20% of the total energy input for cathodes of lower conductivity such as iron. (Rich, 1961).

At the anode a similar energy balance may be derived

$$(V_a + \phi' + V_g) - (V_e + V_r) = V_\lambda \qquad (2.3)$$

At medium and high currents the effect of electron emission in cooling the cathode is small. If radiation losses are ignored the energy balance equation reduces in both cases to

$$V_c I = W_c + W_e \quad \text{(Holm, 1949).} \qquad (2.4)$$

where V_c = voltage drop in electrode fall region (V)

I = arc current (A)

W_c = power dissipated by conduction (W)

W_e = power dissipated by evaporation of electrode material. (W)

The measurement of values in the energy balance equations is difficult but has been attempted for the anode where the spot size is such that direct measurement of the net power input and anode temperature are possible. Since the application of the results has been mainly to arc welding in inert gases the measurements have been confined to arcs in argon. The heat transfer by conduction from the anode has been measured with a calorimeter at atmospheric pressures in argon and lies between $4kW/cm^2$ at 50A to $5kW/cm^2$ at 150A at electrode separations of 0.6 cm (Schoeck & Eckert, 1961). Measurements obtained by Nestor (1962), and Wilkinson & Milner (1960), indicate that the power intensity is considerably higher at the centre of the anode spot than at the edge. This is due to the action of the plasma jet which entrains high conductivity material into the central region of the arc.

An analysis of the possible physical processes occurring at an anode in air at 1 Atm indicates that the total power input to the anode is of the order of $5x10^4$ W/cm^2 to $1x10^6$ W/cm^2 most of the input power being dissipated by evaporation (Cobine & Burgher, 1955). The analysis was used to calculate the evaporation at the anode surface as a function of the anode spot area by assuming all the input power to be dissipated by evaporation. The results indicate that for a high current static arc, heat transfer from an anode is mainly by evaporation, which has also been deduced for cathodes at high currents (Holm, 1949). This is in agreement with the measurements made of conduction losses which are more than an order of magnitude less than the total heat transfer.

A simplified energy balance (equation 2.4) was derived by Holm for the conditions at the cathode root. This showed that as the arc current and area of the cathode root increase the power density at the cathode increases with the area of the cathode spot, whilst the thermal conduction to the electrode increases with the radius of the spot. This is of importance to continually operating high current arcs such as those used in a plasma torch as it implies that water cooling of the electrode becomes less effective at high currents.

At low values of arc current, below about 1A for carbon and 5A for copper and tungsten the heat transfer from the cathode is entirely by conduction and the electrode erosion is a minimum. At higher arc currents depending on the thermal properties of the electrode material, above about 10A for carbon and 1,000A for copper or tungsten the heat dissipation at the cathode root is almost entirely by evaporation. The results obtained in this way were in good agreement with erosion rates measured for similar conditions in switchgear in air at atmospheric pressure at currents above about 1×10^4 A and with results from relays at low currents (Holm, 1949). The minimum erosion rates obtained experimentally were 1.5×10^{-6} g/C for carbon, 13×10^{-6} g/C for copper and 1.93×10^{-6} g/C for tungsten.

The lowest value of erosion obtained was suggested to be due to bombardment by positive ions in a similar way to sputtering at low pressures. The effect of cooling the electrodes or moving the arc with a traverse gas flow or magnetic field has not been investigated quantitatively. Qualitative observation of the behaviour of copper electrodes in air at 1 Atm and currents up to 6,000A indicated that results approaching the minimum values obtained by Holm are obtainable by moving the arc with a magnetic field (Pearce, 1959).

No measurement of the erosion rate at anodes have been found although the erosion is normally believed to be less than that at the cathode.

2.2. Arc Column Processes.

The arc column is the region between the electrodes which is characterised by a lower voltage gradient and current density than the regions immediately in front of the electrodes. It may be regarded as the useful region of an arc in a plasma torch since it is the energy transfer from the arc column that heats the gas throughput.

The characteristics of the arc column depend on the transport properties of the gas used. The gases principally considered here are argon, nitrogen and air which have most frequently been used with plasma torches. An essential difference exists in the behaviour of arcs in monatomic and polytomic gases. A monatomic gas such as argon ionises to give

$$A_r \rightarrow A_r^+ + e \qquad (2.5)$$

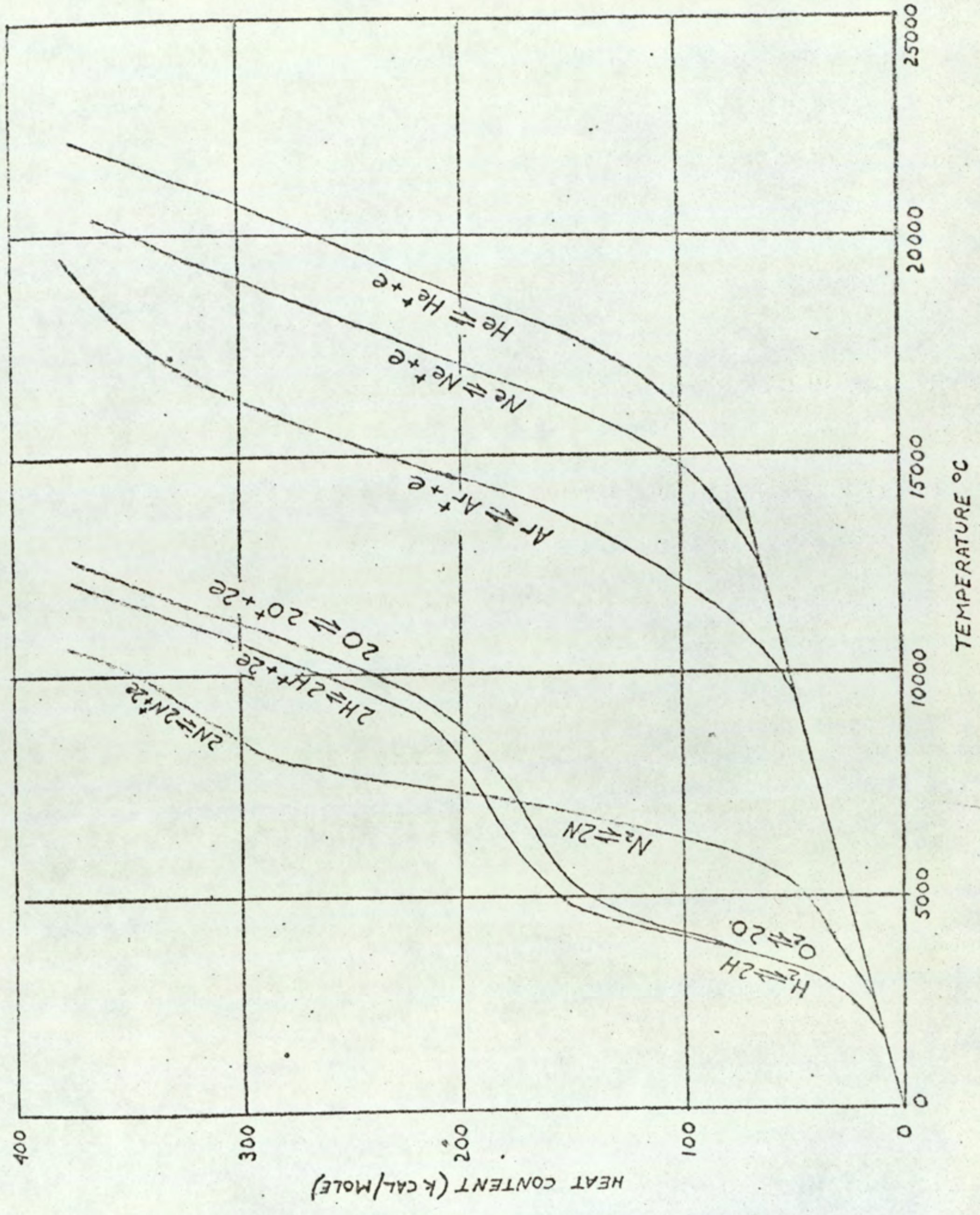
In the case of a polytomic gas such as nitrogen dissociation of the gas molecule is required before ionisation can occur and consequently a higher energy content is required.

For nitrogen $N_2 \rightarrow 2N$ at dissociation (2.6)

and $2N \rightarrow 2N^+ + 2e$ at ionisation (2.7)

The variation of the total energy content for several gases with temperature is shown in Fig. 2.7.

The behaviour of the arc column and the axial voltage gradient have the greatest effect on the arc power input and efficiency of conversion of the electrical power input to the heated gas. The voltage gradient of the arc column which influences the choice of



HEAT CONTENT OF VARIOUS GASES AS A FUNCTION OF TEMPERATURE AT 1ATM (REED, 1968)

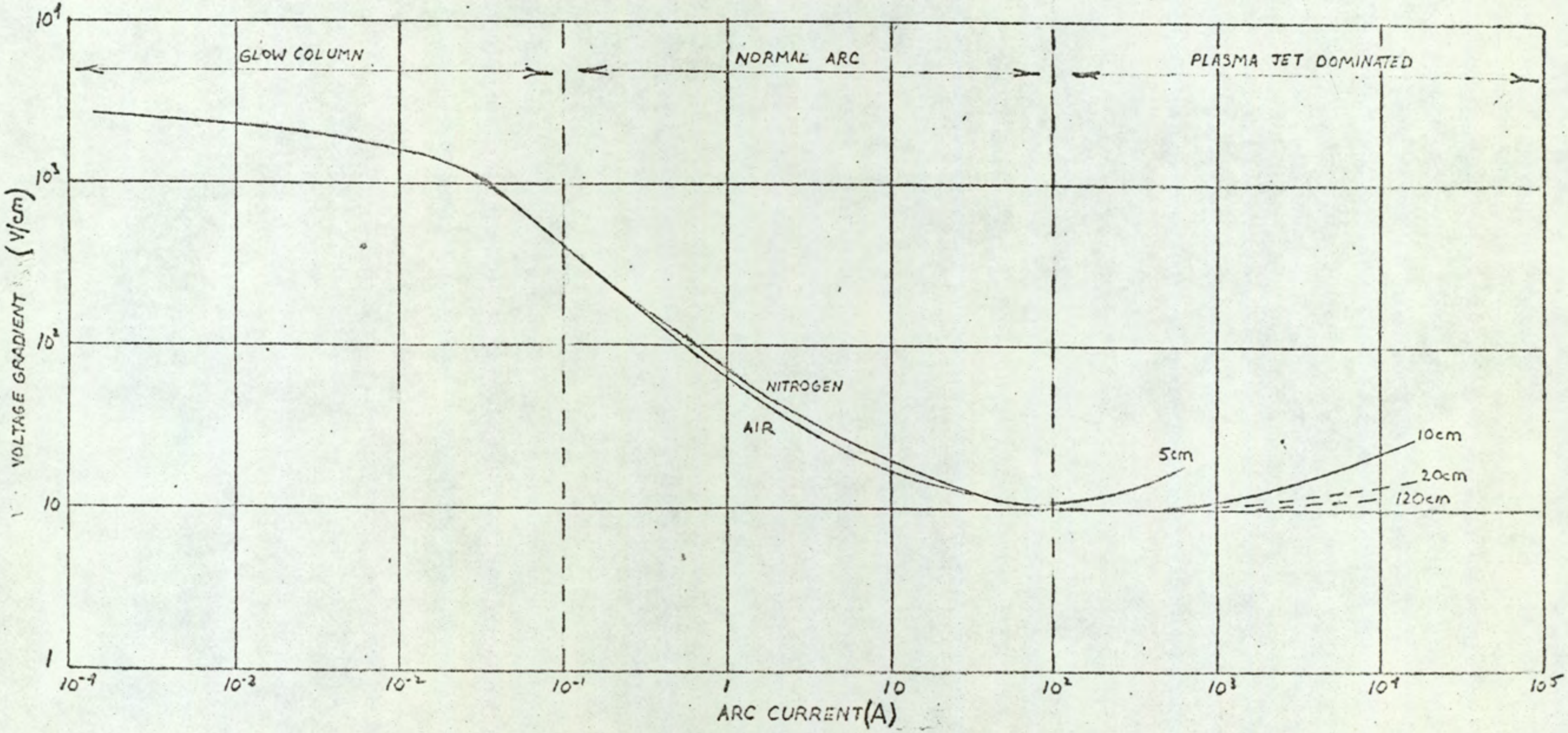
FIGURE 2.7

electrode separation can be increased by constricting the arc or by forced convection. Both constriction and forced convection are important factors in the design and operation of a plasma torch and are considered here. The constricting effect of the relative motion between the arc and ambient gas when moved with a traverse magnetic field is considered separately.

2.2.1. The Free Burning Arc.

The voltage gradient of the free burning arc column has been widely investigated but many of the results obtained suffered from a lack of generality and errors due to the difficulty in estimating the true arc length. By eliminating the sources of error due to fluctuations in arc length and the electrode fall voltages the voltage gradient of the arc column for several gases has been measured (Suits, 1939(a)), over pressures of from 1 Atm to 50 Atm and at arc current of 1 A to 10 A. Similar results were obtained for both carbon and metallic electrodes when the concentration of metal vapour in the arc was negligible.

The results at atmospheric pressure for the variation of the voltage gradient with arc current and other results (Strom, 1946, King, 1961), have been used to extend the range of arc current from 10^{-4} A to 10^{5} A. The variation of the voltage gradient of free burning arcs in air and nitrogen with arc current is shown in Fig. 2.8 (King, 1961). The effect on the voltage gradient of contamination from the electrodes is to lower the voltage gradient due to the decreased ionisation potential of the electrode vapour. This was minimised at high currents by making measurements on long arcs between water cooled copper electrodes. The voltage gradient in



VARIATION OF VOLTAGE GRADIENT OF ARC COLUMN WITH ARC CURRENT AT VARIOUS ELECTRODE SEPARATIONS (KING 1961)

FIGURE 2.8

a short high current arc might differ greatly due to the effects of electrode vapour and transition regions. An indication of the order of magnitude of this difference can be obtained from the variation of the voltage gradient with the electrode separation at high currents in Fig. 2. 8. believed to be due to the interaction of plasma jets which have most effect at small electrode separations.

The change of the slope of the curve of the voltage gradient of the arc column from negative to positive at high currents is attributed to the pinch effect (Maeker, 1955) (see also 2. 12). The axial pressure gradient along the arc column is highest at the cathode where the constriction is greatest and the flow of charged particles from the cathode into the arc column also entrains surrounding gas, and electrode material in vapour and aggregate form (Reed, 1960, von Engel & Arnold, 1960, 62(a)). Particles of electrode material will cause a decrease in the voltage gradient of the arc column as the conductivity is increased due to the lower ionisation potential of the electrode vapour. Entrainment of colder surrounding gas will cause an increase in the voltage gradient in the arc column and may even cause the gradient of the arc E-I characteristic to become positive.

The degree of ionisation of air and copper vapour has been calculated from the Saha equation (Holm, 1958), assuming ionisation potentials of 14eV and 7. 8eV respectively, and is shown in Table 2. 3.

Calculated Degree of Ionisation for Air and Copper Vapour (Holm,1967).

Gas/Vapour	Air				Copper Vapour
Temperature ^{o}c	5,000	10,000	10,000	15,000	10,000
Pressure Atm	1	1	10	1	1
Degree of Ionisation	2.10^{-6}	0.016	0.05	0.38	0.52

Table 2.3.

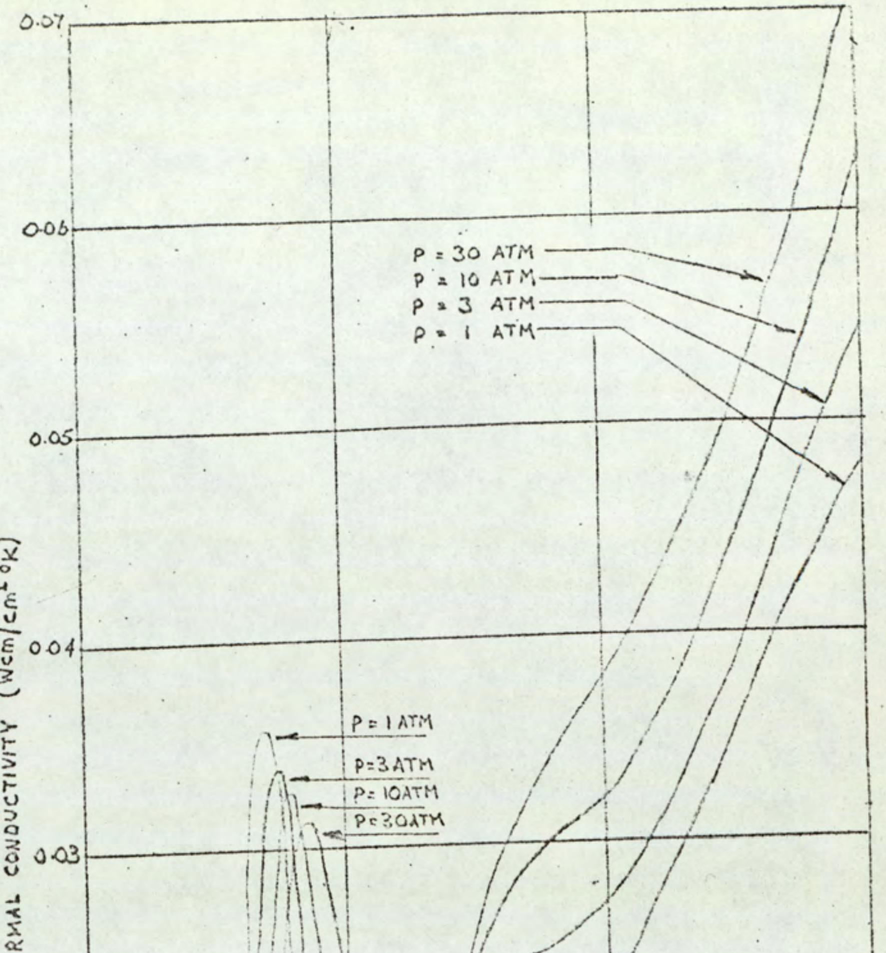
From these results the large influence of impurities on the degree of ionisation can be seen.

The current density in the arc column at medium currents is not accurately known due to the difficulty of defining the arc boundary and will be non-uniform as a result of high radial temperature gradients. Photographic measurements made on arcs at 1 Atm and above in nitrogen indicated a mean current density of about $10A/cm^2$ over a range of 1A to 10A. (Suits, 1939(b)).The current density has been measured above 1,000A with probes and values up to $4,000A/cm^2$ were obtained at the centre of the arc. (Lee et al 1957).

King (1954) calculated the current densities for medium current arcs usinga model based on the energy balance of a static arc column at 1 Atm in air. The results implied that the arc had a constant radius from 20A to 200A with a central core developing at about 40A to 60A and a mean current density at 200A of about $200A/cm^2$. The constant radius nature of the arc up to 200A is consistent with the range of current over which the voltage gradient of the arc column is negative since increase in current density will cause increased power dissipation and conductivity. At currents above 200A the diameter of the arc column increased with arc current. The changes in current density and diameter of the arc column affect the velocity of an arc in a tranverse magnetic field causing transitions due to the variation in current density.

A cored arc develops at currents in the region of 40A to 60A in air or nitrogen at 1 Atm and at lower currents when the arc is subjected to a forced axial gas blast. This is attributed to the peak in thermal conductivity due to the effects of molecular dissociation that occurs between 6,000^{o}c and 7,000^{o}c for air at 1 Atm (King, 1957). The appearance of a second core was precondicted at about 15,000^{o}c where another peak in the thermal conductivity of air occurs due to the effect on the total thermal conductivity of the diffusion of electrons and singly ionised atoms.

A unique temperature cannot be specified for the arc column because of the high radial temperature gradient that exists. The maximum temperature at the centre of the arc column and hence the currents at which the peaks in thermal conductivity occur can be specified. These depend on the presence of electrode vapour and the axial constriction of the arc column. A further consequence of the peaks in thermal conductivity is the existence of temperature ranges over which a stable arc cannot exist due to the negative variation of the thermal conductivity with temperature over this range. These occur between about 7,000^{o}c and 10,000^{o}c and between 14,000^{o}c and 20,000^{o}c (Yos, 1963), and are shown in Fig. 2.9.



VARIATION OF THERMAL CONDUCTIVITY OF AIR WITH TEMPERATURE AND PRESSURE (YOS, 1963)

FIGURE 2.9

calculated as a function of gas temperature and pressure.

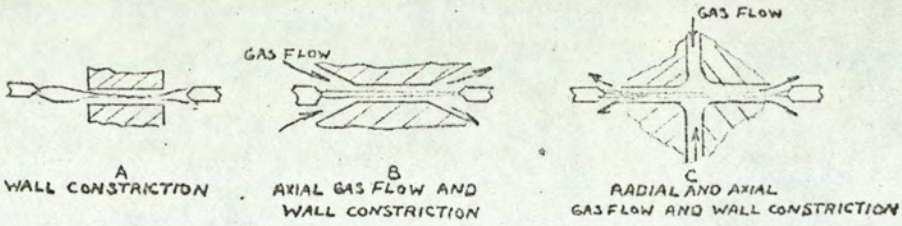
The arc column at 1 Atm and above may be considered as being in a state of quasi-thermal equilibrium since the electric field gradient is low and the gas pressure high. As a result velocities of electrons and ions are similar and the temperature difference has been found to be within 50°c (Saha, 1920).

The time required to establish thermal equilibrium in the column of a mercury arc has been measured (Witte, 1934), as about 0.6×10^{-3} seconds. It will however vary to some extent with the gas used, electrode geometry and properties, particularly the thermal conductivity. The effect of the delay in establishing equilibrium in the arc column is to prevent the arc current from varying rapidly with sudden changes in arc voltage and to reduce the variations in arc current when the arc is subjected to rapid voltage fluctuations. (See also section 2.3.). As a result the delay has a marked and normally beneficial effect on arc stability.

The predominant energy loss mechanisms from the arc column of a medium or long free burning arc in air at 1 Atm is by convection. Radiation losses are small despite the high temperature of the arc column because of the narrow radiation bands. As the gas pressure increases the radiation bands broaden until at high values of gas pressure up to 90% of the input power may be dissipated by radiation.

2.2.2. The Effects of Forced Convection and Constriction.

In a plasma torch the arc may be subjected to both forced convection and constriction. Constriction of the arc may be caused due to the proximity of a cold surface, or convection by transverse or axial gas flow relative to the arc. The different methods of constricting an arc are shown in Fig.2.10 but are difficult to analyse quantitatively since the effects seldom occur alone.

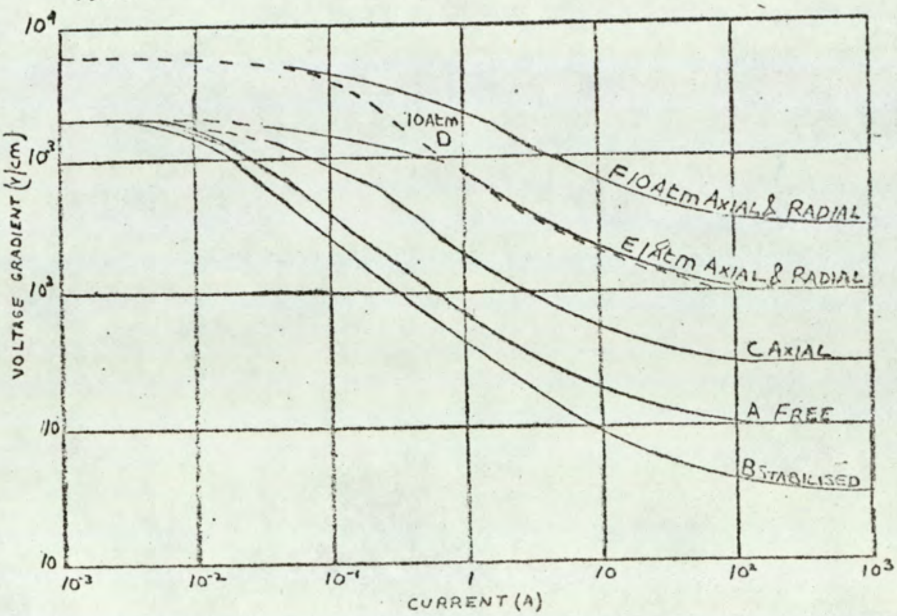


Methods of Constricting an Arc.

Figure 2.10.

Constriction for example in high pressure gas discharge lamps is accompanied by an increase in gas pressure, and where the arc is constricted by an orifice it is accompanied by a gas flow and forced convection. Similarly the effect of forced gas flow in switchgear is difficult to separate from constriction and the increased gas pressure.

The effects of different methods of arc constriction and convection on the voltage gradient of the arc column are shown in Fig. 2.11. (King, 1964). Curve A is the voltage gradient in the



Voltage Gradient as a Function of Current (King, 1964)
Figure 2.11.

arc column of a free burning arc in air or nitrogen which has already been shown alone in Fig. 2.(8). Curve B corresponds to the voltage gradient in an arc contained inside a rotating tube which reduces the effects of convection. Curves C and D were obtained for an arc subjected to an axial gas flow at 1 Atm and 10 Atm respectively. Curves E and F were obtained with an arc subjected to an axial and radial gas flow . The marked effect of constriction and convection at moderately high currents is shown here but the relative effects cannot be distinguished.

The effect of gas flow transverse to the arc column may be studied by holding the arc stationary with a transverse magnetic field at the same time subjecting it to a gas flow but the conditions are not exactly comparable as the effect of the magnetic field is not the same over the entire length of the arc (Guile et al, 1957(a). Dimensional analysis has been carried out for this condition and also for a wall stablised arc (Lord, 1963). In the same way the effect of forced gas flow may be simulated approximately by moving the arc with a transverse magnetic field in still gas, with the same limitations. The behaviour of an arc in a transverse magnetic field and the effects of relative motion between the arc and the ambient gas are considered in more detail in section 2.4.

The effect of constriction and convection is to increase the voltage gradient in the arc column by causing it to contract. As a result the arc changes to a concentrated arc at lower values of current than a free burning arc (King, 1955, 57). If the arc current remains approximately the same the power density, voltage gradient, and temperature in the arc column increase. Current densities of up to $1 \times 10^5 A/cm^2$, voltage gradients of 80V/cm and temperatures up to 50,000°c have been obtained in a wide variety of devices that have been reviewed by Skifstad (1962).

The effect of constriction of the arc column on the arc root behaviour may increase the pumping action of the plasma jet. If the gas flow is transverse, movement of the arc root may cause decreased erosion and a reduction of electrode vapour in the plasma jet. The effect of axial flow or constriction is to reduce the freedom of arc movement and such arcs are sometimes referred to as wall or gas stabilised.This is utilised in the constricted section of a plasma torch nozzle where part of the arc column is stabilised by the gas flow on the axis of the constricting nozzle.

The effect of gas pressure on the voltage gradient and current density in the arc column has been investigated by Suits (1939), (a), (b)). The variation of the voltage gradient in the arc column E with gas pressure P was found to increase with gas pressure according to the relation

$$E \propto P^n. \qquad (2.8)$$

Values of n obtained by Suits for various gases are shown in Table 2.4.

Values of n for various gases over a range 1 Atm to 50 Atm, at 1A to 10A (Suits 1939, a & b).

Gas	H_g	A	N_2	Air	CO_2	H_e	H_2O	H_2
n	0.26	0.54	0.60	0.60	0.60	0.73	0.59	0.70

Table 2.4.

A small increase in n with arc current was shown. The arc diameter D was found to decrease with increase in gas pressure P up to 30 Atm according to the relation

$$D \propto P^{-m} \qquad (2.9)$$

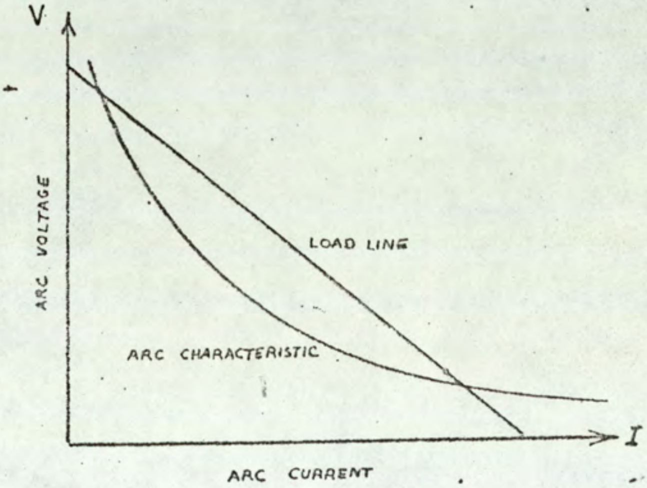
where m = 0.3 at 1 Atm

and m = 0.38 at 10 Atm and above

2.3. Dynamic Behaviour and Stability of an Arc.

Consideration of arc stability determines the operating conditions and interaction of an arc with its supply circuit. Since the arc normally has a negative dynamic impedance the supply circuit has a large influence on the arc behaviour. The dynamic behaviour of the arc is an important factor in the consideration of the operation of a plasma torch since one of the potential advantages of a plasma torch is to provide a more stable electrical load than existing arc furnaces. Stable operation is also important in continuous flow process for example in chemical processing. The various factors which influence arc stability are considered here.

The criterion for the stability of an electric arc requires the sum of the gradients of the resistance characteristic of the arc and the gradient of the load line to be positive. (Kaufman, 1900).



Arc Characteristic and Load Line.

Figure 2.12.

i.e. $\frac{dv}{di} + R > 0$ (2.10)

where $\frac{dv}{di}$ = dynamic resistance of arc (Ω)
R = stabilising resistance (Ω)

The load characteristic and arc characteristic are illustrated in Fig. 2.12. Using this criterion the static operating point of a d.c. arc, and some indication of the r.m.s. values of an a.c. arc may be obtained.

Although the Kaufman criterion may be satisfied the lifetime of arcs on cold cathode electrodes is finite and may be predicted on a statistical basis (Copeland & Sparing, 1945). The arc life was found to vary with the electrode material and external circuit constants, and to increase with arc current and gas pressure. The longer lifetime obtained with increase in arc current was attributed to the decrease in probability of arc extinction with more than one cathode root, and the effect of higher gas pressure caused a lower diffusion of vapour from the cathode root (Farrall & Cobine, 1965).

The arc lifetime is dependent on a large number of external factors which are difficult to allow for quantitatively. A measure of arc stability may however be obtained from tests carried out in nitrogen at 1 Atm between copper electrodes at 10A for which the measured lifetime for more than half the trials was less than 30 milliseconds (Farrall & Cobine, 1965).

The source of this instability has been associated with the cathode spot mechanism on cold electrodes and the rapid variations that occur with it resulting from the continuous decay and re-formation of the cathode spots (Kesaev, 1958 and 1963 I, II).

The arc may be extinguished in very short times since the conditions in the cathode fall region are not in thermal equilibrium. Times of extinction of a mercury arc subjected to a sudden fluctuation in current of 10^{-7}s have been obtained (Smith, 1942). The mechanism of extinction was believed to be due to disruption of the cathode fall region.

A further source of instability is due to variations occurring in the arc column caused by convection. This causes the free burning arc to take up a continually changing tortuous shape which can shunt itself. Shunting may also occur at the arc electrodes. As a result the arc voltage varies with the length of the arc column causing fluctuations in the arc current.

Various methods of improving the stability of electric arcs used for mercury arc rectifiers, welding, and arc furnaces have been investigated. Improvements in the stability of welding arcs using consumable electrodes up to about 600A have been obtained by introducing compounds of low ionisation potential into the arc stream with cored, coated or impregnated electrodes (Cobine & Gallagher, 1951). Hollow electrodes through which a gas of ionisation potential lower than air has been passed have also been used (Charles & Cowen, 1960).

The overall effect of these methods is apparently to lower the arc impedance, decreasing the arc voltage, the voltage gradient, and temperature in the arc column. The reverse effect may however be obtained if the effect of electrode jets is significant as in a Beck arc. (Finkelnburg, 1949). The effect of reducing the voltage gradient in the arc column at a constant electrode separation is to reduce the arc power if the arc current does not increase proportionately. At the same time the ratio of series impedance to arc impedance increases which tends to improve the stability. A similar effect might be obtained by using a higher voltage supply and increased stabilising impedance without decreasing the arc power.

Although methods of improving arc stability by the introduction of compounds or gases of low ionisation potential into the arc improve the arc stability at low and medium arc currents up to about 600A, they are less effective at higher values of arc current. This change in behaviour has been attributed to the practical difficulty of introducing the core material or gas into the arc column when large electrodes are used and the arc root covers only a small part of the electrode surface (Lunau, 1966).

In power supplies used for welding it is customary practice to increase the stability of the arc by using a value of series impedance considerably greater than that required by the Kaufman criterion. High voltage high frequency sources have been superimposed on the main arc supply in both welding and arc furnace applications (Mathews & Harrison, 1963). The high voltages have been found to assist restriking of a.c. welding arcs after current zero without touching the electrodes together but no improvement in the stability of arc furnaces has been reported. Forced gas flow and external magnetic fields both axial and transverse have a marked effect on arc stability and normally tend to improve the arc stability by reducing the degree of freedom of random movement of the arc.

The dynamic behaviour of electric arcs is governed mainly by the duration of the disturbance, the characteristics of the arc, and the equilibrium times of the arc column and cathode fall regions which have already been discussed. The equilibrium times may be taken as not more than 1×10^{-3}s in the arc column (Witte, 1934),

50×10^{-6} s to establish the cathode fall (Froome 1948) and 1×10^{-9} s to disrupt the cathode fall (Mierdel, 1936). The dynamic behaviour of the arc is mainly dependent on column processes except at ignition and extinction of the arc. This has been very little studied except in the region of current zero, which is of particular interest in circuit breaker design. Various models have been proposed for high current arcs (Cassie, 1938, Mayr, 1943), but have little application to the dynamic behaviour of an arc away from the region of current zero.

The variation of the arc parameters will depend to some extent on the duration of the disturbance. If the duration is such that the disturbance of arc voltage, is over in less than 1 millisecond the variation in the arc column conditions will be too slow to follow the disturbance.

The behaviour of an a.c. arc can be considered as a special case of dynamic behaviour. Low frequency fluctuations of the order of a few cycles a second enable the arc to closely follow the static characteristic shown in Fig. 2.12. As the frequency increases the arc current tends to lag the arc voltage defined by the static characteristic due to the finite time required for thermal equilibrium at the new value of voltage to be established. As a result the dynamic characteristic lies above the curve when the current is increasing and below the curve when it decreases.

There is no quantitative data available on the optimum values of stabilising impedance required for a given application. Welding arcs are normally operated with a ratio of open current voltage to arc voltage of about 4:1. Large a.c. arc furnaces customarily operate at a power factor before correction of about 0.7 indicating a ratio of open circuit to arc voltage of 2:1.

The relative effects of variation in the value of series impedance is not known.

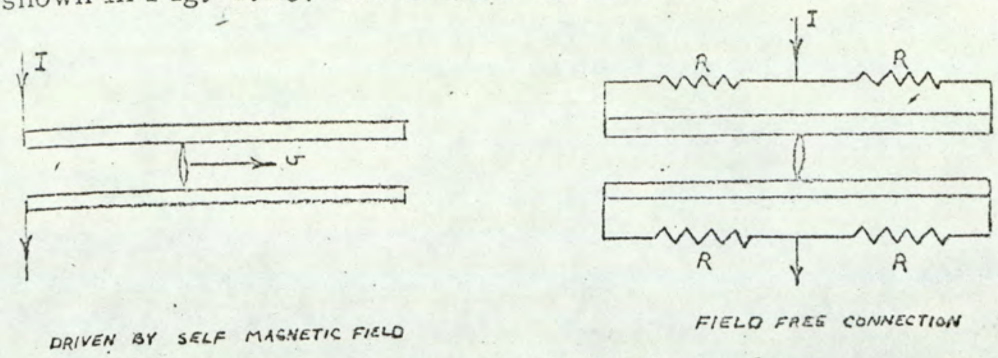
2.4. The Behaviour of an Arc in a Transverse Magnetic Field.

Applied and self magnetic fields have been used to move the arc at a high velocity over the electrode surface in order to reduce local erosion at arc electrodes and improve the uniformity of the thermal distribution in the plasma torch output. The relative motion between the arc and surrounding gas has the effect of constricting the arc column and increasing the axial voltage gradient along it. The arc voltage is also affected by the shape of the arc between the electrodes which may be considerably greater than the electrode separation.

The dependence of the arc velocity and voltage on the magnetic field are discussed for a wide range of conditions.

The range of interest of arc conditions is the same as outlined at the beginning of the Chapter and the range of magnetic flux density is such that the arc motion is always in the forward direction. The effects of low magnetic flux densities less than 0.01 Wb/m^2 are not normally of interest.

Any practical continuously operating plasma torch is likely to use an electrode configuration in which the arc repeatedly traverses the arc electrodes, such as coaxial electrodes. The majority of information available on the behaviour of arcs in transverse magnetic fields is for arcs making only one traversal between discontinuous electrodes such as parallel rail electrodes shown in Fig. 2.13. The limitations of the application of these



Open Ended Parallel Rail Electrodes.

Figure 2.13.

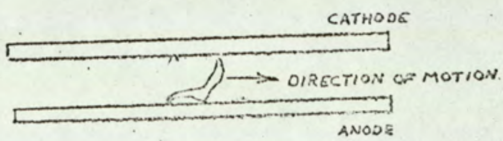
results and others obtained from electrode configurations other than co-axial electrodes are considered.

2.4.1. The Effect of the Electrodes and Arc Column on Arc Motion.

The motion of an arc in a magnetic field was at first considered to be similar to the motion of a conductor carrying a current in a transverse magnetic field and the force in the forward direction was assumed to be opposed by aerodynamic forces only (Escholz, 1921). Conditions at the arc roots may also affect the arc motion (Guile et al 1957(b)).The velocity of a short arc in air at 1 Atm between parallel rail electrodes using the self magnetic field of the arc current or an external magnetic field was also affected by the flux density at or just below the cathode surface. This condition is known as the root dominated mode. Further experiments showed that the cathode root velocity was also affected by the cathode material, surface finish, electrode separation and the thickness of the oxide layer on the cathode surface (Secker & Guile, 1959, Lewis & Secker, 1961). The cathode tracks were found to vary with increasing arc velocity from

1. Sticking.
2. Continuous low speed.
3. Discontinuous high speed.
4. Continuous high speed.

The sticking track was accompanied by massive evaporation of cathode material whilst the continuous high speed tracks showed very little loss of material even at high currents (Spink & Guile, 1965). The discontinuous behaviour varied with the ratio of inductance to resistance in the circuit. The anode motion was found to be mainly discontinuous but some regular motion was observed. The irregular movement of the anode and shunting of the arc column on the anode surface shown in Fig. 2.14. caused quite appreciable voltage fluctuations.



Shunting of the Arc Column at the Anode Surface.

Figure 2.14.

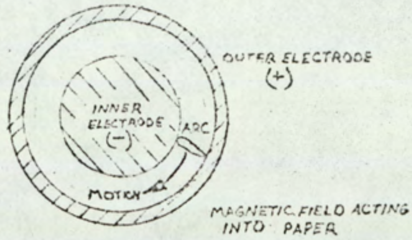
The transition between the root and column dominated modes is not rigidly defined. The arc motion generally changes from root dominated to column controlled with increase in arc velocity when the aerodynamic retarding forces on the arc column exceed the retarding forces at the arc root.

Spink & Guile have observed root domination at velocities up to 50 m/s for arcs in air at 1 Atm between open ended parallel brass rail electrodes 0·12cm to 10·2cm apart. At velocities above this the arc motion became influenced by the arc column. Column domination has also been shown to occur at electrode separations as small as 2 mm (Blix & Guile, 1965).

2.4.2. The Variation of Arc Velocity with Magnetic Field, Arc Current and Electrode Configuration.

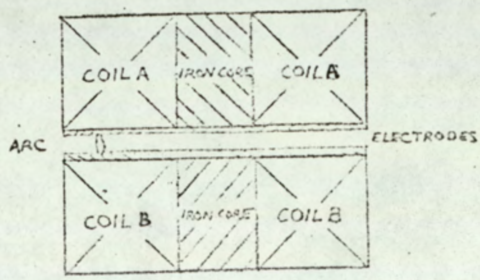
The arc velocity has been measured between parallel brass rail electrodes in air in external and self-magnetic fields up to 0.128 Wb/m^2 from 100A to $1x10^4$A. with electrode separations of 0.12 cm to 1.44 cm (Spink & Guile, 1965). Different electrode lengths were used at a constant electrode separation of 3.2 mm and the final velocity reached by the arc was found to decrease as the electrode length was reduced below 30 cm, the maximum length used. Reduction in electrode length of 33%, 50% and 66% using clean polished cathodes caused reductions in the measured velocity of 10%, 20% and 45% to 65% for currents of 500A, $1x10^3$A and $6x10^3$A respectively.

The velocity of arcs moving between co-axial circular electrodes Figure 2.(15) and open ended and continuous rail electrodes has been measured over a wide range of values of arc current, magnetic flux density and electrode separation. Measurement of the velocity of a radial arc between co-axial brass electrodes with a constant electrode separation of 1.27 cm have been made (Adams., 1965). The radius of the inner electrode was varied from 2.54 cm to 17.8 cm and the arc



COAXIAL CIRCULAR ELECTRODES, AXIAL MAGNETIC FIELD

FIGURE 2.15



RADIAL MAGNETIC FIELD AND ELECTRODE CONFIGURATION
USED BY BURKHARD (1966)

FIGURE 2.16

velocity increased with the radius of the central electrode tending to the value obtained for parallel rail electrodes. The arc velocity along the straight section of the continuous rail electrodes was greater than at the curved ends. If any conditioning at the cathode surface occurs after the first revolution the effect is obscured by the decrease in velocity that is obtained with curved electrodes (Adams, 1965).

The opposite effect was found for co-axial graphite electrodes when the electrode radius was varied with a constant electrode separation of 0.7 cm at 360A and 0.094 Wb/m^2 and 0.047 Wb/m^2 in air. The electrode radius was reduced until the period of revolution was below about 5 milliseconds when the arc velocity increased. A possible explanation may be that when the period of revolution was of this order the electrode may remain sufficiently hot for thermionic emission to be significant but when the period is longer the arc root mechanism is no longer thermionic.

Results have been obtained for an axial arc between copper electrodes in air rotating in a radial magnetic field (Fig 2.16) which indicate that the arc root conditions the electrodes (Burkhard, 1966). Arc currents of 50A and 100A, a magnetic flux density of 0.056 Wb/m^2 and an electrode separation of 0.6 cm in air at 1 Atm were used. The diameter of the arc track was 8 cm. Clean and polished electrodes, electrodes with varying thickness of oxide layer and electrodes with a track from previous arcing were used. In all cases the arc velocity increased most rapidly when previously arced electrodes were used. The rate of increase was less as the thickness of oxide layer was increased but was lowest for polished electrodes. The final velocity obtained on previously used electrodes at 50 A after about 4 revolutions corresponding to a distance of about 1.1 m was 55 m/s

40 milliseconds after arc initiation. The initial acceleration was very rapid a velocity of 37 m/s being obtained in 10 milliseconds corresponding to about 67% of the final velocity in less than 1 revolution. It is not apparent from these results whether the increase in arc velocity on subsequent revolutions is due to

(1) Conditioning of the electrodes.

(2) Conditioning of the arc gap causing the arc to move its own wake.

(3) Further acceleration of the arc, continuous electrodes being equivalent to infinitely long discontinuous electrodes.

It is therefore at least possible that the rotating arc used by Burkhard was still accelerating, after the first revolution, and that the final arc velocity was not reached on the rail electrodes used by Spink and Guile. The longer electrodes used by Adams which were 120 cms long may have enabled the final velocity to be reached. For previously arced electrodes since the initial acceleration of the arc is so rapid the error involved is likely to be small.

The force acting on an arc in a magnetic field is given by

$$F = B i l \sin\theta \qquad (2.11.)$$

where F = force acting on arc column (Nm)

B = magnetic flux density (Wb/m^2

i = arc current (A)

l = arc length (m)

θ = angle between arc current and magnetic field (rad)

The arc velocity is not simply related to the force and is dependent on both the magnetic field strength and arc current. The velocity may be represented by the relation

$$u \propto B^{p}.I^{q} \qquad (2.12)$$

A unique arc velocity does not exist for a rotating arc. The velocity at the inner electrode surface which is normally the cathode has been used A rotating arc tends to take up either a radial or involute shape(see also 2.4 . 4.). In either case the region at the cathode root is virtually normal to the cathode surface and tends to lead the arc. No ~~cases~~ measurements have been found where the central electrode was made the anode.

An extensive survey (Roman & Myers, 1966), of the behaviour of moving arcs between co-axial cylindrical electrodes and parallel rail electrodes over a very wide range of conditions has shown that generally

$$0.55 < p < 0.65 \qquad (2.13)$$

$$0.4 < q < 0.5 \qquad (2.14)$$

A functional relationship for the arc velocity in a magnetic field has been obtained (Dautov & Zhuzov, 1965). Values obtained over a wide range of conditions have been correlated with this to give the relation

$$\frac{ud}{I} \doteqdot 4.6\left(\frac{I}{Bd}\right)^{-0.6} \qquad (2.15)$$ (Adams et al, 1967).

The results indicated that the correlation applies for arcs of moderate length whose parameters are influenced by the electrode separation but may not apply to long arcs where electrode effects are negligible.

The effect of gas pressure has been investigated for a d.c. arc rotating between parallel co-axial carbon in nitrogen (Adams, 1967). Arc currents of 200A to 500A, electrode separations of 0.3 cm to 1.9 cm and magnetic flux densities of 0.04 Wb/m^2 and 0.05 Wb/m^2 were used. The diameter of the inner electrode was 1.27 cm. The gas pressure was increased up to 18 Atm. The arc velocity varied between 130 m/s to 32 m/s corresponding to about 3,200 r/s to 800 r/s with gas pressure according to the relation.

$$u \propto P^{-0.44} \qquad (2.16)$$

where u = arc velocity

P = gas pressure

The effect of an axial gas flow on an arc between co-axial brass electrodes 1.27 cm apart was also investigated (Adams, 1967), with the same electrode arrangement used previously (Adams, 1965). The arc current varied between 360A to 490A and a magnetic flux density of 0.047 Wb/m^2 was used. The axial gas flow causes a sudden drop in velocity from about 64 m/s (400 r/s) with no gas flow to 32 m/s (200 r/s) at a gas flow rate of 6 g/s. Little further decrease occurred as the gas flow-rate was increased up to 24 gm/s.

2.4.3. The Variation of Arc Voltage with Arc Velocity and Current of an Arc Moving in a Transverse Magnetic Field.

The variation of arc voltage with magnetic flux density and arc current has been less widely investigated than the variation of arc velocity. Consequently there are fewer results available and it is not easy to obtain generalised relations for the variation of arc voltage. The voltage of a moving arc generally fluctuates due to shunting of the arc column at the electrode surface and sticking at the arc roots. (See also 2.4.1).

The voltage depends on

1. The arc velocity.
2. The arc current.
3. The geometry of the electrodes.

Since the arc voltage is dependent on the electrode configuration as well as the separation it is necessary to consider results from different electrode configurations separately.

In addition an e. m. f. will be induced in an arc moving in a magnetic field given by

$$e = B \ell u \sin \theta \qquad (2.17)$$

where
e = induced e. m. f. (V)
B = magnetic flux density (Wb/m^2)
u = arc velocity. (m/s)
θ = angle between arc current and direction of magnetic field. (rad)

Since ℓ is generally of the order of 10^{-2} m and u is of the order of 100 m/s while the total arc voltage is greater than 25V the effect of the induced e. m. f. is normally negligible at 1Atm.

The variation of arc voltage and voltage gradient in the arc column with the magnetic flux density and arc current is of the form

$$E \propto B^r I^s \qquad (2.18)$$

and
E = voltage gradient (V/m)
B = magnetic flux density (Wb/m^2)
I = arc current. (A)

The voltage gradient of arcs between parallel brass rail electrodes in air at 1 Atm have been measured over half a cycle obtained with a mechanical switch synchronised to the mains frequency (Spink & Guile, 1965). Magnetic flux densities of 0.032 Wb/m^2 to 0.160 Wb/m^2 at arc currents of 100A to 10,000A and arc velocities up to 300 m/s with electrode separations of

0.32 cm to 10.2 cm were used. The relation

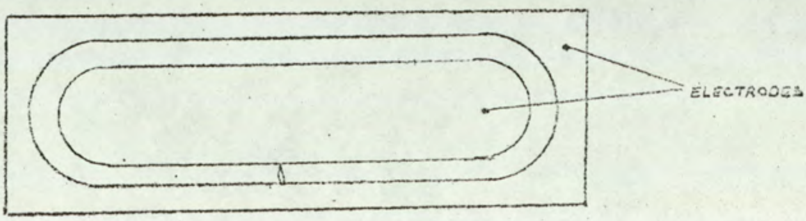
$$E \propto (B\ I)^{0} \qquad (2.19)$$

was obtained except at arc currents greater than 1,000A when the arc voltage increased slightly possibly due to the action of plasma jets (King, 1961). (See also 2.2.1.).

Results obtained with d.c. generators over several half cycles using open ended and continuous brass rail electrodes in air at 1 Atm have been obtained (Adams, 1965). Arc currents of 100A to 3,700A and magnetic flux densities of 0.02 Wb/m^2 to 0.13 Wb/m^2 and velocities of 30 m/s to 180 m/s were used with the open ended rail electrodes. The relation

$$E \propto B^{0.3} \qquad (2.20)$$

was obtained. The continuous parallel rail electrodes shown in Fig.2.17 were used, which enable the arc to repeatedly traverse



Continuous Parallel Rail Electrodes.

Figure 2.17.

the electrodes over the range 200A to 2,700A, 0.02 Wb/m^2 to 0.12 Wb/m^2 and 40 m/s to 340 m/s to obtain the relation

$$E \propto B^{0.4} \qquad (2.21).$$

The voltage gradient was approximately independent of arc current and electrode separation in both cases. The difference between the results obtained by Adams and those by Spink and Guile may be due to the greater accuracy possible when d.c. is used, in the measurement of the arc voltage. The difference between the results for open ended and continuous electrodes is not significant for the range of magnetic flux density used.

The voltage of a rotating arc between co-axial carbon and brass electrodes in an axial magnetic field has also been measured (Adams, 1964). The carbon electrodes were used at magnetic flux densities between about 0.01 Wb/m^2 to 0.1 Wb/m^2 and the arc current between 100A and 500A. The velocity varied between 16 m/s and 185 m/s and rotational frequencies of 500 r/s to 4,500 r/s obtained. Measurements of arc voltage with an electrode separation of 0.65 cm with different diameters of the inner electrode from 2 cm to 9.2 cm and also with the diameter of the inner electrode constant, varying the electrode separation from 0.65 cm to 3.2 cm, were made. The arc voltage tended to increase with the magnetic field, electrode separation, and internal diameter of the electrode and decreased with arc current. The relation

$$E \propto B^{0.27} \tag{2.22}$$

was obtained. The brass electrodes were used over a range of current of 200A to 450A and magnetic flux density of 0.02 Wb/m^2 to 0.13 Wb/m^2. The electrode separations were 1.27 cm and 2.54 cm and the diameter of the inner electrode was varied between 5 cm to 36 cm. The velocity varied between 50 m/s to 130 m/s and rotational frequencies of 110 r/s to 470 r/s. No significant variation in arc voltage occurred with variation in the electrode diameter or arc current. The voltage gradient was not obtained, as only two different values of electrode separation were used. The variation of arc voltage was approximately the same as was obtained for the parallel rail electrodes and was approximately independent of the arc current.

The continual fluctuation in voltage of a moving arc makes the arc voltage difficult to estimate. As a result it is more difficult to generalise about the arc voltage and voltage gradient in the arc column.

A functional relationship for the voltage gradient in the arc column has nevertheless been obtained (Yas'ko, 1966). Values over a wide range of conditions have been correlated to obtain the generalised electric characteristic (Adams et al, 1967).

$$\frac{Ed^2}{I} = \left(\frac{I^2}{d^3 U}\right)^{-\frac{2}{3}} \times 10^{3} \qquad (2.23)$$

where E = voltage gradient of arc column

d = electrode separation

I = arc current

U = arc velocity.

The correlation is less satisfactory than those obtained from the magnetic characteristic. (2.15).

2.4.4. The Shape of an Arc Rotating in its Own Wake.

The shape of a rotating arc between brass electrodes with the cathode at the centre has been photographed (Adams, 1964). At electrode separations above 2 cm the arc was approximately involute in shape with the cathode region radial but at smaller separations the entire arc was approximately radial. The effect of column domination and possible reduction in the plasma jets at high arc velocities will have a marked effect on the arc behaviour and the arc may become involute shaped at smaller electrode separations at higher velocities (Naylor & Guile, 1967). Adams observed no indication of the arc ~~moving in its own wake or~~ becoming diffuse at velocities up to 130 m/s with corresponding periods of rotation of 0.3 milliseconds.

A diffuse arc in which the entire annular arc gap became filled with a luminous discharge has been reported (Mayo & Davis, 1962). The arc was rotated between co-axial copper electrodes 0.33 cm apart with an inner diameter of 3.5 cm in air at 1 Atm and above in a variable axial gas flow. The diffuse behaviour was observed over a range of axial magnetic flux densities of from about 1 Wb/m^2 to 2 Wb/m^2 and arc currents of 1,200A to 3,800A using high speed photography. As a direct result of the arc becoming diffuse it was claimed that the arc became more stable, the erosion of the electrodes was decreased and the dynamic impedance of the arc became positive. The same diffuse arc was also referred to by Phillips (1964).

An apparently diffuse arc was obtained with an arc rotated between a concentric copper anode and tungsten cathode (Shepard & Winovich, 1961, Boldman, 1962). The central tungsten cathode was 1.9 cm diameter with an electrode separation of 2.3 cm. A magnetic flux density of 0.12 Wb/m^2 at arc currents up to 2,100A in nitrogen flowing at 2.7 g/s was used. High speed photography at 4,000 frames/second and 4 microseconds exposure indicated that the arc was diffuse.

A conical arc has been observed in argon between a pointed tungsten cathode above a hole in a plate anode (Levakov & Lyubavskii, 1965). An axial magnetic field of up to 0.05 Wb/m^2 at arc currents of 20A to 300A was used. The maximum diameter of the hole in the anode was greater than 1 cm and electrode separations of up to 0.6 cm were used. High speed photography indicated that the discharge was uniform but no details of the photographic observations were given.

An arc rotated between copper electrodes 0.8 cm apart with an inner electrode (cathode) diameter of 1.6 cm has also been reported to be diffuse at gas pressures lower than 10 Torr in Helium and Argon gas flows. (Powers & Patrick, 1962). Arc currents of about 200A and magnetic flux densities of 1 Wb/m^2 were used. Photographic observation at 1,000 frames per second at an exposure time of 25 microseconds, and a camera with an exposure of 4 milliseconds were used. The arc appeared diffuse and in addition a search coil indicated that a circumfrential Hall current was present shown by voltage fluctuations in the search coil when the field was switched on and off. This cannot however be regarded as conclusive evidence for the existence of a Hall current as the voltage fluctuations may be caused by switching the field coil. The existence of a diffuse arc and a circumfrential

Hall current has been implied(Harder & Cann,1964) but not experimentally confirmed.

2.5. Summary of the Most Useful Arc Parameters.

The results discussed in the preceding sections may be summarised as follows.

Electrode Processes.

The electrode processes primarily affect the power losses to the electrodes from the arc and evaporation of electrode material. These are affected by the electrode fall voltages and current densities at the arc roots. The cathode fall voltage and current density at the cathode root on a refractory electrode is typically of the order of 3V to 15V and 1,000 A/cm^2 depending on the electrode material, geometry and gas. The cathode fall voltage and current density on a cold cathode electrode are of the order of 11V to 16V and 10^6 A/cm^2. When the cathode root is moved rapidly over the surface of a refractory electrode the current density at the arc root approaches that on a cold cathode material.

The anode fall voltage and current density is normally less than at the cathode and depends on the geometry, gas, anode material, and cooling. Since the constriction of the arc column is less at the anode the total heat transfer from the arc is normally higher although the heat flux density at the cathode may be higher.

The main method of heat dissipation at the electrodes of high current static arcs is by evaporation of electrode material.

Arc Column Processes.

The conditions in the arc column of a static free burning arc are accurately known. The voltage gradient above 100A is about 10V/cm. The current density remains constant up to 200A but increases with arc current at higher currents. The effect of gas pressure on the voltage gradient, current density and arc diameter is normally small compared with other effects such as constriction in a cooled tube, forced convection or movement of the arc with a magnetic field. Since these seldom occur separately relative effects are difficult to separate. Typically increases in the voltage gradient of the arc column of more than five times are obtained in this way.

Arc Stability.

The main factors affecting arc stability are processes in the cathode fall region which have time constants of the order of 1×10^{-9}s and arc column processes where the time constant is about 1×10^{-3}s. No quantatative assessment of the effect of the magnitude of the stabilising impedance on an arc has been made. Typical values of the ratio of open circuit voltage to arc voltage lie between 5:1 to 2:1.

The Effect of Transverse Magnetic Fields.

The use of transverse magnetic fields to move the arc roots over the electrode surface reduces electrode evaporation. The voltage gradient and the length of the arc column are also increased. The relative effects are difficult to separate particularly in the case of rotating arcs where the arc may take up an involute shape.

The generalised equations for the arc velocity and voltage gradient in the arc column may be used to deduce the operating conditions of a magnetically moved arc to within an order of magnitude. Greater accuracy may be obtainable if the configuration is similar to one that has been previously investigated. The effect of a small tranverse gas flow is to cause ~~an abrupt~~ drop by a factor of the order of a half in the arc velocity.

At high values of tranverse magnetic flux density the rotating arc is reported to become diffuse filling the annular arc gap with a luminous discharge resulting in significant changes in arc behaviour of important benefit to a plasma torch.

Conclusion.

The main features of an electric arc have been delineated over the range of conditions over which a plasma torch is likely to be operated. The results enable a qualitative understanding of phenomena occurring in a plasma torch and qualitative estimates of factors affecting the operation to be made.

CHAPTER 3.

Review of the Development of the Plasma Torch.

A review of the development of the plasma torch with particular emphasis on the influence of the design on the operation and application is presented.

3. REVIEW OF THE DEVELOPMENT OF THE PLASMA TORCH.

This review is unique in that the behaviour of the arc and the influence of the torch design are considered in detail under widely different conditions enabling for the first time a comparison to be made of the different methods of construction and operation of a plasma torch. The results have been used to formulate the basic requirements of a plasma torch for use in industrial process heating. The term plasma torch has been used in the widest sense to include any device in which a flow of gas is heated by an electric arc and includes gaseous reactions which occur between the electrodes, and applications where a hot jet of gas is required.

The chronological development of the plasma torch is considered in 3.1. The electrode geometries that have been used in plasma torches and their influence on efficiency are then considered in 3.2. in terms of the various applications which normally govern the configuration used. Electrode materials are discussed in 3.3. and the use of vortex gas flows for arc stabilisation and movement of the arc root in 3.4. The use of magnetic fields to rotate the arc in a plasma torch is considered in 3.5. Factors affecting arc stability and re-ignition are discussed in 3.6. and the methods of measurement of the temperature and energy at the outlet of the plasma torch are discussed in 3.7. Finally the results directly applicable to a plasma torch for industrial process heating are summarised in 3.8.

The applications of plasma torches are listed in Appendix 3 at the end of the thesis.

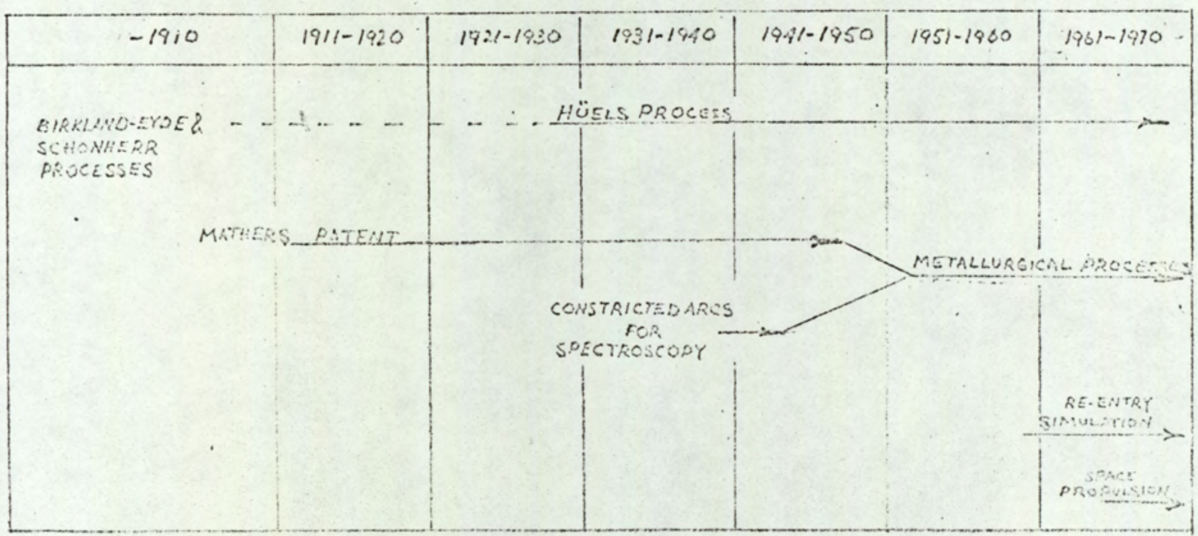
3.1. Chronological Development of the Plasma Torch.

The chronological development of the plasma torch is illustrated in Fig. 3.1. Electric arcs have been used for endothermic gaseous reactions since the end of the last century in the Birkeland-Eyde and Schonherr processes for the fixation of nitrogen.

One of the earliest mentions of a constricted arc is in a patent (Mathers, 1911), which describes a plasma torch similar to those used to-day for metal spraying. It is of interest to note that he too, like the author was interested in applying it to industrial furnace heating, however the existing state of material technology and understanding of the arc behaviour limited its development.

In the early nineteen thirties there was increased interest in the arc as a spectroscopic source and constricted arcs operating at relatively low power inputs were developed. At about the same time the large scale manufacture of acetylene from methane using an arc discharge was established in Germany.

It was not until the nineteen fifties that plasma torches became widely used for industrial processes, principally for metal and ceramic spraying as a result of development in spraying techniques for surfacing rocket and missile nose cones and exhaust tubes. Research in the late nineteen fifties into re-entry simulation for space vehicles has led to the development of high power arc heaters. More recently research into the application of arc heaters for space propulsion has been carried out. It should be emphasised here that not all the information was available when the work described in Chapters 4 to 6 was carried out but has been brought together in Chapters 7 and 8 where the overall results and applicat-



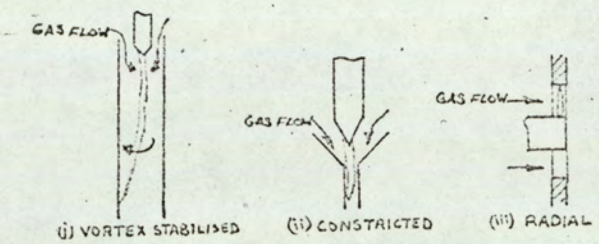
CHRONOLOGICAL DEVELOPMENT OF THE PLASMA TORCH

FIGURE 3.1.

ions are considered.

3.2. Electrode Configurations used for Plasma Torches.

The electrode configuration used in a plasma torch depends to a large extent on the application which forms a convenient method of classification. The principle applications with schematic diagrams showing the essential differences are shown below.



Influence of Application on Electrode Configuration

Figure 3.2.

1. Endothermic gaseous reactions e.g. Hüels torch for acetylene production in which the reaction takes place in the region between the arc electrodes. (i)
2. High temperature low power highly constricted d.c. arc discharges primarily used for spectroscopy. (ii)
3. Metallurgical processing including metal and cermet spraying, cutting and welding using medium power constricted d.c. arcs. (ii)
4. Augmentation of combustion flames. (ii), (iii)
5. Space vehicle research such as re-entry simulation and rocket propulsion using high power d.c. and a.c. arcs. (iii)

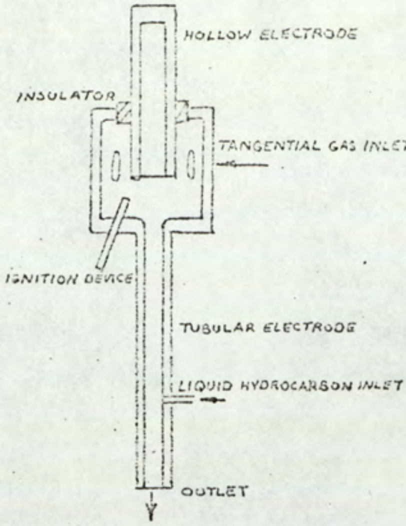
The application of plasma torches to industrial process heating may usefully incorporate features from more than one of these processes. Metallurgical and endothermic gaseous processes are industrial heating processes but are considered here separately since the requirements are quite different from the subject of this investigation outlined in the Introduction.

3.2.1. Plasma Torches used for Endothermic Gaseous Reactions.

When electrical discharges are used for endothermic gaseous reactions the reaction takes place in the region between the arc electrodes. It is not typical therefore of the majority of plasma torches in which the heated gas obtained is used outside the torch body. This application is however considered here because it shares many common features with conventional plasma torches.

The synthesis of nitric oxide from air in the Birkland-Eyde process (Edstrom, 1904), was one of the earliest applications of the use of arcs for endothermic gaseous reactions. Rod electrodes in a transverse magnetic field were used at powers up to 0.5 MW at 50 Hz. The process was discontinued with the introduction of the manufacture of nitric oxide from the oxidation of ammonia about 30 years ago.

The Hüels process for the manufacture of acetylene from the by-products of petrol refining has been used in Germany since the early nineteen thirties (Gladisch, 1962). A simplified diagram showing the essential features of this torch is shown in Fig. 3.3.



Vortex Stabilised Arc Heater.

Figure 3. 3.

The arc is struck between the two tubular electrodes at the closest separation. The action of the vortex gas flow is to stabilise the arc column in the centre of the electrodes on the axis of the reactor vessel. The effect of this is to drive the arc roots away from the position of minimum electrode separation enabling long arcs and high arc voltages to be used. Typical operating conditions are an arc length of 100 cm with an electrode voltage of 7 kV, 1 150 A and 8.1 kW. Rectified a. c. is used at a power factor of about 0.7. A second inlet is provided below the arc so that the heating process does not take place entirely in the arc region and the process is complicated by quenching actions which also occur in this region.

Recently a similar d. c. arc heater has been developed (Eschenbach et al, 1964), using an axial magnetic field to increase the arc movement in the hollow electrode which was made the cathode.

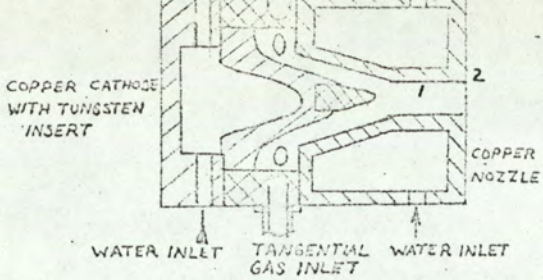
Very high arc voltages enabling high power inputs at low currents and low electrode erosion are obtained with this configuration. The long arc column provides a large reaction region enabling high gas throughputs to be obtained. The effects of the electrode fall voltages are likely to be small compared with containment losses to the walls of the reactor. If no heat output is required at the outlet of the reactor vessel these losses may be acceptable and the method may have a relatively high overall process efficiency. If it is used as a hot gas source with the useful heat transfer from the gas occurring external to the reactor vessel the combined effects of containment losses and additional losses in the heat transfer process external to the torch are likely to make this design impractical on economic grounds. Nevertheless exit conversion efficiencies of up to 70% have been reported by Eschenbach et al, but the method of measurement is not given. Efficiencies obtained for other potentially more efficient electrode configurations indicate that this value may be considerably higher than the actual value (see also 3.2.3).

3.2.2. The Plasma Torch as a High Temperature Laboratory Source.

Constricted arcs from which a jet of high temperature gas is obtained have been widely used for the study of materials at high temperatures (Osborn, 1959), and as light sources for spectroscopy. (Greenfield et al, 1964). Such torches are of interest in that they were essentially the forerunners of the plasma torches used for metallurgical processes to-day. Various forms of constriction in order to provide the high temperatures required have been used including wall constricted arcs, water stabilised arcs (Burhorn & Maecker, 1951), and gas stabilisation (Katz et al, 1960). The efficiency is not of great importance and no attempt to measure it is known since normally only a small quantity of high temperature gas is required for a short time.

3.2.3. Plasma Torches for Metallurgical Processes.

Plasma torches have been used in metallurgical processes principally for metal cutting, welding, material deposition and spheroidising. The torches used for these applications are similar, a stable well defined jet of hot gas being required capable of being directed accurately.



Plasma Torch Used for Metallurgical Processes.

Figure 3.4.

A diagram showing the electrode arrangement for this kind of torch is shown in Fig. 3.4.

The central electrode is normally a refractory cathode, the nozzle which acts as the anode in the non-transferred torch is made of copper. (See also section 3.3.). Magnetic rotation of the arc is not normally used but gas vortex stabilisation is usually applied (Jones & Griffiths, 1963). When the plasma torch is used for material deposition the material is added either in the straight section of the nozzle at (1) or at the nozzle outlet at (2) depending on the material and requirements.

The arc is constricted in the nozzle in both the transferred or non-transferred modes. Very high voltage gradients and arc temperatures are obtained in this way. The heated gas at the outlet is normally luminous in a turbulent but well defined short flame shape. The gas flow is laminar at low gas flow rates and jet lengths of over 90 cm in air have been reported (Moss & Young, 1964). For operation in air with a refractory cathode without excessive oxidation occurring the cathode is sheathed with an inert gas the main gas inlet being downstream of the cathode(O'Brien, 1962).

The main use has been for metallurgical applications involving high cost products or in processes for which the plasma torch offers unique advantages over other methods. Power inputs that have been used are typically of the order of 10kW to 50kW although higher power inputs have been quoted in manufacturers literature.

Efficiencies of up to 75% have been obtained (Okada et al, 1960) at an arc current of 100A from the measurement of losses to the electrodes and torch body. The highest arc voltage used was 60V, the gas used was not stated. The efficiency was found to increase with gas flow rate and with reduction in electrode separation probably due to the arc root running outside the torch on the face of the nozzle which was observed. The straight section of the nozzle used was however only between 0.5 cm and 1 cm long and was 0.5 cm diameter so that the losses due to containment in this region may be quite small compared with those which occur when the arc is contained entirely inside the nozzle.

A maximum efficiency of 82% was obtained with a similar configuration using nitrogen at a power input of 10 kW an arc voltage of 142 V and a gas flow rate of 1 L/s (Jahn, 1963). The maximum efficiency obtained with argon was 56% at a power input of 10 kW and an arc voltage of 35 V. Both measurements were obtained at a flow-rate of 1 L/s throat length of 1.9 cm and diameter 0.6 cm. The efficiency was found to increase with increase in the gas flow rate.

The exit conversion efficiency using a 2% thoriated tungsten cathode and a copper anode with a throat diameter of 0.4 cm. (Stokes et al, 1960) has been measured. The arc voltage varied between 33 V and 180V, the throat length was unspecified. Efficiencies of approximately 56% apparently independent of the power input at constant gas flow rate over a range of power input of 3:1 was obtained. Approximately 5% of the input power was dissipated at the cathode the remainder of the losses occurring at the anode which was the nozzle.

The values of efficiency obtained seem rather high for the arc voltages and electrode geometry used. Losses at the arc root regions might be expected to be about 25% of the total power input at the low arc voltages used. Conduction convection and radiation losses to the torch body and in particular the walls of the nozzle might be expected to be high for a constricted arc. If the difficulties in the measurement of the input power due to high frequency fluctuations(Jordan & King, 1965) and errors in the measurement of efficiency if only the electrode losses are considered it appears that these values of efficiency are likely to be higher than the actual efficiency by amounts of 10% or more.

3.2.4. Electrically Augmented Flames.

Augmentation of the temperature and thermal energy of a combustion flame with an electric discharge has been considered for a number of years. The main application is for small increases in temperature which would be difficult or impossible by normal combustion processes which are limited to about 2,000°c. The increase in specific enthalpy of polytomic gases rises rapidly above about 2,000°c due to dissociation of the gas molecules. As a result there is little advantage to be obtained by increasing the flame temperature by large amounts since the energy contribution from the fuel becomes negligible.

A three phase electric arc using three rod electrodes, to augment the output of an oil fired burner has been described (Southgate, 1924). Few details of the arc itself were given but apparently voltages of from 600V to 6,600V were used up to power inputs of about 150 kW. If a star connected electrode system and a ratio of open circuit voltage to arc voltage of 2.1 are assumed the corresponding arc current is 76A at the higher value of voltage. The high values of arc voltage might be attributed to the effect of the elongation of the arc along the gas stream by the jet of combustible gas.

More recent work has been carried out on low current high voltage discharges. The turbulence of the heated gas jet has been claimed to prevent a constricted arc from developing and a diffused discharge was obtained (Karlovitz, 1962 (a),(b)). Electrical power inputs of 4.6 kW at 4.7 A and 1,800 V with a combustion input of 9.3 kW and overall efficiencies in terms of the power input and output energy measured with a calorimeter of 94% were obtained. At the high arc voltages and with the unconstricted configuration used the high efficiency obtained is possible. This method of producing a discharge appears however to be limited to relatively low power inputs due to the low currents necessary to prevent a constricted arc from developing.

3.2.5. The Application of the Plasma Torch to Space Research.

Plasma torches have been developed for space research applications. The main uses have been

1. To assist in simulating the conditions encountered by a space vehicle at re-entry into Earth's atmosphere.
2. As a possible space propulsion unit.

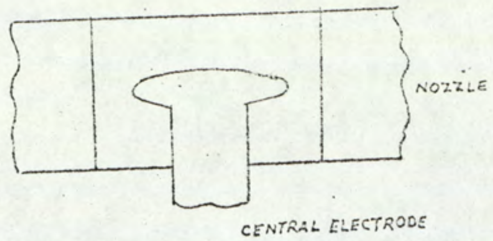
The first application has received most attention up to now.

Conventional blow down wind tunnels in which a high pressure chamber is allowed to discharge through an expansion nozzle into a low pressure chamber are unable to reproduce the conditions at re-entry of a vehicle into the Earth's atmosphere. Under these conditions in order to simulate a velocity of Mach 8 on altitude of at 36,000 m a temperature of 2,900^{o}c and pressure of 67 Atm is required (B unt and Olsen, 1961(b)).

A low level of contamination of the heated gas is necessary in order that the re-entry conditions are correctly simulated but the operating times are normally less than 1 minute. Because of the short running time the efficiency is not critical except that the cost of power supplies and auxillary equipment will be increased if the efficiency is low.

Vortex stabilised torches of the type described in 3.2.1., Fig. 3.3. operated from d.c. have been used for re-entry simulation with a supersonic expansion nozzle at the gas outlet (Eschenbach et al, 1964).

Co-axial tubular electrodes shown in Fig. 3.5. made

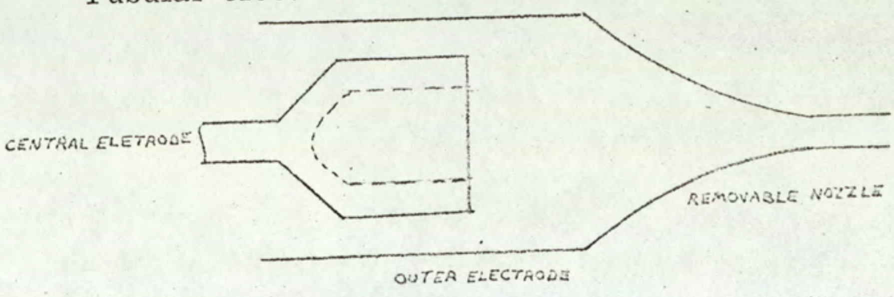


Electrodes used by Greer (1960).

Figure 3.5.

of copper and using an axial magnetic field to rotate the arc have been used operated from a d.c. power supply at power inputs of up to 70 kW at 400A (Greer, 1960). Efficiencies of about 10% were obtained. The heated gas at the nozzle exit passed through a water cooled section common to the torch body so that the measured efficiency was lower than the real exit conversion efficiency.

Tubular electrodes with a modified central electrode



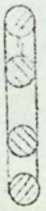
Electrodes used by Mayo and Davis (1962)

Figure 3.6.

recessed at the end to discourage the arc root from attaching on it were used by Mayo and Davis (1962). Power inputs of up to 1.2 MW at up to 3,400A were used and efficiencies of between

25% and 80% have been reported, apparently in terms of losses to the electrodes and torch body. The torch was designed to operate at gas pressures up to 75 Atm with a correspondingly robust construction and it is likely that during the short running time the cooling conditions may not have reached a final steady state. The efficiency measured may be rather larger than the actual efficiency apart from possible errors in the measurement of the power input that have been discussed.

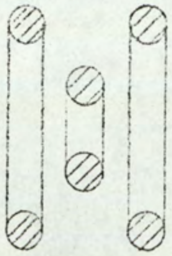
Co-axial copper ring electrodes with the arc gap in the axial plane shown in Fig. 3. 7. have been widely used with d. c. and a. c.



Co-axial Ring Electrodes with Radial Arc Gap.
Figure 3. 7.

Bunt et al (1961(a)) used the self magnetic field due to the arc current to rotate the arc in the same way that has been used with parallel rail electrodes (see also 2.4. Fig. 2. 13.) with gapped electrodes so that the electrical connection was to one end of each electrode only. Both round and square electrode geometries were used the latter being reported to be less subject to bow out of the arc radially (Raezer et al, 1964). A minimum efficiency of 40% was predicted for this configuration (Bunt et al, 1961(a)), but no measured value was reported.

Three phase equi-spaced ring electrodes shown in Fig. 3. 8., in an external magnetic field with electrode separations of 1. 8 cm to 6. 35 cm and arc currents of 800A have been used (Phillips, 1964). An efficiency of 15% was reported but no details were given as to how it was measured.



Three Phase Equi-Spaced Ring Electrodes.

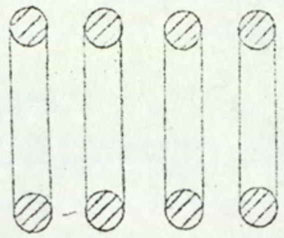
Figure 3. 8.

A plasma torch capable of working from d. c., single or multi phase a. c. has been described (Maniero et al, 1966). Continuous ring electrodes with an external magnetic field

Ring Electrodes with Axial Arc Gap.

Figure 3. 9.

shown in Fig. 3. 9. were used with electrode separations of from 0. 97 cm to 7. 6 cm and with arc currents up to 10^4A. No values of efficiency are quoted for this heater. A three phase system with four electrodes connected in line shown in Fig. 3.10 has been reported but no operating details were given (Winkler et al, 1964).



Three Phase Four Electrode System.
Figure 3.10.

It is likely that integral multiphase electrode systems will have an inherently lower efficiency than the d. c. or a. c. single phase heater due to the additional area of cooled electrodes in close proximity to the heated gas.

3.3. Materials used as Electrodes in Plasma Torches.

One of the main requirements for industrial applications of an electrode material for use in a plasma torch is a low erosion rate so that continuous operation for long periods is possible. In addition, for certain applications very low contamination of the heated gas may be required. Electrode erosion is caused principally by

(1) Evaporation due to thermal processes at the arc roots.
(2) Loss of material caused by bombardment of the cathode by excited or charged particles (von Engel & Arnold, 1960).
(3) Electrode evaporation due to heat transfer from the heated gas.

(4) Chemical combination of the electrodes with the heated gas to form volatile compounds, or compounds which have poor adhesion to the electrode surface.

The relative magnitudes of the erosion processes are not known and might be expected to vary with the operating conditions In many cases where (3) and (4) can be made small at high arc currents (1) is the main loss mechanism whilst at low currents the effect of (2) is greatest (Holm, 1949). (See also 2.1.4.).

The erosion rate may also be affected by the physical properties of the electrode material, the electrode separation and geometry, and the electrode cooling.

Electrode materials may be divided between refractory and non-refractory electrodes. Refractory electrodes such as graphite and tungsten have high melting points and are capable of sustaining a stationary cathode spot by thermionic emission alone but can also sustain cold cathode emission under certain conditions. (See also 2.1.1.). Non-refractory materials such as silver and copper have lower melting points and cannot sustain a cathode spot by thermionic emission alone but have higher electrical and thermal conductivities allowing more effective cooling to be obtained. Some physical properties of electrode materials that have been used are shown in Table 3.1.

Table 3. 1.

Some Properties of Materials that have been Used for Plasma Torch Electrodes.

Material	Density g/ml	Specific Heat J/g. °c.	Electrical Conductivity $ohm^{-1}cm^{-1}$ $x10^{6}$	Thermal Conductivity $Wcm/cm^{2}{}^{o}c$	Melting Point °c	Boiling Point °c	Reference
Amorphous graphite (pyrolytic)	1.8-2.2	-	$0.4-0.5x10^{-3}$	6.71-16.4 (20^{o})	3870	4200	Samsonov, 1964
Anisotropic graphite							
a axis	2.18	-	2.85	1.74	-	-	Robba, C1967
c axis	2.22	-	$2.85x10^{-3}$	0.0865	-	-	
Copper	10.5($20^{o}c$)	0.379($0^{o}c$) 0.398($975^{o}c$)	0.642($0^{o}c$) 0.047($1083^{o}c$)'	3.85($0^{o}c$) 3.56($700^{o}c$)	1083	2580	Kaye & Laby, 1966
Iron	7.9($20^{o}c$)	0.645 (0-$1100^{o}c$)	0.112($0^{o}c$) 0.012($700^{o}c$)	0.76($0^{o}c$) 0.34($700^{o}c$)	1539	2900	"
Silver	10.5($20^{o}c$)	0.233($0^{o}c$) 0.247($427^{o}c$)	0.664($0^{o}c$) 0.052($1200^{o}c$)'	4.18($0^{o}c$) 3.62($300^{o}c$)	960	2180	"
Tungsten	19.3($20^{o}c$)	0.142 (20-$100^{o}c$)	0.204($0^{o}c$) 0.0257($1200^{o}c$)	1.9($0^{o}c$) 1.2($700^{o}c$)	3380	5500	"
Zirconium	6.5($20^{o}c$)	0.276 (0-$100^{o}c$)	0.025($0^{o}c$) 0.0091($100^{o}c$)	0.21($0^{o}c$) 0.19($300^{o}c$)	1850	4400	"

'Measured during molten stage.

Graphite has been very widely used in plasma torches for both metallurgical, laboratory and rocket research applications. The main disadvantage of graphite electrodes is the combination of carbon with oxygen that occurs if air is to be heated. This is particularly disadvantageous in a re-entry simulation facility where reducing rather than oxidising conditions may result.

Pyrolytic graphite obtained by the decomposition of carbon containing gas on a heated substrate exhibits highly anisotropic properties (Knippenburg et al, 1967). In particular the thermal and electrical conductivities vary by factors of 100 and 1,000 respectively depending on the axis of measurement the high conductivity plane lying parallel to the crystal layers.

Measurements of erosion rates of a rod cathode of pyrolytic graphite with the high conductivity axis parallel to the electrode axis at arc currents of 120A to 320A in non oxidising gases have been made (Leutner, 1962). The results show erosion rates below those obtained with ordinary graphite and of the same order as the minimum values postulated by Holm (1949) for carbon at 1A. When the pyrolytic graphite was used as the anode with the maximum conduction axis in the direction of optimum cooling (perpendicular to the electrode surface) the arc was stable and the erosion rate less than for normal graphite but when the high conductivity axis was parallel to the electrode surface the arc was difficult to establish and was unstable with rapid erosion occurring.

Amorphous graphite has been rejected in favour of tungsten in torches used for metallurgical applications because of the reduced erosion and cross-sectional area necessary to carry the arc current. Tungsten also oxidises rapidly when used with air and in order to overcome this the cathode is sheathed with argon with the air inlet downstream of the cathode (Okada & Maruo, 1960). The mechanical properties of the tungsten are improved by swaging and the addition of about 2% thorium. The poor resistance to thermal shock is thought to make it unsuitable for use at currents in excess of about 1,000A (Shepard & Boldman, 1959). Very recently oxidation resistant tungsten based alloys, (typically 89% W, 10% Cr, 1% Pd) with self-healing properties have become available but up to now no information is available on their application as arc electrodes.

In d.c. torches used for metallurgical applications the anode is normally made of copper rather than tungsten. The effect of the gas vortex produced by tangential gas inlets causes random movement of the anode root in the nozzle and the higher thermal conductivity of the copper electrode help to prevent erosion due to local overheating which will normally be higher than that at the cathode. The ability to machine the relatively complex shape required for a nozzle may also contribute to the widespread use of copper as an anode material. A chemical analysis carried out during this investigation of the anode of a commercial torch for metal cutting showed that it was made of a phosphor bronze alloy. This is the only case known of cold cathode materials other than copper, silver or iron (Hüels torch) being used. The effect of the phosphorous content on the thermal and electrical conductivities is to reduce them and the erosion rate might be expected to be larger. This discussed in more detail in the light of further experimental evidence in 5.2.6.

The oxidation of refractory electrodes in an oxidising gas has been overcome by using zirconium oxide for the cathode (Weatherby & Anderson, 1965). Efficient cooling of the cathode which has a thermal conductivity of about 0.12 of that of tungsten (see also table 3.1) was obtained by using the zirconium in the form of an insert 0.3 cm diameter and 0.4 cm long in a well cooled copper block. In use the arc tended to stabilise on the zirconium insert on which it remained and useful cathode life-times in oxygen of between 3 hours and 11.2 hours were obtained at arc currents of 600A and 300A. The actual erosion rate was not given. The application of this technique would however appear to be limited to the maximum diameter of the zirconium insert above which cooling becomes ineffective.

Generally when a.c. has been used non-refractory electrodes have been used. Both electrodes become alternatively anode or cathode and the high power input to the anode at the anode root requires a material of high thermal conductivity to prevent excessive evaporation. The non-refractory materials such as copper and silver have higher thermal conductivities but lower melting points (Table 3.1.) so that the arc has to be moved over the electrode surface to reduce evaporation. Arcs on refractory electrodes may also be moved with magnetic fields or a vortex gas-flow but at high velocities behave as cold cathode materials and as the thermal conductivities are generally lower than cold cathode materials the evaporation will be greater. (See also 2.1.1.). The effects of oxidation prevent their operation for long periods in air and difficulties in forming them into the complex shapes and poor resistance to thermal shock make non-refractory electrodes a preferred alternative where possible.

The most widely used non-refractory electrode material has been copper. Silver electrodes have been used in air (Boatright et al, 1964), and are reported to result in an increase in electrode life of about three times compared with oxygen free copper electrodes used under similar conditions. The arc heaters used in the manufacture of acetylene in the Hüels process (Gladisch, 1962), originally used copper electrodes but iron is now used without excessive erosion occurring with a considerable saving in cost. Use of a non-refractory material for the cathode requires some means of moving the arc root to prevent excessive local heating at the cathode surface. The interaction of an arc with a transverse magnetic field has been used to move the arc roots at high velocities over the electrode surfaces to prevent local overheating. If the velocity is sufficiently high the temperature of the electrode surface at the arc roots may be considerably less than the melting point of the electrode material (Phillips, 1964). Under these conditions the main cause of physical erosion may be due to sputtering (Holm, 1949, Pearce, 1959), or the transfer of potential energy from excited atoms (von Engel & Arnold, 1960). Under these conditions it may be possible to use phosphorous de-oxidised copper rather than oxygen free copper or even phosphor-bronze despite the lower thermal and electrical conductivities, without significantly increasing the erosion rate. This appears to have been done since there is no mention in any of the work encountered of copper of any special quality being used except for Boatright et al (1964) who used oxygen free copper. The lower rate of erosion obtained by Boatright with silver electrodes may have been due to the arc velocity (which was not specified) being insufficient to prevent melting of the electrode surfaces in which case the value of thermal conductivity would be expected to have an appreciable effect on the erosion rate. The configuration used was however similar to that used by Mayo and Davis at axial magnetic flux densities of 1.2 Wb/m^2 to 1.5 Wb/m^2 and arc currents of 1,200A to 1,600A. Comparison with other results (Phillips, 1964), indicate that this is unlikely but with a rod and tubular electrode configuration the arc root may anchor on the end of the rod. (See also section 4.2.4.). In this position the axial magnetic field has a reduced effect on the motion of the arc root and at the resulting lower root velocities the effects of thermal and electrical conductivities may be significant.

Copper electrodes, in particular copper cathodes have been used mainly with air as the heated gas. Chemical combination to form copper oxides does not appear to be severe and it is likely that once a layer of oxide has been formed further oxidation occurs slowly. The presence of an oxide layer assists the maintenance of a stable arc, and where gases other than air are used it may be desirable to pre-oxidise the arc electrodes (Doan & Myer, 1932).

Porous anodes have been used in preliminary experiments (Sheer et al, 1964). These would have particular advantage for arc devices used for space propulsion since the gas to be heated also serves to cool the anode. The increase in efficiency obtainable would however appear to be outweighed for industrial applications by the high gas pressure and increased complexity even if reliability and erosion rates comparable with water cooled non-porous electrodes were obtained.

3.4. Gas Vortex Stabilisation.

Gas vortex stabilisation obtained by injecting the gas tangentially into the body of the plasma torch has several effects.

1. The arc is stabilised by constraining its axial position (King, 1964), and by discouraging the arc column from shunting itself on the walls of the nozzle.
2. The point of attachment of the arc on the electrodes is rotated so that local heating and heat losses at the electrode surfaces are reduced.
3. The increased axial convection due to the gas flow results in an arc column of smaller diameter with a higher axial voltage gradient and a higher radial temperature gradient (Braun, 1963). By preventing shunting of the arc column a longer arc is obtained enabling higher arc voltages to be used.

Gas vortex stabilisation has been quite widely used at low power levels less than 1MW for stabilising d.c. arcs used as spectroscopic light sources (Katz et al, 1960), and for cermet spraying (Jones & Griffiths, 1963). Gas vortex stabilisation has also been used in arc heaters for space research applications in conjunction with movement of the arc root by a magnetic field. (See also 3.2.5.).

No measurements of the rotational velocity of the gas or arc (which are not necessarily equal) have apparently been made in a vortex gas flow. The velocity will normally be considerably less than that obtainable by using a magnetic field which can be greater than 100 m/s. The principal advantage of vortex stabilisation lies in the axial stabilisation of the arc between axial electrode configurations. Where a radial arc configuration is used vortex stabilisation may be undesirable.

3.5. Movement of an Arc in a Plasma Torch by a Magnetic Field.

Magnetic movement of the arc in a plasma torch by the interaction of the perpendicular components of the arc current and external or self magnetic field normally enables faster rotational speeds to be obtained than with a gas vortex. The increased arc velocity also results in increased convective heat losses and a higher voltage gradient in the arc column. Unlike the effect of vortex gas-flow the arc is not constrained in a particular position or prevented from shunting on adjacent conducting electrode walls. Quite the reverse may happen the arc taking up involute and other unstable shapes (Adams, 1964), and frequent shunting of the arc column may occur.

The use of a.c. arc supplies makes rotation at high velocities essential as both electrodes are normally made of copper and excessive evaporation at the electrode surfaces and in particular the cathode would otherwise occur.

Magnetic movement of an arc may be obtained using the self-magnetic field due to the arc current in each electrode in the same way as it is used with self-driven arcs on rail electrodes. Alternatively a separate external magnetic field may be used with continuous electrodes.

The self magnetic field has been extensively used in re-entry simulation where the high arc currents used normally in excess of 1,000A enable high arc velocities to be achieved in this way. The magnitude of the self magnetic field will decrease with distance of the arc from the electrodes. This is not the most effective region if the arc is in the column dominated mode. (See also 2.4.1.).

Rotation of the arc in a plasma torch has been obtained with an external field coil and continuous co-axial ring and square electrodes described in 3.2.5. Fig. 3.7. (Bunt & Olsen, 1961(a),(b). The self magnetic field with gapped electrodes 2.54 cm diameter were also used at currents up to 20×10^{3} A, at which the flux density at the electrode surface was 3.1×10^{-2} Wb/m^2. Self magnetic fields have also been used to rotate the arc using single phase and three phase three electrode a.c. electrode systems (Winkler et al, 1964). The arc was found to cross the circumferential discontinuity in the ring electrode provided it was small of the order of 0.1 cm but at larger spacings the arc halted at the gap and damaged the electrodes.

External magnetic fields have also been used in several different configurations similar to those used with self-magnetic fields but without the discontinuity in the electrode. Higher values of magnetic flux density at the centre of the electrode gap and the arc current, can be obtained independently of the arc gap. Values of up to 0.1 Wb/m^2 are normally used but magnetic flux densities of up to 2 Wb/m^2 have been used. (Mayo & Davis, 1962).

At moderate electrode separations of the order of 1 cm at which the movement of the arc tends to become column dominated the arc velocity is affected more by the field at the centre of the arc gap (Spink & Guile, 1965), where the effect of the self-magnetic field due to the current in the electrodes is least. If an external field coil is used the magnetic field may be controlled independently of the arc current so that the magnetic flux density and arc current may be varied separately. ~~This apparently has not been done.~~

If the field coil is connected in series with the arc or the self-magnetic field of the arc current is used some measure of self-stabilisation might be expected. A rise in arc voltage causes the arc current and magnetic flux density to decrease. Under these conditions the arc velocity will fall and the arc voltage will tend to decrease restoring the original operating point. This has not been reported although it may be inferred from the results of Mayo and Davis. An increase in arc stability was obtained with a series connected field coil but was attributed to the arc becoming diffuse.

External magnetic fields have generally been supplied with d.c. and used with d.c. arcs. Self magnetic fields have been normally used with a.c. arcs so that an a.c. magnetic field in phase with the arc current is obtained although a d.c. field supply has been used with an a.c. arc (Phillips, 1964). No report of an external a.c. field being used with an a.c. arc has been found although it might be expected that the elimination of the separate d.c. power supply might be desirable. If the field and arc currents are in phase, the magnetic flux density will be low when the arc current is small. The arc velocity and voltage would vary with the arc current and the variation in arc voltage might be expected to be more nearly sinusoidal.

The shape of a rotating arc between co-axial electrodes in still air at atmospheric pressure over a range of arc velocity of 40 m/s to 140 m/s has been studied (Adams, 1964). An involute shape was normally obtained except at small electrode separations less than 2 cm., when it became approximately radial. It is therefore likely that the combined effects of the gas flow and rotational arc movement will cause the arc to take up a highly irregular shape. As a result the arc will move round the arc gap in an unpredictable manner leading to considerable differences between predicted and actual behaviour.

The effect of the magnetic field at the arc root will be unchanged if the arc root is confined to the region of the electrodes perpendicular to the axial magnetic flux density. This can be obtained with parallel tubular electrodes with insulated ends or with self driven arcs. If the arc is in the cathode root dominated mode little change in arc velocity is likely to occur.

3.6. Arc Stability and Re-Ignition in the Plasma Torch.

Arc stability has already been considered in 2.3. For continuously operating devices stability has two implications

1. Arc interruption (the extreme case of instability).
2. Fluctuation in arc voltage, current, and power input.

The electrode separation is normally fixed in a plasma torch unlike some continuously operated arc devices such as arc furnaces. For continuous operation a separate re-ignition mechanism may be necessary unless the arc voltage is sufficient to break down the arc gap at the minimum electrode separation as in the Birkland-Eyde and Hüels torches where the open circuit voltage is several thousand volts.

D.C. Plasma torches used for laboratory and metallurgical applications which operate from lower voltage supplies, typically of 100V to 200V open circuit voltage, use separate manually controlled high voltage capacitor discharge systems to ignite the arc.

The arc heaters used for re-entry simulation for short times generally less than one minute normally rely on the vapourisation of a fuse wire across the electrodes to ignite the arc with no provision for re-ignition (Boldman, 1962). Three-phase electrode systems, particularly four electrode arrangements will in any case be inherently more stable than d.c. or single phase d.c. systems as there is normally more than one arc present.

The stability of an arc is improved by increasing the resistance or inductance if a.c. is used in series with the arc supply. The wasted power or increased kVA is acceptable in low power d.c. torches used for spectroscopy and metallurgical processes for high cost products, and ratios of open circuit to arc voltage of 4:1 or more may be used (Okada et al, 1960).

The power consumption of the larger arc heaters used for re-entry simulation is such that unnecessary power or kVA losses are inconvenient because of unwanted power dissipation and increased capital cost. A d.c. battery supply with an open circuit voltage of 2,400V and a current of 32kA has been reported (Bunt et al, 1966). The normal operating conditions were at about 1,000V and 1,000A resulting in an unwanted resistive power dissipation of 14MW. The problem of power dissipation in stabilising the arc is not as important when a.c. or rectified a.c. is used since the required voltage drop may be obtained with an inductive reactor. Under such conditions the ratio of open circuit to arc voltage may be up to 10:1 (Maniero, 1966) with a corresponding power factor of about 0.1.

3.7. The Measurement of the Thermal Properties at the Outlet of a Plasma Torch.

The thermal properties of the heated gas obtained from a plasma torch that are of most interest are the temperature and the specific enthalpy of the gas at the torch outlet. Since we are concerned mainly with the production of a heat source for high temperature processes the lowest temperature of interest is taken as 1,000°c below which alternative contamination free heat sources are available. The upper limit extends to at least 26,000°c(King & Jordan, 1964).

At the lower temperature limit platinum resistance thermometers, although normally used only up to 300°c may be used up to 900°c (Kostowski, 1962). The relatively bulky nature of the resistance element which is usually sheathed results in a relatively slow response time and mean values, both time and spatially integrated will be obtained in this way. The introduction of a probe into a region in which high temperature gradients exist will also affect the local temperature distribution and gas flow.

Thermo-couples can be used up to considerably higher temperatures and some examples of high temperature thermo-couple materials together with their maximum continuous operating temperatures are given below in Table 3.2.

Table 3.2.

Maximum Continuous Operating Temperatures for Various Thermo-Couple Materials (Kingery, 1959).

Material	Maximum Continuous Temperature °c.	Limiting Conditions of use.
Pt-20%Rh/Pt-40%	1,880	None
Ir/Ir-40%Rh	2,300	None
W/W-Rn	2,800	Reducing Atmosphere

Silicon carbide/graphite thermo-couples have been used but are unstable and can only be used in a limited range of conditions. Thermo-couples can normally be made smaller than platinum resistance thermometer elements and may also be used unsheathed. Due to their finite size they will still only indicate mean values but have the advantage that they may be used for direct measurement.

Sampling methods have been used(Raezer & Olsen, 1962), for the measurement of temperatures in excess of the melting point of the thermo-couple and the maximum permissible temperature of operation has been extended in this way by about four times (Tschang, 1966). These methods rely on the rate of rise of temperature of a probe placed for a short time in the heated gas stream which can be deduced if the dwell time in the gas stream and the maximum probe temperature are known. Since the time spent in the heated gas stream is short and frequently of the same order as the time taken to move in and out of the gas stream,this method is liable to appreciable errors which are difficult to compensate for. The probe will also disturb the temperature gradient and gas flow and the value obtained will be a time and space integrated value. Relative values obtained in this way may have some value for comparative purposes.

Optical pyrometers of the disappearing filament type which measure the monochromatic brightness of a heat source of known emissivity may be used above about 1,500^{o}c but the estimation of the co-efficient of emissivity may lead to appreciable errors. Total radiation pyrometers are more affected by this but have the advantage that once they are calibrated they may be made self-indicating and the voltage output may be used for control purposes. The response time of both methods is of the order of 0.1s to 1s and since a finite sighting area is required the values obtained are mean values. Total radiation pyrometers can be used from temperatures of about 700°c upwards with no apparent upper limit although calibration may be difficult at very high temperatures.

All the methods of temperature measurement discussed up to now give time and space averaged values of temperature due to the finite size of the probe or sighting area required. In addition they may be subject to large errors if exposed to direct radiation from the arc in which case the true gas temperature is not obtained. The temperature distribution in the region of an arc or plasma jet, particularly if operated from an a.c. power source, may be highly non uniform and vary rapidly with time. Measurements of temperature obtained in this way require careful interpretation, since the mean value obtained may have little or no real significance. Spectroscopic measurement of temperature enables temperatures above 3,500°c to be determined (Hill, 1962). If a spectrophotometer is used measurements may be made in very short times over very small regions so that the spatial variation of temperature may be determined (King & Jordan, 1964).

The mean temperature and enthalpy of the total gas output only are required for many engineering applications. The mean temperature may be determined using a calorimeter from which the mean specific enthalpy of the heated gas can be obtained if the gas flow rate is known. The variation of specific enthalpy with temperature has been determined for most gases and a mean value of temperature can be deduced from this. At low and medium power inputs continuous flow calorimetry is practical whereas at very high powers intermittent techniques may be required. A similar method to that used in the intermittent thermometer has been used to measure heat transfer rates at the outlet of a plasma torch (Stokes et al, 1960), using a large probe so that a mean value is obtained. If the probe is large enough to be in contact with most of the heated gas the results are likely to be more accurate than the measurements of temperature obtained in this way since it is the mean value that is required.

Calorimeter measurements will themselves be subject to radiation errors even at moderate temperature rises above the ambient temperature. These can be reduced to a minimum by minimising the external surface area of the calorimeter and allowing only a small temperature rise above ambient to occur.

3.8. Summary of Results Applicable to a Plasma Torch for Industrial Process Heating.

Electrode Materials.

Refractory and low melting point electrode materials have been used. Refractory electrodes usually tungsten are normally used as cathodes in d.c. plasma torches where the comparatively low current density at the cathode spot, good stability, oxidation resistance and low erosion rate make them suitable for use at medium currents with non-oxidising gases. If oxidising gases are used materials such as zirconium oxide should be used. Copper is almost invariably used as the anode material to enable the heat flow at the anode root which is larger than at the cathode to be dissipated.

If a.c. is used the thermal conductivity of refractory materials is insufficient to conduct the heat dissipated at the anode resulting in rapid evaporation. An axial magnetic field may be used to move the arc roots over the electrode surfaces but if used with refractory electrodes at high velocities the emission at the cathode may change~~s~~ to the cold cathode mode. For operation from a.c. it is desirable to use the same material for both electrodes. A material with a high enough thermal conductivity to enable conduction of the heat away from the electrode roots without excessive evaporation of electrode material occurring is required. This limits the choice of materials to the high conductivity metals such as copper, silver and aluminium which operate in the cold cathode mode. In order to prevent excessive evaporation at the cathode due to the increased power density at a cold cathode it is necessary to move the arc rapidly over the electrode surface.

Electrode Configuration.

The electrode configuration used is governed by the exit conversion efficiency and the required temperature and enthalpy of the heated gas. For normal industrial processes of the type envisaged here the very high temperatures that are obtainable with convected and constricted arcs are unlikely to be required. A range of operation with an upper limit of 5,000^{o}c and a lower limit of 1,000^{o}c, below which resistive heating may be used, has been chosen. A constricted arc is therefore not required for this purpose although it may be necessary for arc stability.

The measured efficiency obtained with constricted arc torches varies over a wide range for similar conditions. Possible sources of error leading to values of efficiency higher than the actual values have been shown. An unconstricted radial arc is likely to be more efficient and suitable for industrial heating processes than an axially constricted arc. Values of efficiency obtained with multiphase electrodes are normally lower than single phase systems due to the larger area of cooled electrode surfaces in close proximity to the heated gas. No report of a systematic measurement of efficiency has been found for a.c. torches and no attempt to verify efficiency measurements by obtaining a thermal balance has been made.

Arc Movement.

The arc velocities obtainable with gas vortex stabilisation have apparently not been measured but appear to be considerably less than velocities easily obtainable using transverse magnetic fields to rotate the arc. Self-magnetic fields eliminate the need for additional power supplies and field coils but are only effective at high arc current and the effect of varying the magnetic field independently of the arc current cannot be obtained. No mention of the use of separate a.c. field coils with an a.c. arc has been made but the problem of synchronising the arc and field current appears formidable.

No indication of the optimum magnetic flux density, arc velocity or frequency of rotation has been found although the general tendency has been to progressively increase the magnetic flux-density. The majority of investigations have been carried out below $0.1\ Wb/m^2$ but results obtained in one case at up to $2\ Wb/m^2$ indicate that substantial improvements in the arc behaviour are achieved at these high magnetic fields.

Supply Voltage and Arc Stability.

The use of a. c. power supplies with high open circuit voltages to enable ignition and breakdown of the arc gap after current zero and low arc voltages results in low power factors and increased running and capital costs. Relatively low open circuit voltages in conjunction with an auxillary ignition system would seem to be the best compromise but no mention of this has been found.

No indication of optimum values of series stabilising impedances has been found. In arc furnaces typically the ratio of open circuit to arc voltage is 2:1 but ratios of up to 10:1 have been used with plasma torches.

Measurement of Temperature, Enthalpy and Efficiency.

The spatial variation of the temperature in the heated gas at the outlet of the plasma torch has been measured spectroscopically. The results appear to be of little value to the engineer who requires measures of real factors which will influence the process to be carried out. The nearest approach to this is a spatial and time averaged mean value which can be obtained using a calorimeter . Mean values are not necessarily obtained using probes which may also disturb the conditions in the heated gas stream. Transient probe techniques introduce further uncertainties due to the time spent passing through the gas.

The differences obtained in the measurements of efficiencies indicate the need for thermal balance methods so that all the heat dissipated can be accounted for. The measurements of efficiency that have been reported for plasma torches with constricted nozzles appear to be unreasonably high.

CHAPTER 4.

Preliminary Investigations.

The purpose of the preliminary investigations was to determine the areas in which further research was required by determining the main factors which influenced the plasma torch behaviour. A plasma torch was built and tested under various conditions in order to establish these factors.

4. PRELIMINARY INVESTIGATIONS.

Much of the work reviewed in Chapter 3 was published during the course of this investigation. Little information was available on a. c. torches most information being of a qualitative nature on the d. c. plasma torches used for metal cutting and spraying. As a result the initial investigations were carried out on a d. c. torch similar to those that were already in use at the time.

The progress of the investigations is illustrated in Fig. 4.1. A low power d. c. plasma torch, described in 4. 1.1, was constructed first to obtain familiarity with the device and its operation. The electrical characteristics in particular are easier to measure and analyse when d. c. is used providing a basis for analysis when operated from a. c. The plasma torch was then converted to a. c., described in 4. 2., which is inherently more difficult to operate and analyse.

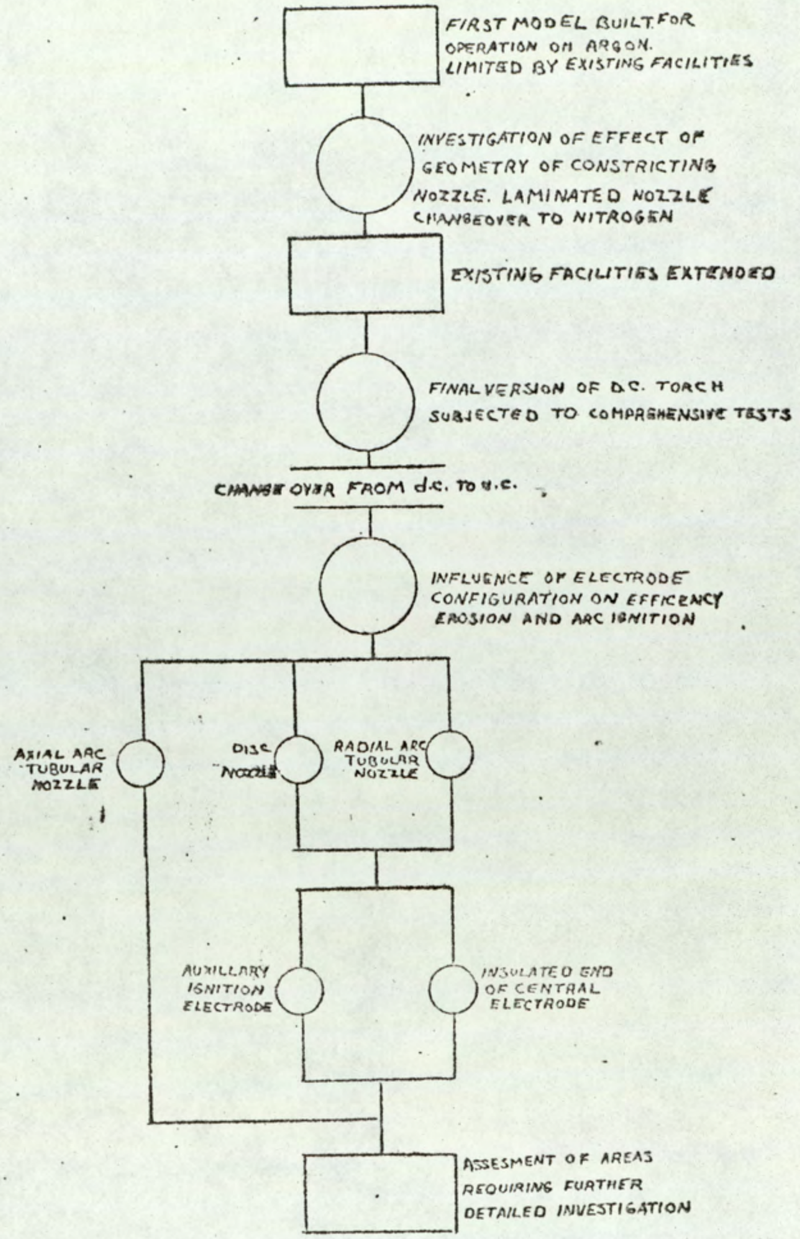
The main parameters of interest were the lifetime of electrodes before erosion became excessive, the influence of the nozzle shape and gas flow-rate on the overall behaviour of the torch, and the conversion efficiency of the torch in terms of losses directly to the arc electrodes.

$$\eta = \frac{W_{IN} - W_L}{W_{IN}} \times 100\% \qquad (4.1.)$$

where η = conversion efficiency (%)

W_{IN} = electrical input power to arc

W_L = power losses in plasma torch



PRELIMINARY INVESTIGATIONS

FIGURE 4.1.

The scaling up of the plasma torch, which presents problems due to increased electrode evaporation at higher arc currents was one of the first requirements, rather than to investigate in detail the behaviour of the torch. Many of the initial measurements were necessarily restricted in their range by the power facilities and instrumentation available at the time.

4.1. Initial Design Considerations.

The initial design conditions were difficult to formulate as so little data of any kind was available. The two main conditions which influence the nozzle design are

(1) The highest gas flow-rate corresponding to the lowest mean gas temperature.

(2) The lowest gas flow-rate corresponding to the highest mean gas temperature.

If a sub-sonic nozzle is used as is normal practice the highest gas flow-rate is limited by the gas flow at sonic velocity.

i.e. $\dot{m} = a' u_0 \rho$ (4.2)

where a' = area of nozzle at which the velocity is sonic (m^2)

u_0 = sonic velocity (for the conditions in the nozzle) (m/s)

ρ = density of gas where the velocity is sonic. (g/m^3)

This is normally satisfied and the conditions at minimum gas flow-rate have more effect on nozzle design.

The effect of the nozzle is to constrict the arc due to the proximity of the cooled walls, the increased convection losses from the arc column and the higher local pressure.

The voltage gradient in the arc column may be expressed

$$E = f\left(\frac{1}{d}\right), g(u), h(P) \qquad (4.3)$$

where f, g and h are functional relations

d = diameter of constriction

u = gas velocity

P = gas pressure

and $U \overset{\bullet}{\propto} \frac{1}{d^2}$ (4.4.)

below sonic velocity

The voltage gradient is difficult to predict due to its dependence on the electrode geometry. Depending on the relative effects of constriction ~~and~~ convection and gas pressure, the voltage gradient in the arc column may be increased from 10 V/cm to 500 V/cm (King,1964). If the effect of radial constriction is due to radial gas flow the voltage gradient varies between 10 V/cm and 100 V/cm.

The minimum gas flow-rate is governed by the highest temperature required. The gas temperature is given by

$$W\eta = \int_{T_1}^{T_2} \dot{m} C \, dT \qquad (4.5.)$$

and

$$\dot{m} = AU\rho \qquad (4.6.)$$

where W = electrical power input (W)

η = conversion efficiency

$\dot{m}$ = gas flow-rate (g/s)

T_1 = initial gas temperature (^{o}c)

T_2 = final gas temperature (^{o}c)

C = thermal capacity of gas (j/g^{o}c)

A = area of nozzle at outlet (cm^2)

U = velocity of gas at outlet (m/s)

ρ = density of gas at outlet. (g/m^3)

The efficiency is affected by the proximity of the nozzle walls (constriction loss) and by the time taken in passing through the nozzle.

i.e. The containment loss

$$X = f\left(\tfrac{1}{d}\right), g\left(\tfrac{1}{t}\right) \qquad (4.7.)$$

where f, g are functional relations

t is the effective time during which losses occur to the nozzle

i.e. $t \geq t_r$

$$t_r \propto \frac{1}{U} \propto d^2 \tag{4.8}$$

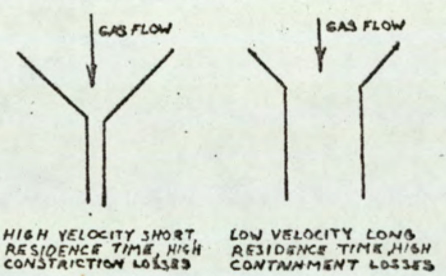
t_r = residence time in nozzle.

And the efficiency (ignoring losses at arc roots)

$$\eta = f(d), g\left(\frac{1}{d^2}\right) \tag{4.9}$$

or in terms of the gas velocity

$$\eta = f\left(\frac{1}{Ut}\right), g(U) \tag{4.10}$$



The Effect of Nozzle Diameter on Losses to Nozzle

Figure 4.2.

The two extreme conditions are illustrated in Fig. 4.2.

The effect of reducing the gas flow-rate may therefore not increase the gas temperature but only increase the losses to the nozzle. For a given gas flow-rate an optimum value of gas velocity or nozzle diameter exists at which the efficiency is a maximum. The lowest efficiency will occur at the lowest gas flow-rate at which the maximum temperature will normally be required.

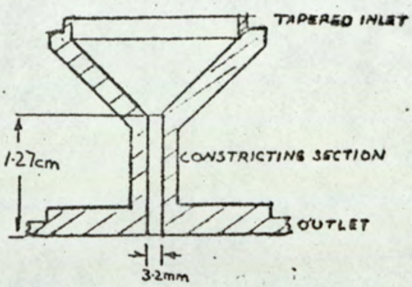
To obtain the maximum temperature required

$$\frac{d\eta}{d\dot{m}} \leqslant \frac{d}{d\dot{m}}\left(\frac{W}{\dot{m}}\right) \tag{4.11}$$

It is difficult to estimate the variation of efficiency with gas flow-rate which can normally only be determined by experiment. One of the functions of the preliminary tests was to determine this condition.

4.1.1. The D.C. Plasma Torch.

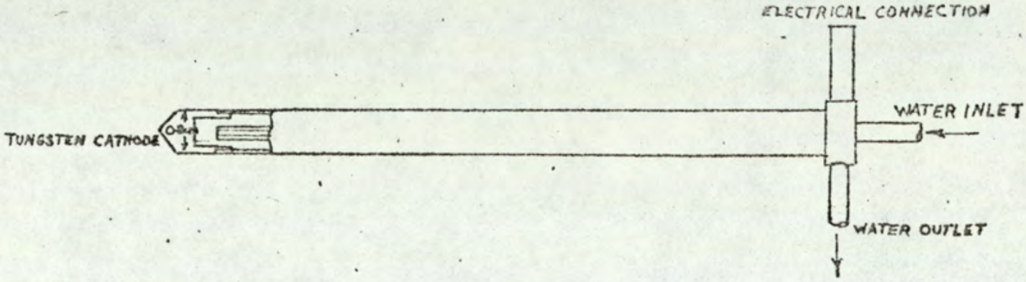
The first version of the plasma torch was designed so that the nozzle dimensions could be easily changed. The nozzle shown



The Nozzle.

Figure 4.3.

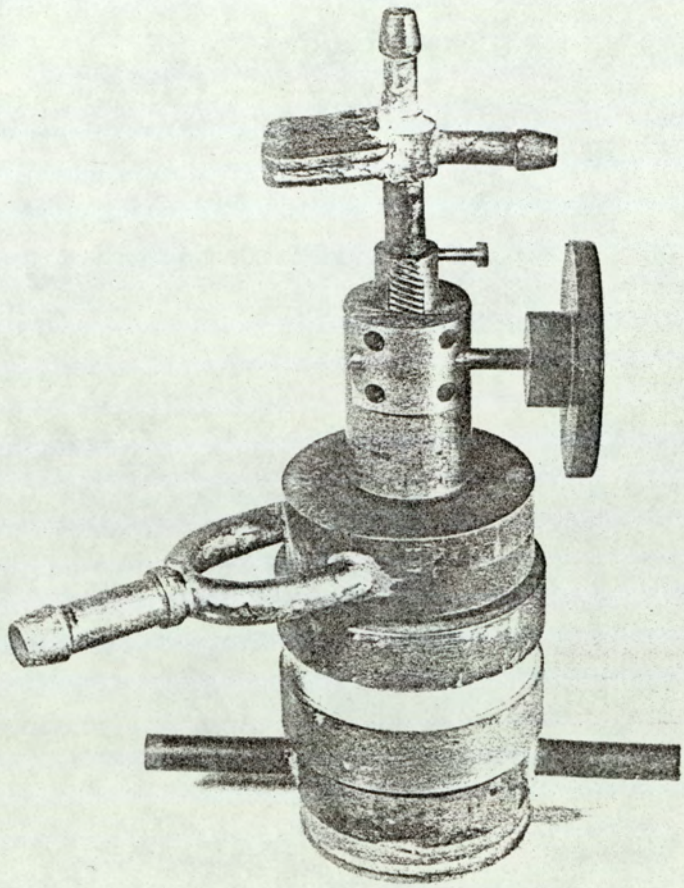
in Fig. 4.3. was copper and consisted of a tapered inlet followed by a parallel constricted section. The nozzle screwed into a water cooled chamber in the body of the torch with O ring seals at the joints. The complete torch which is shown in Fig. 4.5.



The Central Electrode.

Figure 4.4.

The central electrode shown in Fig. 4.4. consisted of two co-axial stainless steel tubes to allow water cooling of the tungsten



The First D. C. Plasma Torch.

Figure 4. 5.

cathode which was silver soldered into the end of the outer stainless steel tube. The central electrode was held in a sleeve in a rack and pinion which allowed axial variation of the position of the central electrode for igniting the arc. The axial separation of the cathode from the anode was measured with a micrometer head mounted above the cathode, a zero reading being obtained with the electrodes touching. The top of the torch acted as a plenum chamber, the gas flowing from the top of the torch into the body of the torch through a ring of axial outlets which helped to maintain a uniform gas flow in the torch. The electrodes were separated by a ceramic insulator which formed the body of the torch.

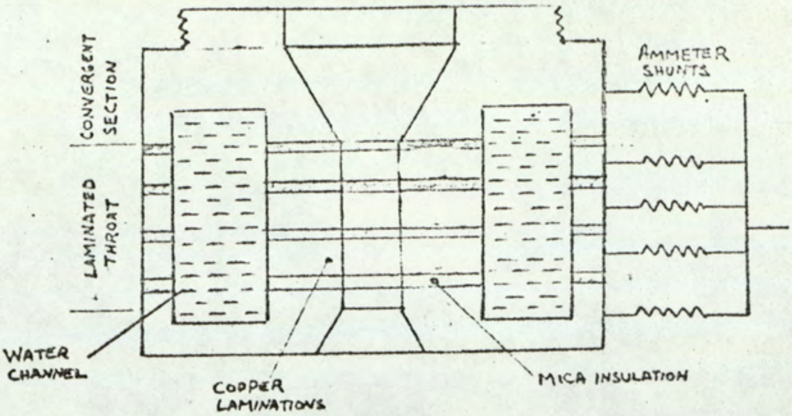
In order to investigate the behaviour of the arc in the nozzle two possible methods were considered.

1. Optical observation by cutting an axial slit in the wall of the throat.
2. Electrically by measuring the current in various sections of the throat.

Both methods suffer from the disadvantage that they alter the normal operating conditions in the nozzle. The effect of the axial slit is likely to be greater than the thin insulating layers required to separate the throat sections.

The current in various sections of the nozzle was therefore measured using a nozzle with a laminated body.

The laminated nozzle is shown in Fig. 4.6.



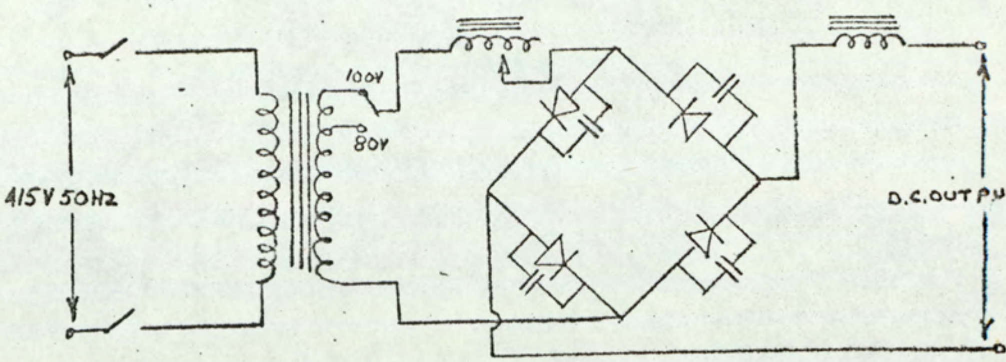
The Laminated Nozzle.

Figure 4.6.

The copper laminations were insulated from each other and from the end with pieces of natural mica 0.01 mm thick. Separate connections were made through ammeter shunts to each lamination and the current measured in each lamination with a moving coil ammeter. The inlet side of the nozzle was arranged so as to screw into the torch body.

4.1.2. The Power Supply and Instrumentation.

The power supply consisted of a switched output welding transformer with a separate rectifier unit shown in Fig. 4.7.



D. C. Power Supply.

Figure 4.7.

The arc current and voltage were measured with moving coil instruments and the gas pressure at the inlet to the torch was measured with a Bourdon tube pressure gauge.

4.1.3. Variation of Electrical Characteristics and Influence of Nozzle Design at Low Gas Pressures.

The first tests carried out on the torch used argon. Highly stable and quiet operation is obtained with argon as it is a monatomic gas and needs less energy for ionisation than a polytomic gas which is dissociated before ionisation can take place. Argon is however costly and is unlikely to be used for a large scale process of the kind envisaged.

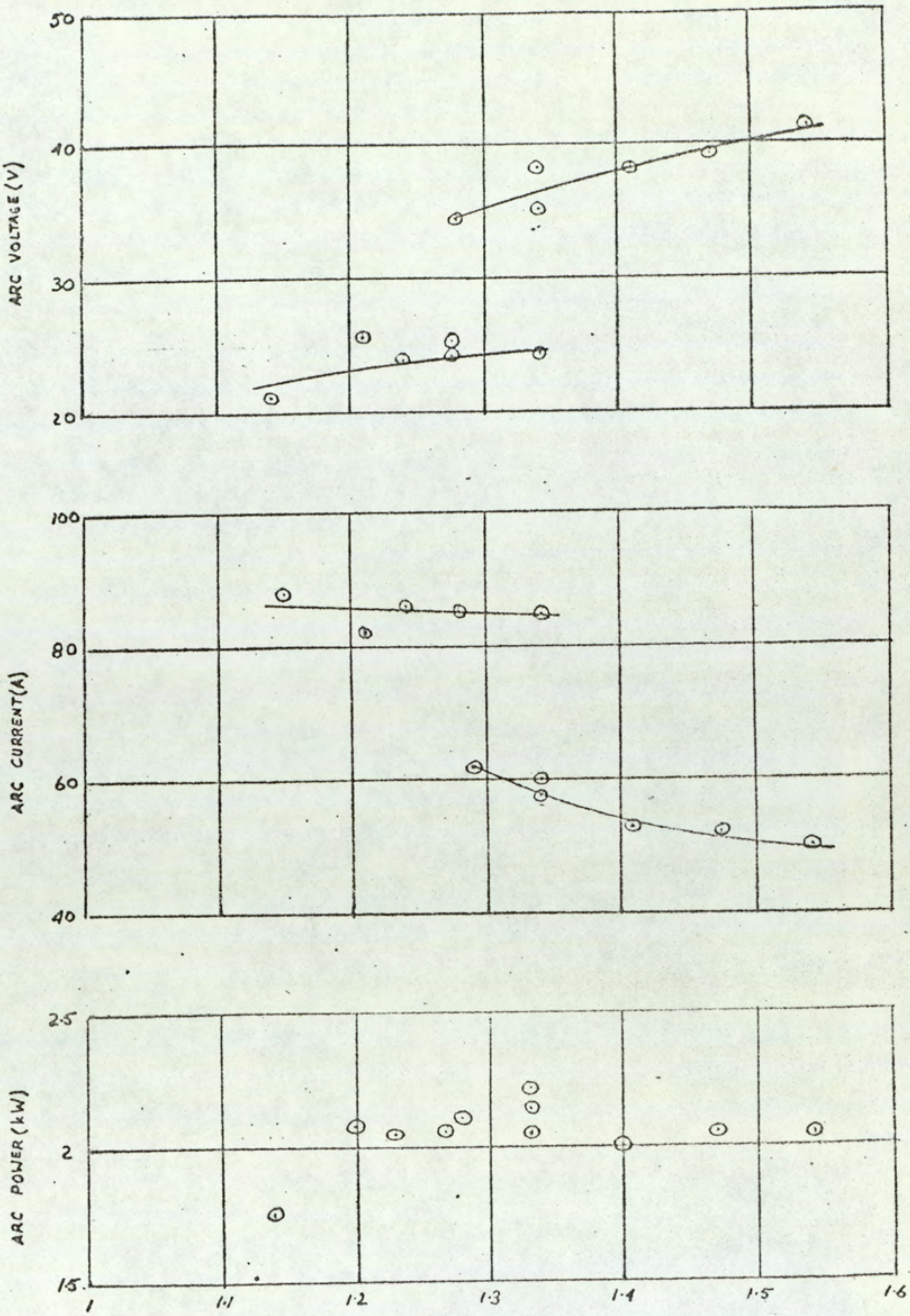
Subsequent tests used nitrogen, as the behaviour of a medium or long arc in nitrogen is similar to that in air (King, 1961), without the disadvantage of oxidation of the electrodes occurring. For most industrial processes air is likely to be the cheapest gas to use provided that it does not have any harmful metallurgical or chemical effects. If this occurs nitrogen is a likely second choice. An arc behaves in a similar way in nitrogen and air and a change from nitrogen to air could be made if required at a later date whilst still allowing many of the results for nitrogen to be applied. The behaviour in nitrogen was quite different from that in argon being generally unstable and more noisy and the maximum electrode separation possible was reduced. This is due to the greater energy required to obtain the same degree of ionisation with a polytomic gas.

The effect of the angle of taper of the inlet taper to the nozzle and the tip of the central electrode were investigated. The angle of convergence of the nozzle inlet and the tip of the central electrode were varied separately from 30^{o} to 60^{o} with no apparent change in the electrical parameters or other behaviour of the torch. (Tests described later showed that the arc was normally contained inside the nozzle throat. Subsequent tests were carried out with an angle of 45^o for both central electrode and the nozzle inlet.

The electrical characteristics of the plasma torch as a function of gas pressure in nitrogen with the electrode separation, supply voltage and series resistance constant are shown in Fig. 4. 8. The arc voltage may be regarded as the independent variable and is of most interest. The series impedance is approximately constant so that the current decreases with increase in arc voltage and the power input is almost independent of the gas flow-rate.

There is a distinct transition between the behaviour of the arc at gas pressures above and below about 1. 25 Atm. Below about 1. 25 Atm the luminous gas at the outlet of the nozzle formed a regular shape similar to the flame of an oxy-acetylene burner with the characteristic golden yellow colour which has been associated with active nitrogen (Strutt, 1916), several centimetres long and accompanied by a high pitched whistle. At gas pressures above 1. 25 Atm, the flame became much shorter and turbulent and was accompanied by the low pitched fluctuating noise typical of medium and high current arcs. The transition did not occur exactly at 1. 25 Atm and the pressure at which the transition from laminar to turbulent flow occurred could be raised to about 1. 5 Atm if the pressure was increased slowly, in a similar way to the transition from laminar to turbulent flow of water in a pipe with increasing water flow-rate.

The long laminar jets at low gas flow-rates have been attributed to the self-pumping action of the plasma jets (Reed, 1963). Jets of luminous gas 90 cm long in the laminar mode with a power input of 15 kW in air have been reported (Moss & Young, 1964). The



VARIATION OF ARC VOLTAGE, CURRENT AND POWER WITH GAS PRESSURE

FIGURE 4.8

heated gas was not specified. The pumping action of the plasma jets may explain the production of a laminar jet but does not explain the considerable length that has been obtained at quite low power inputs at which the heat losses might be expected to prohibit the formation of a long jet.

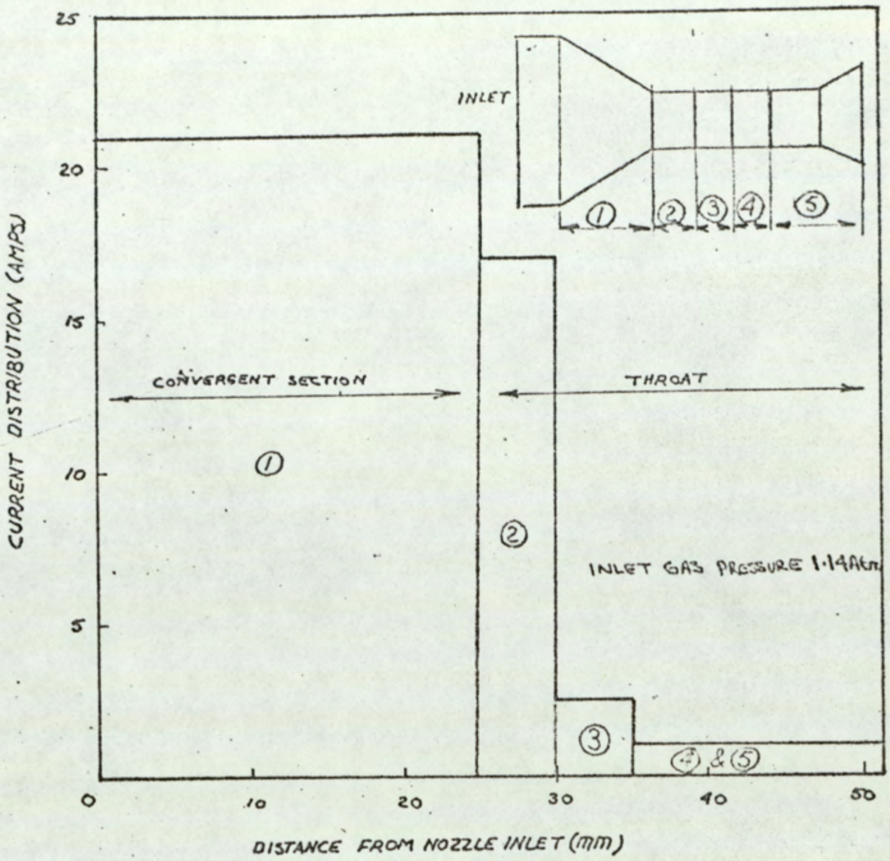
A more likely explanation is the presence of active nitrogen either in the heated gas or at the outlet of the nozzle when discharged into air. Nitrogen has a metastable state in which it can remain excited for considerable periods at low pressures. When the excitation energy is given up it gives off the characteristic golden yellow which was observed with the laminar jet. At atmospheric pressure in air the lifetime is less but is still sufficient to observe it as a jet when active nitrogen was discharged from a vessel into air at atmospheric pressure (Strutt, 1916). The length of the jet, unlike ionised gas, will be independent of thermal losses and depend only on the rate of de-excitation which will be influenced by impurities. If the gas flow is laminar little mixing will occur and a long jet may be produced. If the gas flow is turbulent mixing will occur causing rapid de-excitation and a short flame length. The onset of turbulence has been attributed to constriction of the arc in the nozzle when it was drawn into the nozzle at the higher gas flow-rates. (Moss & Young, 1964).

The current distribution obtained with the laminated nozzle is shown in Fig. 4.9. At the gas pressure used the output jet was laminar. The current distribution indicates that even at these low gas pressures the anode root moves axially in the nozzle and extends at least 1 cm into the constricted section.

The total mean current in the convergent section

$$\sum i_{conv} = 21A \qquad (4.12)$$

and the total current in the constricted section



CURRENT DISTRIBUTION IN THE LAMINATED NOZZLE.

FIGURE 4.9.

$$\sum i_{cons} = 22A \tag{4.13}$$

The turbulent mode was accompanied by a higher arc voltage than in the laminar mode. This is due to the increased cooling of the column which may be caused by constriction in the nozzle or the development of a cored arc (King, 1957).

The arc voltage is apparently more dependent on the gas pressure in the turbulent mode, but the effect of the gas pressure over the range investigated is likely to be small. The voltage gradient E of the arc column is given by

$$E \propto P^n \tag{2.8}$$

and $n = 0.3$ for N_2

where P = gas pressure in Atmospheres.

The apparent increase in arc voltage with gas pressure observed is therefore more likely to be due to the increased effects of forced convection and constriction in the nozzle throat which occur at the higher gas flow-rate and increased gas pressure. By comparison when the output is in the laminar mode the arc voltage is almost independent of the gas pressure which is to be expected if the gas flow is insufficient to constrict the arc appreciably.

If a value for the sum of the electrode fall voltages of 25 volts is assumed and a voltage gradient of 10 volts/cm in the arc column, it is possible that the arc may remain within the inlet to the nozzle without being appreciably constricted or convected in the laminar mode.

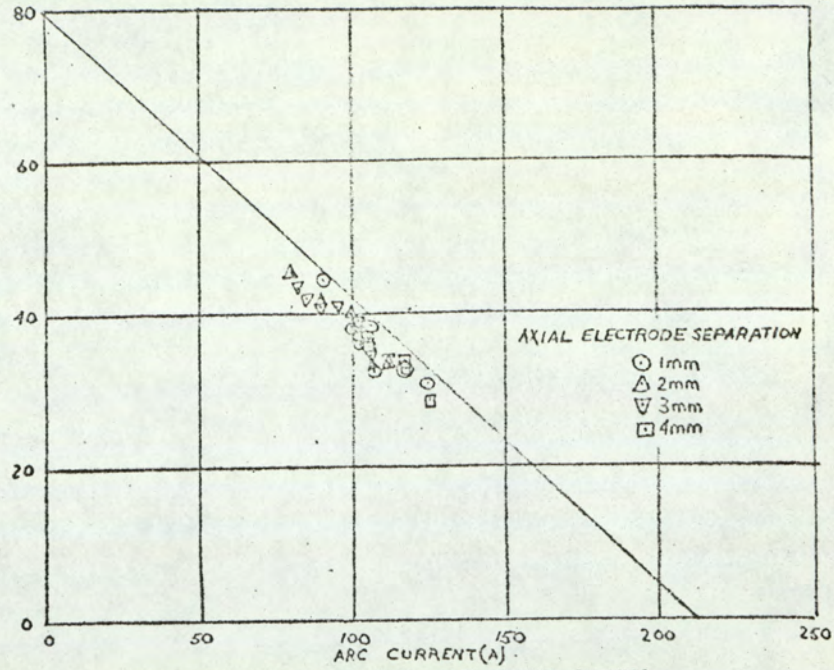
4.1.4. Variation of Electrical Characteristics with Gas Flow-Rate.

A flow-meter was now available so that gas pressure and flow-rate could be measured. Measurements were obtained as a function of gas flow-rate at the highest current obtainable which was kept at a constant setting. The load curve for this setting and the operating points is shown in Fig. 4.10.

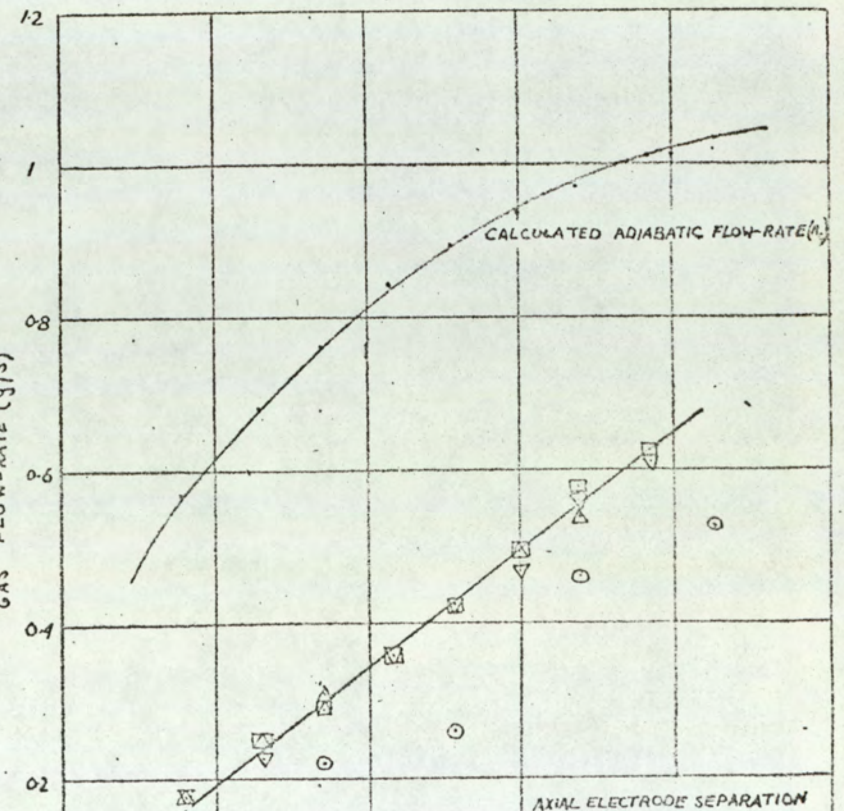
The stability of the torch is indicated by the regular distribution of the operating points below the load line.

The variation of the gas flow-rate with gas pressure (Fig.4.11) is approximately linear except for the electrode separation of 1 mm over the range investigated and is about half the adiabatic gas flow-rate calculated without the arc. The effect of the arc on reducing the gas flow-rate is very marked. At a separation of about 1 mm the gas-flow-rate is considerably below that obtained in the other tests probably due to choking of the nozzle by the cathode so that the gas pressure drop across it is increased for a given gas flow-rate.

The variation of arc voltage current and power with gas pressure and flow-rate are shown in Figs. 4.12 and 4.13 at various electrode separations. In all cases the minimum gas pressure used was above that at which the transition from laminar to turbulent behaviour occurred and the plasma torch output was turbulent in all the tests. It was not possible to reduce the gas pressure and flow-rate further as excessive erosion of the electrodes occurred at the higher value of arc current now used.



LOAD CHARACTERISTIC AND OPERATINGS POINTS
FIGURE 4.10



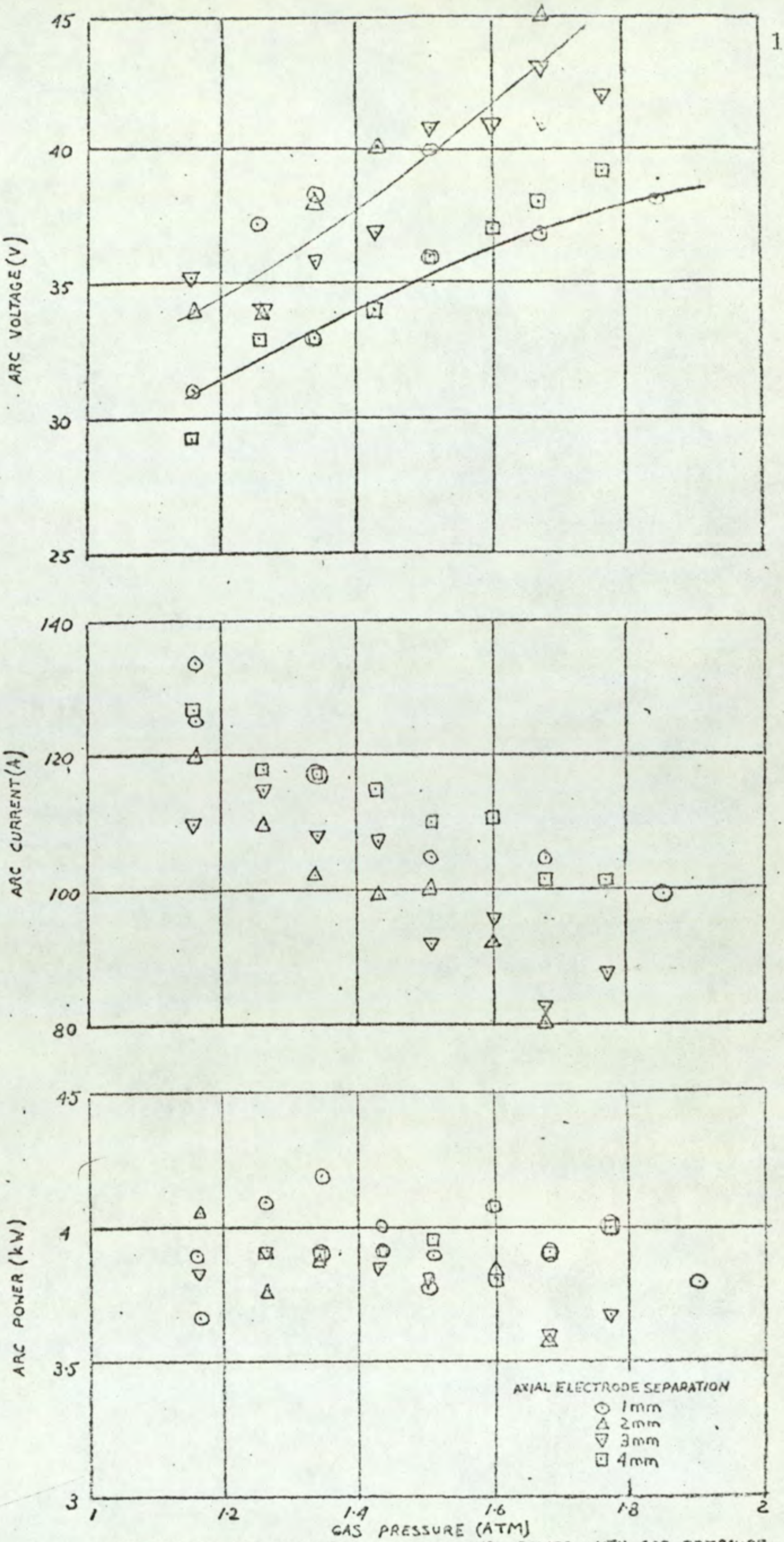
VARIATION OF GAS FLOW-RATE WITH GAS PRESSURE (N_2)
FIGURE 4.11

In general the readings obtained for arc voltage and current varied more consistently with the gas pressure than the gas flow-rate. During the tests it was observed that considerable fluctuations occurred in the gas flow-rate while readings were taken but the gas pressure remained steady. The fluctuations in the gas flow-rate are likely to be caused by movement of the arc column in the throat of the nozzle, particularly axial movement due to shunting of the arc column by the walls of the nozzle (Jordan & King, 1965). This movement is likely to result in considerable fluctuations in both the gas flow-rate and gas pressure which were apparently not even damped out by the gas in the torch body and the plenum chamber. The fine bore connection to the pressure gauge and the mechanical inertia of the movement of the gauge have a more effective damping action and account for the stable readings of pressure obtained. This was advantageous since it was consistent with the other measurements which were also mean values. The measurements of arc voltage and current are therefore discussed primarily as a function of gas pressure although in most cases the same comments will be applicable for their variation with the gas flow-rate.

The variation of the arc voltage with the gas pressure in Fig. 4.12. shows the arc voltage and the rate of increase of arc voltage both increasing with the gas pressure. The arc voltage tends to fall with increase in the electrode separation except at 1 mm electrode separation.

The voltage gradient in the arc column will tend to increase with the gas pressure according to the relation

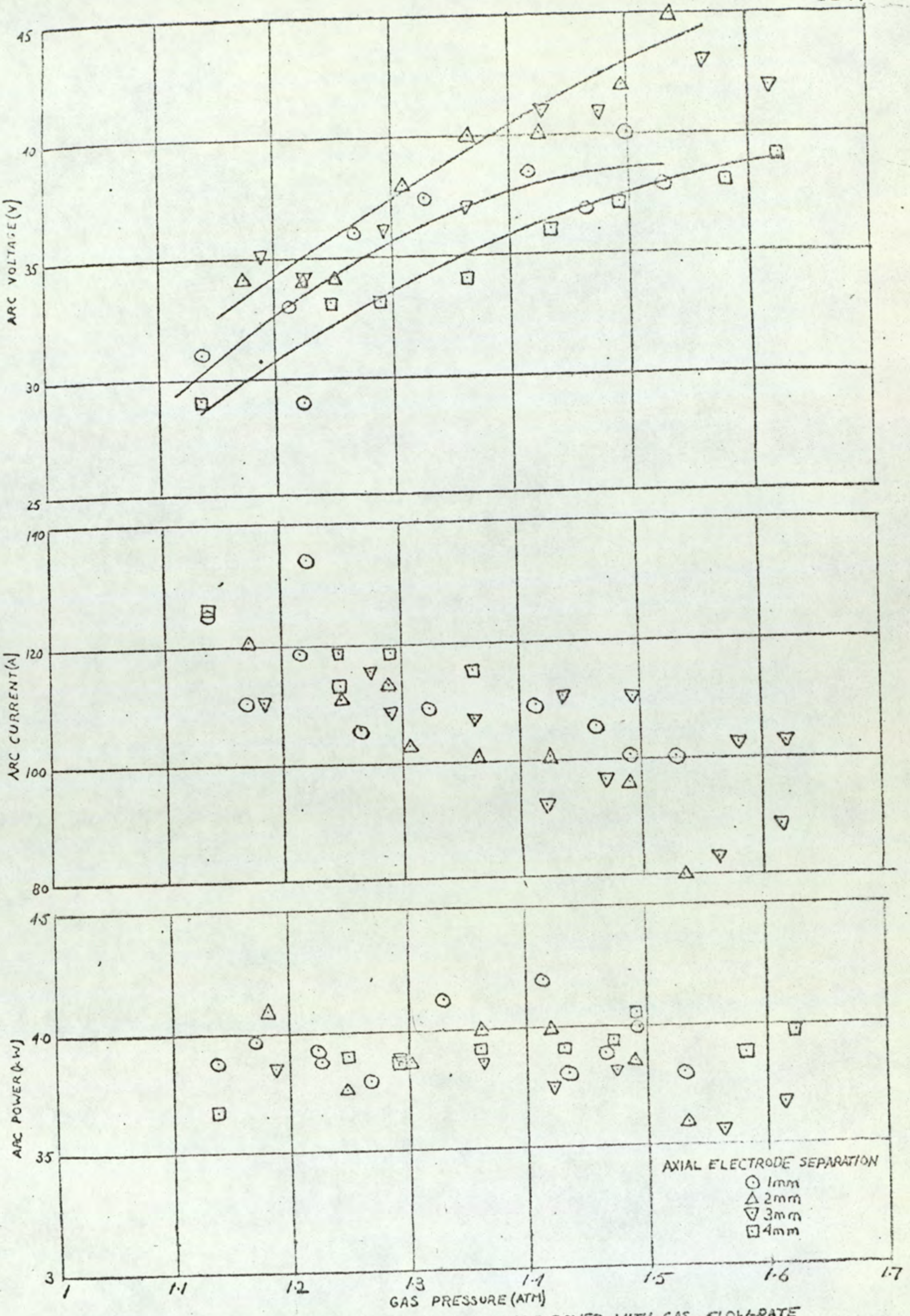
$$E \propto p^n \qquad (2.8)$$



VARIATION OF ARC VOLTAGE, CURRENT AND POWER WITH GAS PRESSURE
FIGURE 4.12

If a value of 25 volts is assumed for the combined anode and cathode fall voltage drops an increase in the arc column voltage of over 60% has occurred for a pressure increase measured at the gas inlet of up to 3 Atm. The pressure in the region of the nozzle is not known but will be less than at the gas inlets. Provision was made to measure the pressure in the throat of the nozzle with a piezo-electric pressure transducer but later modification of the nozzle shape made this unnecessary. The corresponding increase in the arc column voltage due to increase in the measured gas pressure is only about 40%. The actual pressure in the nozzle will be rather less than this, indicating that the effects of increase in arc length forced convection, and constriction of the arc column or all three on increasing the arc voltage are significant. It is difficult to assess the relative effects of simultaneous increases in arc length, gas pressure, gas flow-rate and the effect of constriction on the arc voltage. Reference to the variation of the arc voltage with gas pressure in the previous test shown in Fig. 4. 8. indicates that constriction convection and extension of the arc are more dominant than the increase in arc voltage due to the increase in the gas pressure.

At very small electrode separations of the order of 1 mm the effect of the cathode will be to choke the inlet to the throat resulting in a higher gas pressure required for a given gas flow-rate. If the arc voltage is dominated more by gas flow-rate than gas pressure the arc voltage might be expected to be low compared with other electrode separations at the same pressure (Fig 4.12) but similar to the arc voltages obtained at the same gas flow-rate. This is shown in Fig. 4. 13. The variation in arc current and power with arc voltage



VARIATION OF ARC VOLTAGE, CURRENT AND POWER WITH GAS FLOW-RATE

FIGURE 4.13

depends on the gradient of the load curve in the region of the operating points. Since this is approximately linear the arc varies inversely with gas pressure and flow-rate and the power is relatively independent of gas pressure and flow-rate .

Final modifications to the torch were made preparatory to it being operated from a. c. The tungsten cathode was replaced by copper and a field coil capable of providing magnetic flux densities of up to 0. 01 Wb/m^2 was used to rotate the arc in the nozzle. Satisfactory operation with d. c. was obtained. Further tests in 4. 2. describe its operation on a. c.

4.1.5. Discussion of the Results Obtained with the D. C. Plasma Torch.

The investigations described in this section have essentially been of an experimental nature. Since the purpose of the project was to develop a high current plasma torch and in particular an a. c. torch, this section formed only a small initial part of the work which was carried out primarily to establish techniques and obtain a working model. As a result such measurements that have been made are not necessarily complete in themselves and have largely been subsidary to the main purpose of the tests.

The results may be summarised as follows.

1. A d. c. plasma torch has been constructed.
2. A new explanation for the long laminar jets observed at low gas flow-rates has been obtained involving active nitrogen.
3. Results obtained with a laminated nozzle have enabled the behaviour of the arc in the nozzle to be investigated.

4. Satisfactory operation with both electrodes made of water cooled copper has been obtained when an external magnetic field was used to rotate the arc.[⧺]

5. The torch has been used with several different nozzle shapes. The constricted section is not necessary to stabilise the arc.[⧺]

6. Over the ranges investigated the arc voltage is more dependent on constriction and convection effects than gas pressure.

The satisfactory operation obtained with copper electrodes suggested that the torch might be operated from a. c., when the electrodes reverse polarity on each half cycle. In addition air might now be used as the heated gas as the easily oxidised tungsten cathode was no longer required. Since the stabilising effect of the constriction of the nozzle of the torch was no longer required this constraint on nozzle shape was removed and more efficient designs with reduced containment losses might be used.

⧺ The results which also indicate that this is possible and have been reviewed in Chapter 3 were not available at this stage.

4.2. The Development of the A. C. Torch from the D. C. Torch.

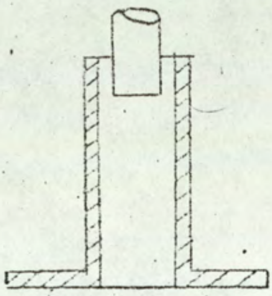
The first alternating current torch was intended to extend the range of tests carried out on the d.c. torch to a.c. torches and to determine the differences in operation and areas where further investigation was required. There was no available information on a single phase a.c. torch similar to that used in the d.c. tests and it was necessary to establish a working model on which the effects of various modifications could be studied.

The main difference in operation from d.c. is the extinction and re-ignition of the arc on each half cycle in the region of current zero. Unless a high ratio of open circuit voltage to arc voltage is used a separate ignition supply is required. A high ratio of open circuit voltage to arc voltage results in a poor utilisation coefficient and a low power factor. It is preferable to operate with low ratios of open circuit to arc voltage, and different methods of igniting the arc after current zero are investigated.

4.2.1. The A.C. Plasma Torch.

The first tests using a.c. were carried out on the torch described in the previous section. A high voltage ignition unit was used to ignite the arc initially and to assist re-ignition of the arc after current zero at each half cycle, described in 4.2.2. The ignition unit was connected in series with the arc supply and supplied an output voltage of about 3 kV. This was sufficient to breakdown a gap of only about 1 mm. It was difficult to maintain the electrode separation at this value due to mechanical tolerances in the design of the torch and erosion of the electrodes, and the arc tended either not to ignite or the electrodes touched and became welded together.

The plasma torch was therefore modified so that the minimum electrode separation was radial and could be accurately maintained. The electrode configuration with a tubular nozzle is shown in Fig. 4.14. A straight tubular nozzle without a constricting

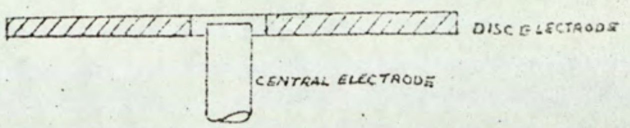


Electrode Configuration Used with Tubular Nozzle.

Figure 4.14.

section except at the inlet was used enabling the effective nozzle length to be varied by moving the central electrode axially. A flat tipped water cooled central electrode was used. The modified version of the plasma torch with the tubular nozzle is shown in Fig. 4.15.

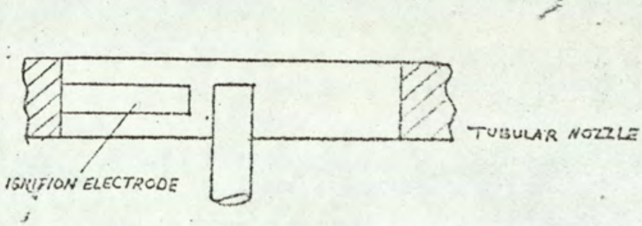
The effect of nozzle shape on efficiency was investigated by comparing results obtained with the electrode at the inlet to the tubular nozzle with those obtained using the flat disc nozzles. Shown in Fig. 4.16.



Disc Nozzle.

Figure 4.16.

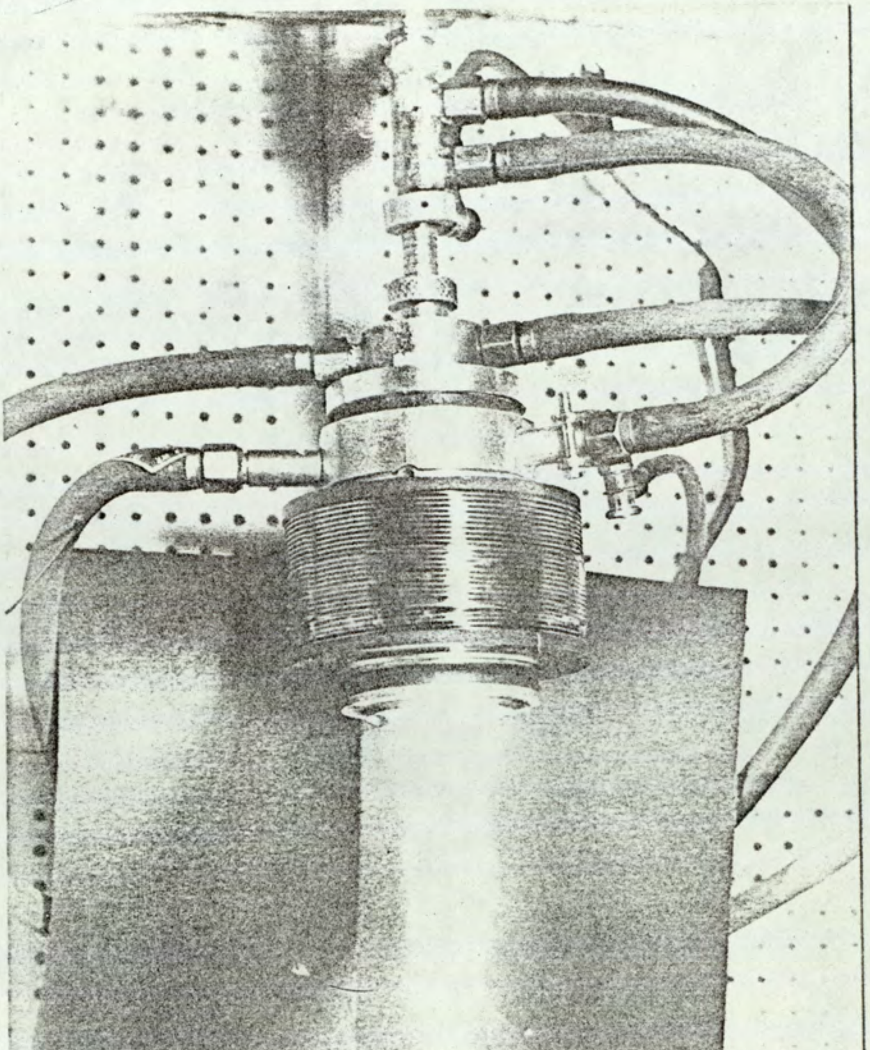
In the course of the tests it was observed that the arc tended to ignite where the electrode separation was a minimum but the arc root then moved radially outwards from the arc gap. This was utilised in the final nozzle design shown in Fig. 4.17 to enable operation of the arc with a large separation between the main



Nozzle with Ignition Electrode.

Figure 4.17.

electrodes but with only a small gap between the inner electrode and the ignition electrode. The reasons for this behaviour are disscussed in 4.2.4.

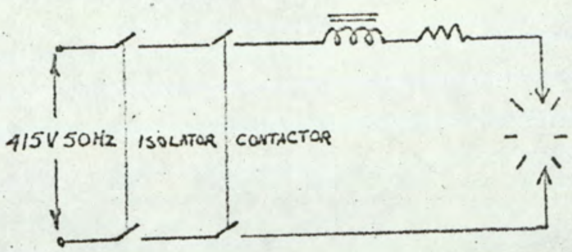


A. C. Plasma Torch with Tubular Nozzle.

Figure 4. 15.

4.2.2. Power Supplies.

The plasma torch was connected between two lines of a star connected 415 V 50 Hz mains supply with a maximum rating of 83 kVA. The circuit is shown in Fig. 4.18.



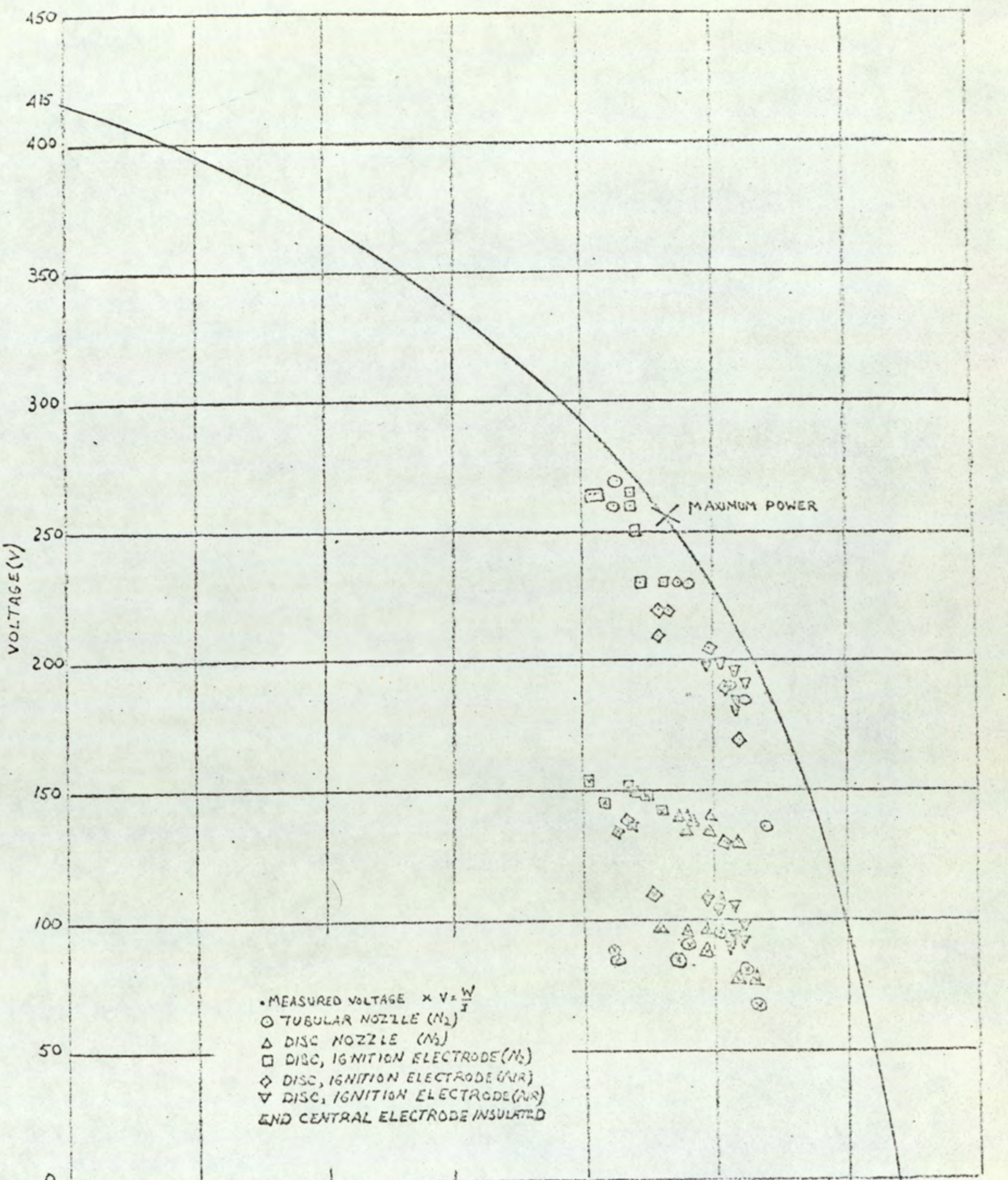
Power Supply Circuit.

Figure 4.18.

Switching was performed with an off load isolator and a contactor with a current rating of 300 A.

The series impedance used to regulate the arc current was provided by an iron cored inductor originally intended for the static balancing of single phase loads. The inductor had a d.c. resistance of 0.037 ohms and a reactance of 2.59 ohms at 50 Hz, which since the iron core of the inductor had an air gap varied by less than 3% from no load to full load. An additional resistance of 0.5 ohms was connected in series with the inductor to prevent the current on short circuit exceeding the maximum supply current of 200A. This was necessary as the main supply was fused at 200A and was used to supply other laboratories.

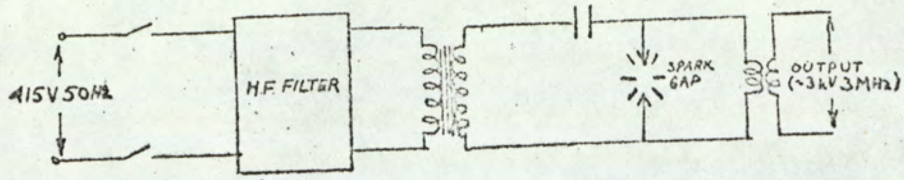
The load characteristic for a purely resistive load is shown in Fig. 4.19. The maximum power input available with the series impedance connected was 30 kW. This cannot necessarily be



LOAD CHARACTERISTIC AND ARC OPERATING POINTS

FIGURE 4.19

realised as the power input also depends on the arc voltage which is in turn influenced by the electrode separation, geometry, gas flow-rate and other factors.



Circuit of the Ignition Unit.

Figure 4.20.

The ignition unit was a commercially available unit normally used with arc welding which supplies a train of high voltage high frequency pulses during each half cycle. The maximum output was about 3 kV at 3 MHz. The output of the ignition unit was connected in series with the power supply with an air cored output transformer.

The field coil current was obtained from a full wave rectifier supplied from a variable voltage transformer. The field coil is shown in Fig. 4.15 surrounding the water cooled tubular nozzle.

The field coil produced an axial magnetic flux density of 0.022 Wb/m^2 obtained at the centre of the coil on the coil axis corresponding to 0.02 $Wb/m^2 \pm 5\%$ in the plane of the nozzle outlet, at a current of 10A.

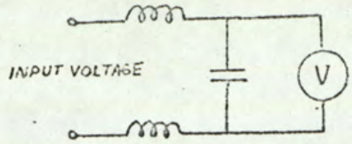
4.2.3. Instrumentation.

Thermo-couple instruments were used to measure r.m.s. values of voltage and current averaged over a period of several cycles.

The arc current may be assumed to be approximately sinusoidal if the duration of current zero is small compared with the period of the supply and the effect of harmonics is negligible which is often the case. The only advantage of a thermocouple ammeter then is the damping effect due to the thermal capacity of the heater and thermo-couple which is normally greater than the effect of mechanical damping. This enables a greater averaging effect smoothing out fluctuations due to non-conduction and transient variations to be obtained, than with other electro-mechanical indicating instruments.

The arc voltage may be considered as a rectangular wave-form, if the duration of current zero and the magnitude of ignition and extinction transients is small. This is not necessarily true for power frequency arcs due to the non linear variation of arc voltage with current and the time taken for the arc column to reach thermal equilibrium, (See also 2.3) but is normally considered a close approximation. An r.m.s. indicating thermo-couple voltmeter will measure the amplitude of the square wave which is approximately equal to the arc voltage a d.c. arc would maintain under the same circumstances across the electrode gap at the same current provided the arc is in thermal equilibrium.

It was found necessary to connect a simple low pass filter in the leads to the voltmeter shown in Fig. 4.21. to eliminate r.f pick up from the high frequency ignition unit. The error due to



H. F. Filter in Voltmeter Circuit.

Figure 4. 21.

voltage drop caused by inserting the filter was estimated at being not greater than ~3% at all times.

The arc power was measured with a dynamometer wattmeter which will indicate the r. m. s. value of the mean arc power. Industrial grade iron cored current transformers were used to step down the arc current.

The indicated voltage and current remained steady for sufficiently long to enable the meters to be read to within their calibration accuracy of 1% at full scale deflection. The indicated power was less steady due to the smaller damping effect. The error was reduced by taking several readings which were averaged and the overall accuracy is estimated at within 5%. The errors involved in using electro-mechanical indicating instruments to measure arc voltage current and power are discussed in more detail in section 6.2.2. where the high overall accuracy required in the energy balance measurements showed the various sources of error.

Instantaneous values of arc voltage and current were obtained with a dual trace cathode ray oscilloscope by photographing a single sweep only. The high frequency ignition voltage superimposed on the arc voltage made it difficult to distinguish the lower frequency components of the arc voltage waveform but did not affect the current waveforms.

The current in the field coil used to provide the axial magnetic field was measured with a moving coil ammeter and the magnetic flux density with a Hall effect probe.

The gas flow-rate was measured using a variable area flow-meter with a calibration accuracy of $\pm$ 2% of the maximum indicated gas flow-rate. The pressure at the inlet to the flowmeter was measured with a Bourdon tube pressure gauge. The major source of error in the flowmeter readings was due to fluctuations in the gas flow-rate caused by the fluctuations in arc current. These were quite small, increasing with the gas flow-rate, and occurred about a mean value so that the overall error involved is not more than $\pm$ 5% of the actual reading.

The conditions at the outlet of the nozzle were photographed at 24 frames/second on Kodachrome IIA colour film at an exposure of $\frac{1}{48}$ s at f. 11.

Erosion measurements were made with a beam balance capable of a maximum load of 200 g. The electrodes were weighed before and after a timed test. After the test they were dried in an oven to remove all traces of water before reweighing them. The change in weight was small compared with the total weight of the electrodes and the accuracy of measurement of the change in weight was probably not greater than 5%.

The temperature of the cooling water was measured with mercury in glass thermometers. Since the temperature difference between the water at inlet and outlet is only of the order of $10^{o}C$ and measurements could be made to $\pm$ $0.5^{o}C$ the overall accuracy is about $\pm$ 5%. The water flow-rate was measured by the time required to fill a 5 litre graduated flask. The overall accuracy of measurement was better than 1%.

Initially, for the first three tests industrial grade nitrogen (99.5% pure) was used supplied from 4,670 litre cylinders through a regulating valve. Subsequently a rotary vane air compressor with a displacement of 255 litres per minute at S.T.P. was used which was just within the limits of the highest gas flow-rates required.

4.2.4. Measurements and Observations.

The independent variable chosen was the gas flow-rate. The arc current and voltage are dependent on the electrode separation, series impedance and gas flow-rate if the supply voltage is kept constant. The arc current could be varied by altering the value of series resistance but this also affects the arc stability. In addition measurements at maximum arc current were of most value in scaling up the torch so that the torch was operated at maximum current throughout these tests.

A range of gas flow-rate of 0.5 g/sec. to 4.5 g/sec. was chosen based on a few trial measurements.

If a conversion efficiency of 100% is assumed this corresponds to a mean specific enthalpy of the heated gas of 30 kJ/g and 3.34 kJ/g at which the mean gas temperatures are about 7,000^{o}c and 2,000^{o}c. In practice the conversion efficiency is less than 100% lying in the region 40% to 80% normally being lowest at low gas flow-rates so that the range of operation chosen corresponds quite closely to the range of temperature required of 1,000^{o}c to 5,000^{o}c.

It would have been useful to have obtained measurements of the arc characteristics at zero gas flow-rate for comparison with values for a free burning arc. The erosion of the electrodes at low gas flow-rates was very rapid and the electrodes were punctured and a water leak occurred after only a few seconds and it was not possible to obtain any readings before failure occurred. For the same reasons the axial magnetic field strength was kept constant at the highest possible value.

It was observed that the luminosity of the heated gas at the outlet of the torch varied appreciably with the axial position of the central electrode. That this corresponded to variation in the energy output was confirmed by putting a piece of steel rod in the output jet which melted rapidly when the central electrode was near the outlet but did not melt at all when the electrode was positioned at the inlet to the nozzle. As a result it was decided to compare the operation of the torch with two different nozzles.

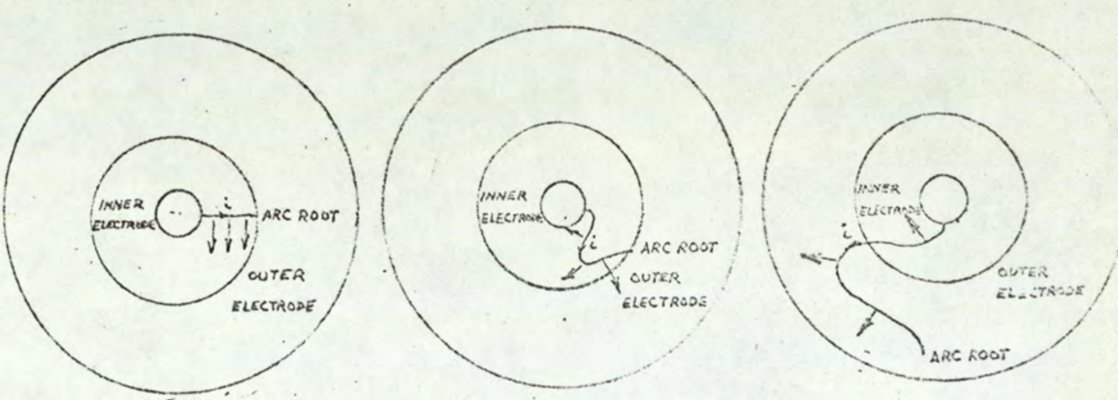
1. The tubular nozzle.

2. A disc nozzle.

The power losses to the electrodes were so strikingly reduced in the case of the disc nozzle that it was decided to confine future investigations to this type of nozzle.

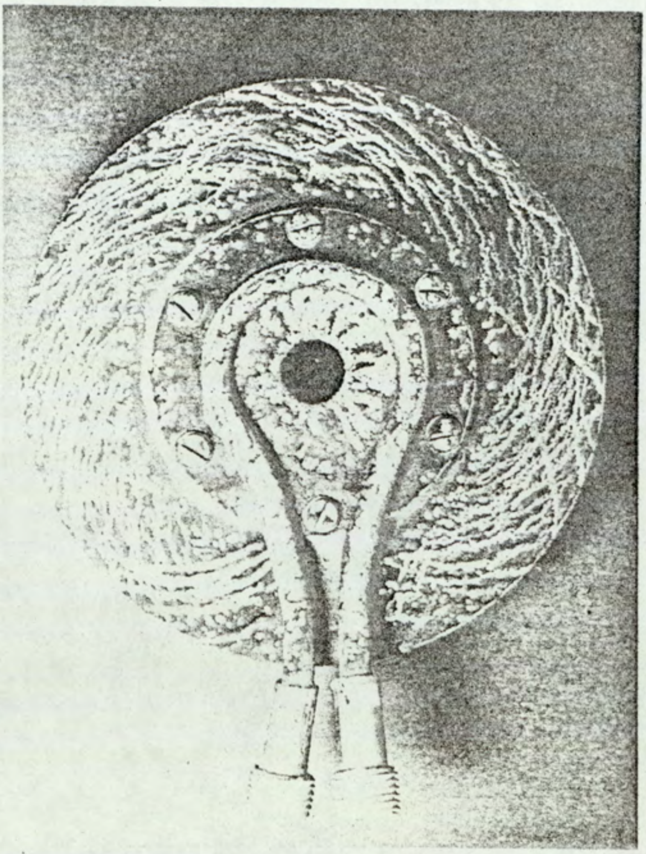
The arc tracks left by the arc root on the disc nozzle shown in Fig. 4.22. indicated that the arc was striking across the narrow electrode gap but then moved outwards from the gap describing a curved path on the surface of the disc. The disc shows the arc tracks and also shows the tendency of the arc to follow the same track on subsequent revolutions where an optimum oxide layer thickness exists (Lewis & Secker, 1961). Similar behaviour occurs in plasma torches using the hollow electrodes described in 3.2.1.and in the Birkland-Eyde process in which the arc root moves away from the minimum electrode gap after it is ignited under the influence of the gas flow in the arc chamber.

The explanation of the behaviour of the arc observed here is believed to be due to the action of the axial magnetic field used to rotate the arc which tends to distort the arc column in the circumferential direction around the annulus between the two electrodes in



Forces Acting on an Arc Rotating between Co-axial Electrodes.
(Magnetic Field Acting Out of Paper)
Figure 4.23.

the manner shown in Fig. 4.23. Radial forces now exist acting on



Arc Tracks on Disc Nozzle.

Figure 4.22.

the tangential components of the arc column and causing radial movement of the arc root on the electrode surface. The arc root on the disc electrode will be perpendicular to it and will also interact with the axial magnetic field. Any distortion of the arc from radial symmetry for example due to sticking of the anode root will also result in a tangential component of arc current. This will interact with the axial magnetic field causing the arc to be deflected radially, the direction of movement being governed by the direction of the axial magnetic field. When the arc current is reversed the direction of motion is also reversed but the radial movement is still in the same direction if the field current is not reversed.

The force due to the interaction of the arc current with the axial magnetic field may be resolved in terms of the forces acting on the arc column and at the arc root on the disc electrode. The forces acting on the arc column are

(i) the circumfrential force

$$F_c = \sum B.i.l.\cos\theta = B.i.d. \qquad (4.14)$$

(ii) the radial force

$$F_r = \sum B.i.l\sin\theta \qquad (4.15)$$

The force acting at the arc root at the surface of the disc electrode

$$F_D = \sum B i l \qquad (4.16)$$

where B = axial magnetic flux density (Wb/m^2)

i = arc current (A)

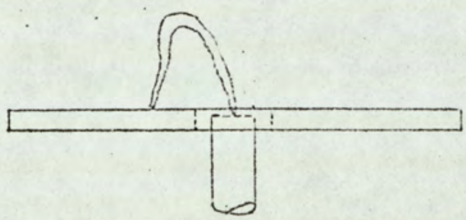
l = arc length (m)

d = electrode separation (m)

θ = angle of deflection of the arc from a radial direction (rad).

The tendency of the arc length to increase from the minimum electrode separation and the arc root to move radially outward was used in the third nozzle shown in Fig. 4.17. This enabled a larger separation between the main electrodes to be used than in the previous test and a more uniform gas flow through the region in which the arc was rotated to be obtained.

The ignition electrode was connected electrically and mechanically to the nozzle so as to project radially into the electrode gap with the minimum electrode separation between the ignition electrode and the rod electrode equal to that used in the previous tests.



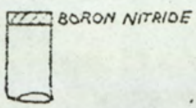
Arc Stabilised on the End of the Rod Electrode.

Figure 4.24.

A film of the arc at the outlet of the disc nozzle taken at 24 frames/s. showed that after the ignition of the arc, the arc root on the central rod electrode remained on the end of the electrode as shown in Fig. 4.24.

The region of the arc near the rod electrode is more stable in this position than in a radial position since the effect of the gas flow is minimised at the arc root. The part of the arc column near the end of the rod electrode is not influenced by the axial magnetic field and tends to remain stationary causing greatly increased vaporisation of the rod electrode.

In order to prevent this and confine the arc root to the side of the rod electrode the end of the rod electrode was insulated



Rod Electrode with Insulated End.

Figure. 4. 25.

with an insert of boron nitride shown in Fig. 4. 25. As a result the arc root was unable to attach itself to the end of the rod electrode and the arc root rotated round the side of the central electrode.

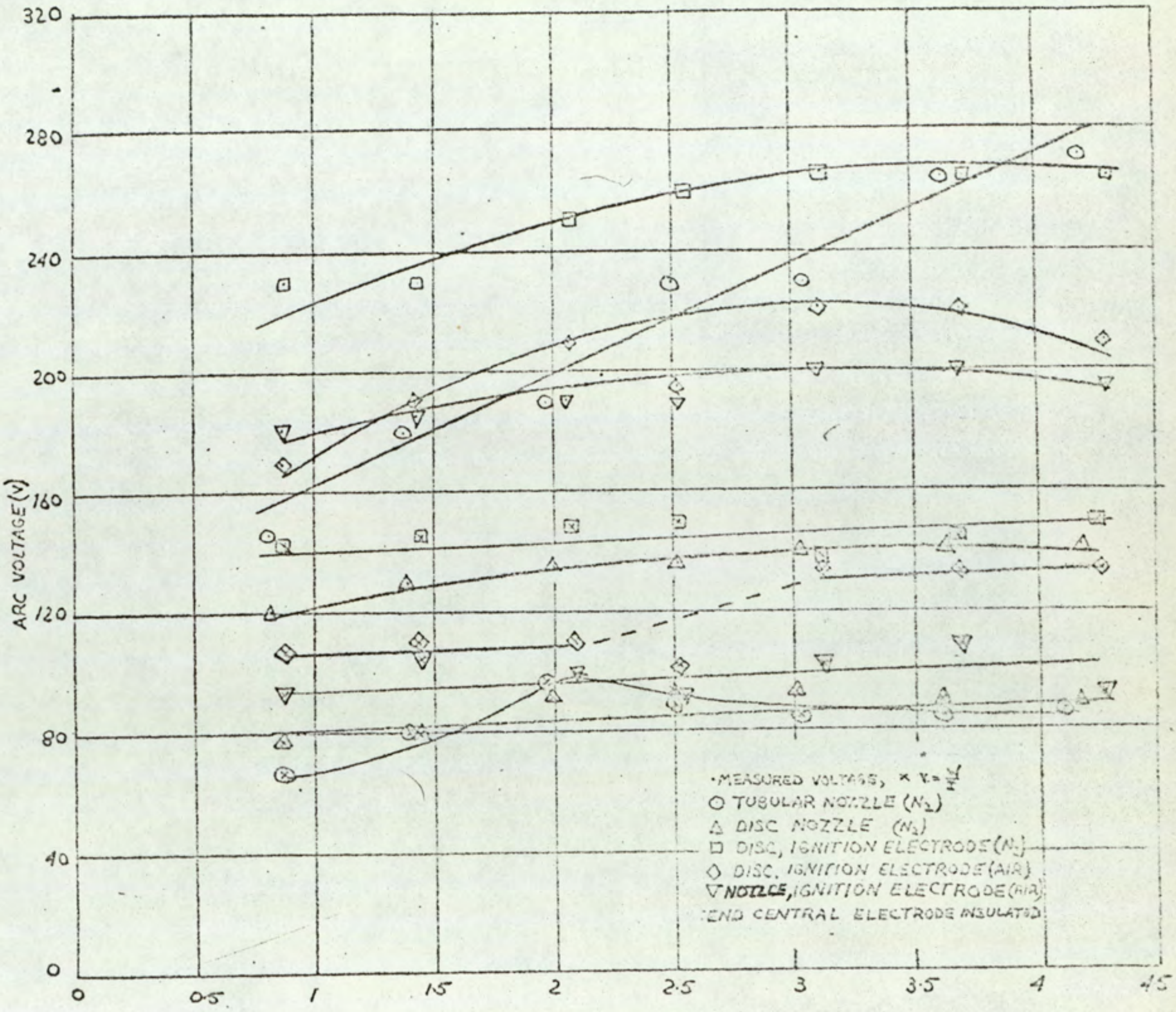
4.2.5. The Electrical Characteristics of the A. C. Plasma Torch.

The variation of arc voltage, with gas flow-rate is shown in Figs. 4.26.

The measured r.m.s. arc voltage 4.26. is surprisingly high and increases rapidly with the gas flow-rate particularly in the case of the tubular nozzle. If 25 volts is allowed for the sum of the anode and cathode fall voltages and the arc length is assumed to be equal to the nozzle length (7 cm) the voltage gradient of the arc column is about 35 V/cm. At the lowest voltage measured a voltage gradient of 18 V/cm exists. These results imply a high degree of arc constriction which is unlikely with the geometry or gas flow-rates used.

Comparison of the power obtained from the dynamometer wattmeter and the product of the r.m.s. values of arc voltage and current shown in Fig. 4.30. indicate an apparent power factor varying between 0.32 and 0.7. This is clearly meaningless as the arc is almost entirely a resistive load. The cause of the apparent low power factor is the non-sinusoidal components of arc voltage and current and in particular the effects of high ignition and extinction voltage transients.

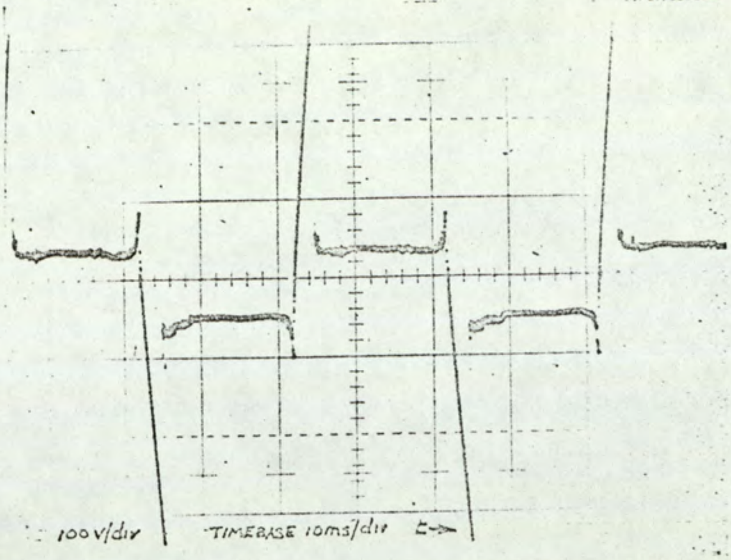
A subsidary test carried out on a free burning a.c. arc in air stabilised with a series resistance, showed that as the electrode separation was increased the apparent power factor decreased from near to unity to below 0.5. At the same time the extinction and re-ignition transients increased to peak values of up to eight times the minimum arc voltage. These transients have rapid rise times compared with that of the fundamental component of the mains supply frequency and were not distinguished from the high frequency ignition voltage superimposed on the arc voltage waveforms obtained for the plasma torch.



VARIATION OF ARC VOLTAGE WITH GAS FLOW-RATE

FIGURE 4.26

A typical voltage waveform of an a. c. arc between graphite electrodes obtained in this way is shown in Fig. 4. 27. for which the r. m. s. voltage is approximately 1. 6 times the minimum



Arc Voltage Waveform Showing High Voltages at Ignition and Extinction.
Figure 4. 27.

or 'plateau' voltage. The high voltage peak at arc ignition, the relative decrease in voltage corresponding to the negative variation of the voltage gradient of the arc column with increase in arc current (King, 1961), and the time required to establish thermal equilibrium in the arc column are shown (Witte, 1934).

The ignition and extinction transients have a greater effect on r. m. s. reading instruments for which the steady state deflection is given by

$$\theta \propto \lim_{T \to \infty} \sqrt{\frac{1}{T}\int_0^T i^2 dt} \tag{4.17}$$

than instruments reading average values for which

$$\theta \propto \lim_{T \to \infty} \frac{1}{T}\int_0^T i \, dt \tag{4.18}$$

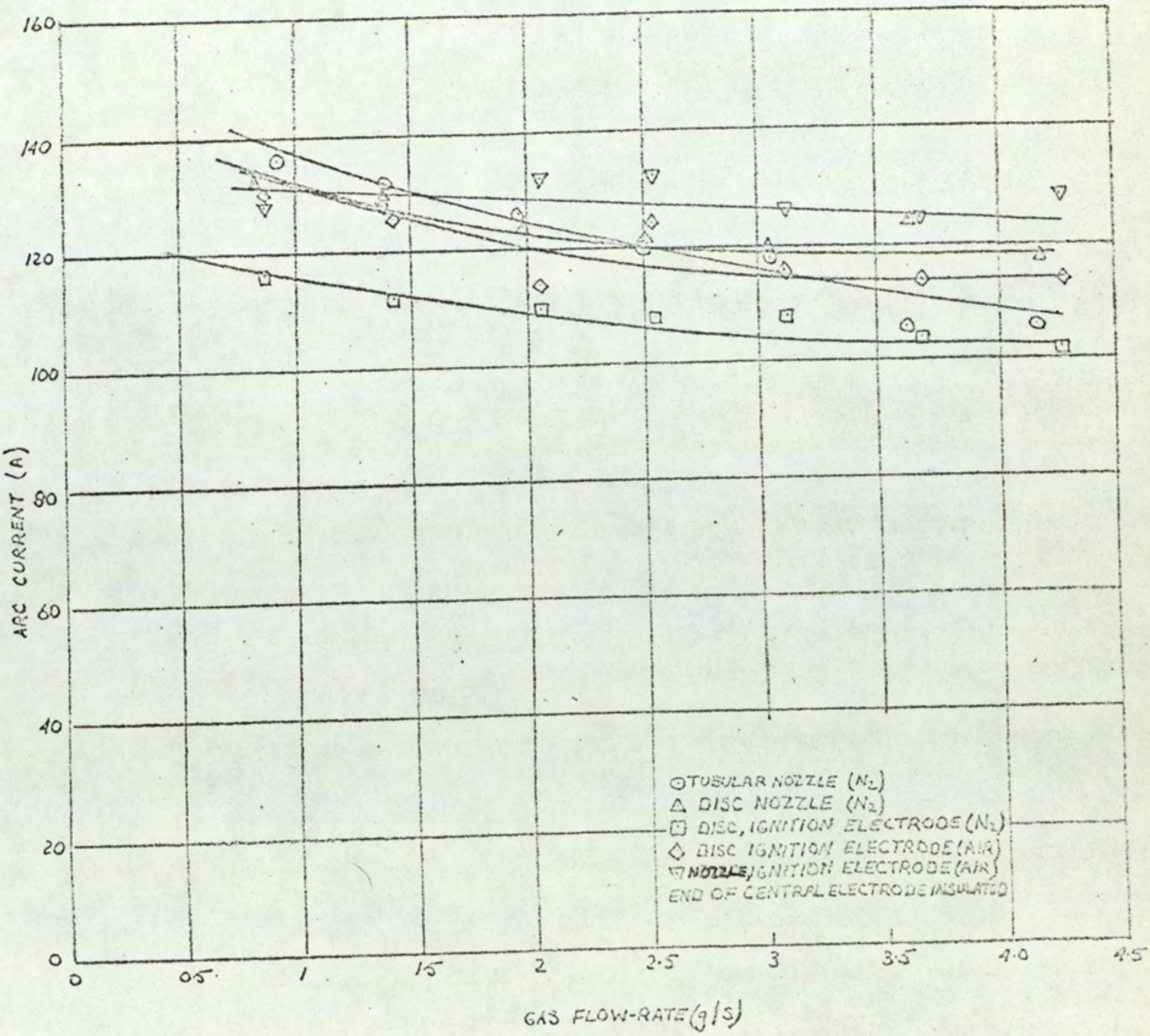
where θ = deflection
i = instantaneous meter current
t = time

The effect of the non linear variation of voltage gradient in the arc column, the voltage gradient decreasing with increasing arc current is to further accentuate this.

If thermo-couple instruments are used to measure the r. m. s. voltage another error will be introduced due to the variation in the thermal time constant of the thermo-couple and heater during heating and cooling. This will tend to result in too high a reading being obtained.

The readings of current Fig. 4.28 will be largely unaffected by these transients since they occur whilst the current is very small or zero and the readings of power will be unaffected for the reasons already discussed. Consequently the r.m.s. value of the fundamental frequency component of the arc voltage waveform may be calculated from the readings of arc power and current obtained. This has been done and the results are also plotted in Fig. 4.26. as well as the measured value of arc voltages. The real significance of the values of arc voltage obtained in this way is not associated with the arc mechanism or behaviour but enables real comparisons between the effective operation of arc devices as they are not subject to errors due to transients and since the waveform is sinusoidal the amplitudes can be compared.

The variation of arc voltage with gas flow-rate shows that the increase in the r.m.s. voltage due to the increase in the re-striking voltage is greater than the increase in the amplitude of the r.m.s. value of the mean and fundamental components of arc voltage with increase in gas flow-rate. This is particularly apparent in the case of the tubular nozzle in which short circuiting or shunting of the arc column by the walls of the nozzle may occur resulting in rapid fluctuations in arc voltage which increase in frequency with the gas flow-rate (Jordan & King, 1965). At high values of gas flow-rate it is likely that whilst the peak voltages increase, the r.m.s. value of the fundamental arc voltage decreases due to the higher arc voltages that occur at ignition and extinction and longer duration of current zero causing the maximum



VARIATION OF ARC CURRENT WITH GAS FLOW-RATE

FIGURE 4.28

in the arc voltage observed in Fig. 4.26.

Comparison of the measured and calculated values of voltage obtained for the disc nozzle with the ignition electrode in air shows that some transition occurs indicated by a maximum in the arc voltage on the curve of measured voltage and by the broken line on the curve using the calculated voltage values. This transition does not occur for the same nozzle in air with the end of the rod electrode insulated.The transition is probably not significant and may be due to the movement of the arc root on the end of the central electrode.

The arc voltages obtained by calculation from the wattmeter readings were higher when nitrogen was used for the same electrode configuration than when air was used, although some air is likely to be present in all the tests except that using the tubular nozzle. It has been suggested (King, 1961) that the lower voltage drop obtained for a free burning arc in air as opposed to nitrogen is caused by the formation of nitric oxide which increases the conductivity of the arc column.

The arc voltage measured for the disc electrode and the nozzle with the ignition electrode are very similar although the separation of the main electrodes was very much larger when the ignition electrode was used. This may be explained by the interaction of the axial magnetic field with circumfrential components of arc current causing the arc root on the outer electrode to move radially outwards to the outer edge of the electrode, discussed in section 4.24. If the effect of the relative velocity between the arc and gas in the nozzle is the same, the arc voltage is governed by the separation between the inner electrode and the outer diameter of the disc electrode which was approximately the same in both cases.

In the limiting case the maximum value of arc voltage will be governed by the minimum value of current required to maintain the arc and by instability of the arc column. If the arc root moves too far outwards the arc will be extinguished.

The maximum arc voltage and length are given by

$$V_A = V_c + V_a + El \quad (4.19)$$

where $$\bar{V}_s = \bar{V}_A + \bar{I}Z \quad (4.20)$$

and V_A = arc voltage (V)

V_c = cathode fall voltage (V)

V_a = anode fall voltage (V)

E = voltage gradient of arc column (V/cm)

l = arc length (cm)

I = arc current (A)

Z = series impedance (ohm)

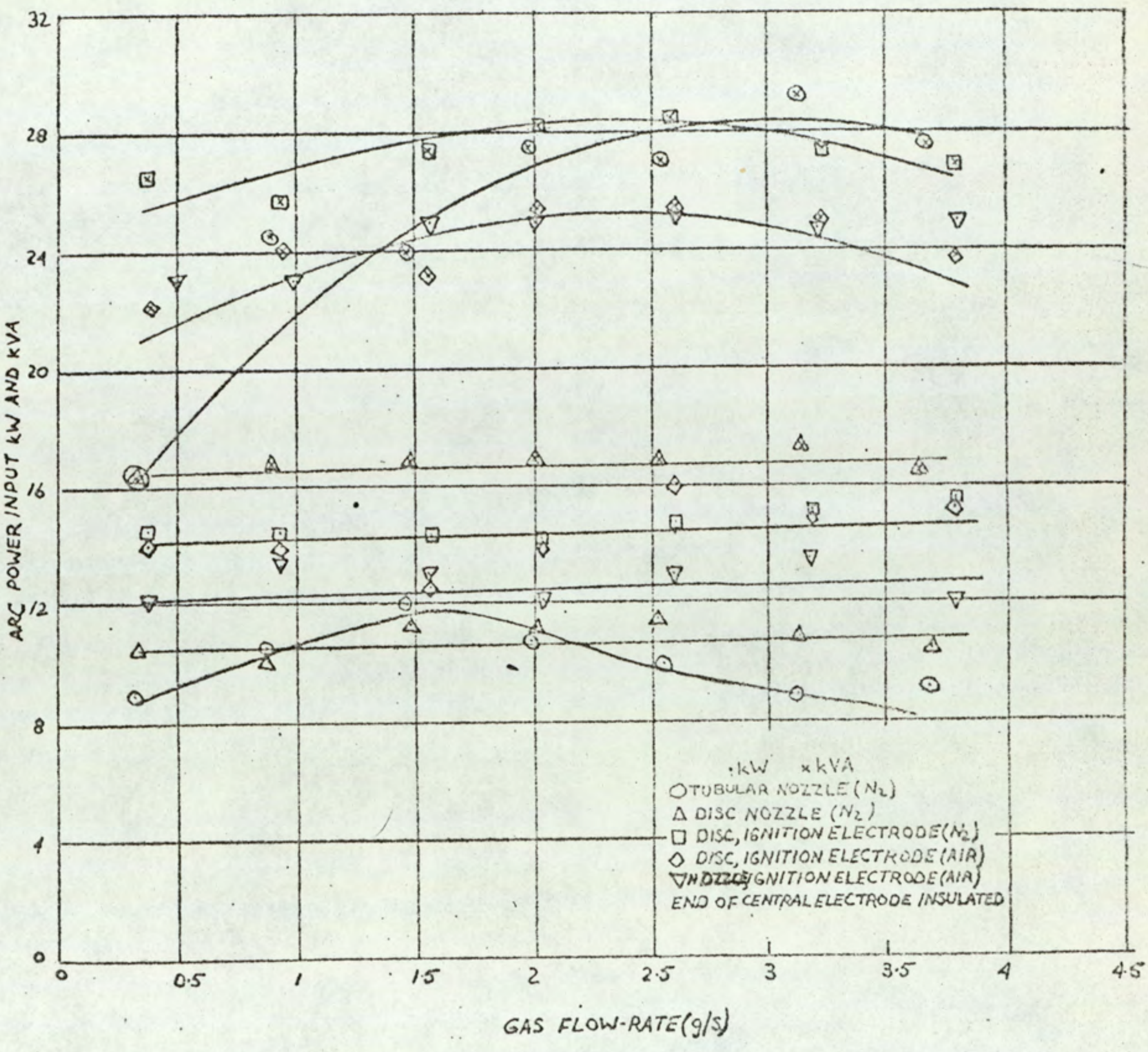
V_s = open circuit supply voltage. (V)

The arc voltage and length may increase for a given power supply until the voltage gradient in the arc column is negative as the current is reduced. Further increase in arc length causes a decrease in arc current and a further increase in arc voltage and the arc becomes unstable and is extinguished.

A lower arc voltage is obtained with an insulated plug at the end of the rod electrode due to the shorter arc path (Fig. 4.25) when the arc is prevented from anchoring on the end of the rod electrode. The variation of the arc current with gas flow-rate and nozzle configuration is smaller than the equivalent variation in the arc voltage. The arc voltage is less than that across the stabilising impedance and therefore the corresponding variation of arc current with arc voltage is less.

Arc current and arc voltage obtained by measurement and values of arc voltage calculated from the wattmeter readings are plotted on the load characteristic Fig. 4.18. relating r.m.s. values of fundamental arc voltage and current. The values calculated from the wattmeter readings lie considerably below the load curve of the power supply, since the values of power and current obtained are mean r.m.s. values averaged over several cycles. Normally the observed values will be beneath the curve but if the arc was very stable so that each waveform was the same as the previous one the mean r.m.s. values should lie on the operating curve. Consequently the distance of the mean operating point from the curve is to some extent a measure of the arc stability.

The variation of arc power with the gas flow-rate shown in Fig. 4.29. has already been discussed in terms of the variation in arc voltage and current. Nevertheless it is notable that the input power is almost constant over a variation in gas flow-rate of 10 : 1 increasing very slightly with gas flow-rate except for the tubular nozzle for which the variation has already been discussed in terms of the arc voltage.



VARIATION OF ARC POWER INPUT AND kVA WITH GAS FLOW-RATE

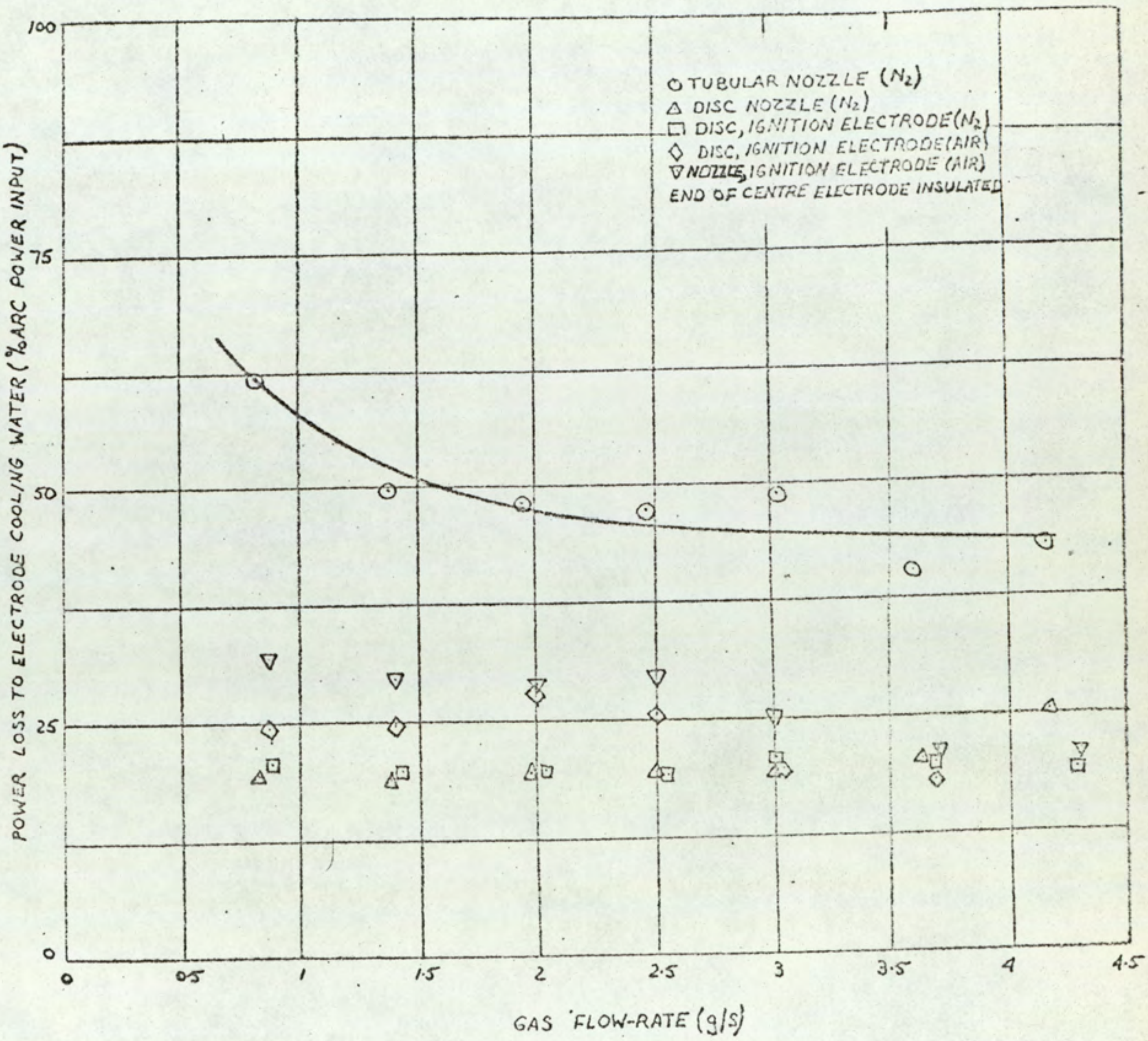
FIGURE 4.29

4.2.6. Measurement of Power Loss at Electrodes and Erosion.

The power loss to the plasma torch electrodes shown in Figure 4.30. has been expressed as a percentage of the total input power and therefore to some extent indicates the inefficiency or conversely the efficiency of the device. Since there will be additional heat losses to the torch body and losses in the field coil which are not accounted for the values obtained for the efficiency in this way will be higher than the actual values.

The percentage of the total input power dissipated at the electrodes decreases generally with increase in the gas flow-rate. As the gas flow-rate is increased the arc will be drawn further out of the nozzle and heat transfer to the electrodes and torch body will be reduced. The total power loss to the electrodes with the disc nozzle tends to increase with the gas flow-rate contrary to the other results. This may be due to the arc roots running closer to the cooling pipes on the face of the nozzle when the arc was forced further out at higher gas flow-rates. The efficiency might be expected to increase with the arc voltage since the power loss at the arc roots is governed mainly by the cathode and anode fall voltages. This is not shown, a difference in arc voltage of 50 volts corresponding to a change in efficiency of only 5% indicating that containment losses are still appreciable.

The tubular nozzle is shown to be considerably less efficient than the disc nozzle for which the arc voltages were similar in air and nitrogen. The results for the disc nozzle with the ignition electrode show that at low values of gas flow-rate the power loss is greater in air, while at higher flow-rates it is greater in nitrogen.



VARIATION OF ELECTRODE LOSSES WITH GAS FLOW-RATE

FIGURE 4.30

A similarly shaped curve was obtained when the end of the rod electrode was insulated. Greater voltage fluctuations were obtained for the arc in air in both cases and the transition that occurred in the arc voltage for the disc nozzle with ignition electrode may account for the change in relative efficiencies in air and nitrogen at high gas flow-rates.

A significant increase in power loss was obtained when the end of the electrode was insulated. These correspond to the lower arc voltage and hence proportionately higher losses at the arc roots.

The erosion was measured at a mean current of 121A over a duration of 203s. The rate of erosion at the rod electrode was $26.4.10^{-6}$ g/Coulomb and 73.2×10^{-6} g/Coulomb at the nozzle. The erosion rate of switchgear contacts measured at a copper cathode in air at 200A was 400×10^{-6} g/Coulomb. At 1A an erosion rate of 13×10^{-6} g/Coulomb was obtained which was postulated as being the minimum value obtainable for copper (Holm, 1949).

4.2.7. Discussion of Results Obtained with the A. C. Plasma Torch.

The results of the series of tests carried out on the first alternating current plasma torch are summarised as follows.

1. The thermal losses to the electrodes are greatly influenced by the nozzle shape.

2. With the nozzle configuration and gas flow-rates used (9:1) the electrical characteristics of the torch are largely independent of the nozzle shape and gas flow-rate and therefore effects due to forced convection are small.

3. The radial forces acting on the rotating arc due to the interaction of the axial magnetic field with the tangential component of arc current allow the use of a small electrode separation to facilitate ignition and re-ignition of the arc on each half cycle with a larger separation between the main electrodes, comparable with that used with a d. c. arc.

4. Insulating the end of the rod electrode appears to reduce the erosion from it, accompanied by a small drop in the arc voltage without any detrimental effect on the arc behaviour.

5. There is very little difference in the electrical characteristics of the torch when nitrogen or air is used. Erosion of the electrodes is not noticably worse when air is used implying that the erosion process is mainly by vaporisation of the electrode material rather than due to oxidation.

The energy losses to the electrodes were appreciably less for the disc nozzles than the tubular nozzle due to the reduced containment loss. The disc electrodes were intended only for comparison with the tubular electrode and are of an impractical design since the mixing of the heated gas at the torch outlet is likely to be very inefficient.

The maximum efficiency of conversion of electrical energy at the input to thermal energy at the outlet of the torch will be governed by the power lost to the electrodes from the anode and cathode fall regions. Since the anode and cathode fall voltages are approximately constant the theoretical maximum efficiency of the torch will be dependent on the ratio of the sum of the anode and cathode fall voltages to the amplitude of the arc voltage if the arc voltage waveform is assumed to be a square wave. If the sum of the anode and cathode fall voltages is taken as 25 volts then to obtain an efficiency of 90% an arc voltage of at least 205 volts is required. The equivalent electrode separation of a medium current free burning arc in air is of the order of 18 cm if a voltage gradient of 10 V/cm in the arc column and a total electrode fall voltage of 25 volts is assumed. Such an arc would be highly unstable.

The voltage gradient of the arc column is increased by constriction in a nozzle but losses due to containment are also increased. If the arc is radial high gas flow-rates would be required to constrict the arc likely to cause distortion of the arc column and further instability. By rotating the arc in an axial magnetic field a high voltage gradient may be obtained and the axial gas-flow used primarily to transfer the thermal energy from the area of the arc. The ~~behaviour~~ electrical characteristics of the torch ~~will~~ may be largely independent of the gas flow-rate and improved mixing in the heated gas and reduced vaporisation of electrode material ~~will~~ may be obtained. If, further, a diffuse arc could be obtained which is reported to be accompanied by an increase in arc stability, efficiency, reduced vaporisation of electrode material and arc voltage increasing with current(Mayo & Davis, 1962) the improvement in the torch performance would be considerable.

The use of an ignition electrode allows much wider electrode separations to be realised; the maximum possible electrode separation is probably governed by the distance moved in the circumfrential direction by the arc root during the time the arc root is moving along the ignition electrode. If this is too large the arc will not rotate or will be extinguished before the arc root on the ignition electrode reaches the outer electrode. Up to now this limiting value of separation has not been reached. Rapid erosion of the ignition electrode was a serious disadvantage of this method. A water cooled electrode would have a longer life but would add to electrode losses and the complexity of the nozzle.

The assumption of equal voltage drops across the stabilising reactor and the arc is based only on conventional empirical practice and does not give any indication of the magnitude of instability. Too high a value of stabilising impedance results in poor utilisation of the power supply and a low power factor. Insufficient impedance results in large fluctuations in arc voltage, current and power and extinction of the arc during a half cycle (Harry, 1966(a)). To choose the optimum value of stabilising impedance further information is required on acceptable levels of instability, the variation of the instability with the magnitude of the series reactance and a method of assessing the magnitude of the instability. This had not been previously attempted.

If the stability is defined by

$$\frac{1}{S} = \lim_{T \to \infty} \frac{\int_0^T |\Delta\phi| dt}{\int_0^T \phi \, dt} \qquad \text{(Harry, 1966(b))} \quad (4.21)$$

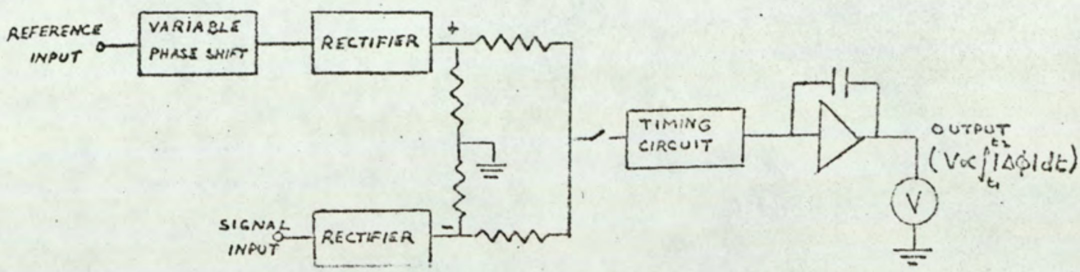
where $\frac{1}{S}$ = the instability

ϕ = a reference waveform or the required or optimum value of arc voltage, current or power.

$\Delta\phi$ = the random or steady state deviation of the actual parameter from the reference waveform

T = period of integration.

The measurement of the instability can be carried out either graphically or with the circuit shown in Fig. 4.31 using



Method of Measurement of Arc Stability.

Figure 4.31.

either a constant pre-set reference waveform or the reference waveform may be derived from the input signal.

The stabilising impedance has other effects on the behaviour of an electric arc (Harry, 1966 (a)). If the series impedance, or resistance in the case of a d.c. arc, is large such that most of the voltage drop occurs across the impedance rather than across the arc then a small change in arc length and hence arc voltage will cause a negligible change in arc current. The arc supply behaves in a similar way to a constant current generator and the arc power is approximately proportional to the increase in arc length. Alternatively if the voltage drop across the series impedance or resistance is small compared with the arc voltage a small charge in arc length and hence arc voltage will cause an appreciable change in arc current and the arc power will tend to remain constant independently of arc length. The result is that by suitably choosing the impedance or resistance in series with a plasma torch it can be made to operate at either constant specific enthalpy output or constant electrical power input independently of the gas flow.

The measurements made in the tests on the first a.c. plasma torch indicate the importance of obtaining measurements directly from waveforms of the arc voltage and current. In practice because of interference from the high frequency ignition unit it was not possible to obtain satisfactory waveforms of the arc voltage. The use of a single high voltage impulse to breakdown the arc gap on each half cycle would enable the ignition pulse to be distinguished from the fluctuations in the arc voltage and might be more easily eliminated in the measuring circuits by using zener diodes. Whilst the only completely reliable means of measuring the electrical characteristics of the arc is by obtaining the waveforms, if the arc current is approximately sinusoidal the arc current may be measured with a thermo-couple ammeter or dynamometer ammeter whilst the arc power may be measured with a dynamometer wattmeter.

Readings of a.c. arc voltage obtained from electro-mechanical indicating instruments have little or no value even if the arc is stable (i.e. does not fluctuate in a random fashion). The presence of the ignition and extinction voltage peaks and the negative gradient of the arc voltage current characteristic have a considerable effect on mean and r.m.s. measurements that cannot be ignored. True r.m.s. indicating instruments are particularly subject to the effects of ignition and extinction peaks since

$$V_{r.m.s.} \propto \lim_{T \to \infty} \sqrt{\frac{1}{T}\int_0^T v^2 \, dt} \qquad (4.22)$$

Even when the waveform of the arc voltage is obtained considerable doubt exists due to its non-sinusoidal nature as to what value to ascribe to it. If appreciable fluctuations of arc current or voltage also occur it is difficult to give a mean value of any significance to the arc waveforms.

It would be useful in future tests to obtain the heat losses to each electrode separately in order to investigate the effects of changes in the electrodes and the overall efficiency in terms of the thermal energy in the heated gas at the outlet of the torch as a percentage of the input energy. This could be carried out with a calorimeter and the results compared with a heat balance including energy losses to the electrodes and losses to the torch body.

Since the usefulness of the torch is to some extent governed by the rate of vaporisation of the electrode material it is important that this should be measured. Preliminary measurements made of the change of weight of the electrodes used in the first alternating current plasma torch indicated that the change in weight obtained before failure of the electrode when a water leak occurred was small compared with the total electrode weight, resulting in a very low order of accuracy being obtained. In order that this should be improved the electrodes should be as light as possible and used for sufficient time to enable accurate measurements of the loss of weight to be made.

4.3. Areas of Investigation where further Research is Required.

For further development of the plasma torch the following areas required investigation.

1. The behaviour of arcs in high transverse magnetic fields at up to 2 Wb/m^2 and the investigation of the diffuse discharge.
2. Measurement of electrode erosion as a function of arc velocity and hence magnetic flux density.
3. Alternative methods of arc ignition.
4. The effect of external parameters on arc stability.
5. Measurement of the conversion efficiency using a calorimeter to measure the energy in the gas at the outlet of the nozzle.
6. An improved method of measuring arc voltage.

The investigation of 1 and 2 is described in Chapter 5 and 3, 5 and 6 are dealt with in Chapter 6. Insufficient time available precluded further experimental investigation of 4.

CHAPTER 5.

Investigation of Rotating Arc Discharges.

The behaviour of rotating arc discharges between co-axial electrodes in a transverse magnetic field are investigated. The existence of a diffuse arc and the erosion rate at the electrodes are studied.

5. INVESTIGATION OF ROTATING ARC DISCHARGES.

The tests carried out on the d. c. and the a. c. plasma torches indicate that substantial improvements in the behaviour of the arc were obtained when the arc was rotated between electrodes in a transverse axial magnetic field. The improvements were

1. A decrease in erosion of the electrodes due to reduction in local heating at the arc root.

2. An increase in arc stability as a result of reduction in random movement of the arc column caused by free convection effects, by superimposing a forced movement on the arc.

3. Increased voltage gradient of the arc column enabling smaller arc gaps to be used for the same power dissipation at a given current.

4. Better distribution of the thermal energy in the gas passing through the nozzle.

The tests in which an axial magnetic field was used to rotate the are were confined to magnetic flux densities of about 0. 2 Wb/m^2. Whilst an improvement in arc behaviour was apparent at the higher magnetic flux density it was difficult to assess quantitatively, particularly since different electrode configurations were used.

The magnetic fields used to rotate arcs in plasma torches had been progressively increased up to about 0. 1 Wb/m^2 but in one case over 2 Wb/m^2 had been used. Improvements were claimed as the magnetic field was increased and substantial improvements were claimed at magnetic flux densities of 2 Wb/m^2.(See also 2. 4. 4.).

5.1. Investigation of the Diffuse Discharge.

Diffuse arcs have been reported to exist at atmospheric pressure when the arc was rotated with a high axial magnetic field over a range of magnetic flux densities of from about 0.1 Wb/m^2 to 2 Wb/m^2 (Shephard & Winovich, 1961, Boldman, 1962, Mayo & Davis, 1962, Phillips, 1964, Levakov & Lyubavskii, 1965). (See also 2.4.4.). The most extensive investigation had been made over the range 1 Wb/m^2 to 2 Wb/m^2 (Mayo & Davis) at which significant improvements were obtained in the arc behaviour, which were attributed to the arc being diffuse. It was therefore of particular interest to investigate the region in which an arc appeared to become diffuse.

Other observations of rotating arcs indicated that the arc tended to decrease in diameter as the arc velocity was increased to magnetic flux densities up to 0.094 Wb/m^2 (Adams, 1964). The existence of a diffuse arc was therefore not conclusively shown. Since all the observations of a diffuse arc at atmospheric pressure had been made photographically it was important to determine whether or not for example it was due to persistence of luminosity in the arc gap rather than ionisation. If a diffuse arc was obtained the change in behaviour and the minimum conditions required to obtain a diffuse arc were required.

It was possible that the advantages of a diffuse arc might be outweighed by the high power input required to the field coil. To indicate the order of magnitude of the power input required at high magnetic fields consider a uniformly wound rectangular coil with constant current distribution for which the optimum Fabry factor is 0.126. Assuming a filling factor of 0.9 and the resistivity of copper at 150°c of 2.6.10^{-4} ohm m, with an internal radius of 0.05 m a power input of 0.893 kW at 0.1 Wb/m^2 and 89.3 kW at 1 Wb/m^2 is required. Even at moderate coil dimensions and magnetic flux densities it can be seen that the power input to the coil becomes an appreciable source of inefficiency.

The production of high axial magnetic flux densities in the region of the nozzle of a plasma torch is governed by the following requirements.

1. An open ended magnet must be used since the heated gas has to be transported with minimum losses away from the arc gap to the region in which it is used. Iron cored magnets with pole pieces in the region of the arc gap cannot normally be used.

2. The internal diameter of the solenoid must be large enough to contain the electrodes and cooling pipes.

The relation between the power input and magnetic field strength for an open ended solenoid is given by the relation first suggested by Fabry (1898).

$$B = \frac{G}{100}\left(\frac{W\lambda}{\rho . a_0}\right)^{\frac{1}{2}} \qquad (5.1)$$

where B = magnetic flux density (Wb/m^2).

G = Fabry factor.

W = power input (W).

λ = filling factor (fraction of total available volume filled by conductors).

ρ = resistivity (ohm . m)

a_0 = inner radius of coil (m).

i.e.

$$W \propto B_x^2 a_0 \qquad (5.2)$$

if G, λ, and ρ are constant.

Before proceeding to the design of the second a.c. torch it was therefore decided to investigate the behaviour of arcs in high magnetic fields where there was insufficient data available. The main purpose was primarily to determine whether there was a value of magnetic field above which further improvement in arc behaviour became negligible which had not been shown previously.

The main variables of interest were

1. Arc rotational speed and frequency arc with particular reference to diffuse behaviour.
2. The variation of electrode erosion with magnetic flux density.
3. Arc voltage as a function of the magnetic flux density and arc current.

5.1.1. The Electrode Assembly and Field Coil.

The most detailed investigation of a diffuse discharge at atmospheric pressure was made by Mayo and Davis. Magnetic flux densities of up to 2 Wb/m^2 and d.c. arc currents up to 2,600A with the field coil connected in series with the arc supply in air at pressures up to 75 Atm were used. Concentric copper electrodes with electrode separations of 0.8 cm and 1.1 cm were used and the internal diameter of the outer electrode was apparently kept constant at 8.7 cms. The change in arc behaviour from a concentrated to a diffuse arc appeared to occur at magnetic flux densities in the region of 0.1 Wb/m^2 to 1 Wb/m^2. The transition from a constricted to a diffuse discharge was deduced by comparing the behaviour of the arc with a similar heater operated at lower magnetic flux densities.

It was not possible to reproduce the conditions used by Mayo and Davis exactly with the facilities available. However, by decreasing the diameter of the inner electrode and keeping the electrode separation at 0.8 cm the conditions for the production of a diffuse discharge should be more favourable since the length of the circumfrential path is reduced.

An increase in gas pressure tends to reduce the arc velocity according to $U \propto P^{-0.11}$ (2.16)

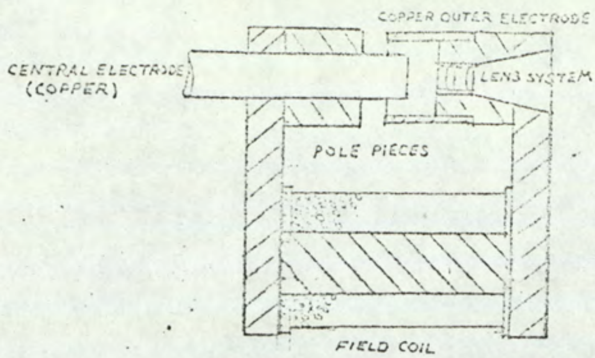
where U = arc velocity (m/s)

P = gas pressure (Atm)

which was obtained for axial carbon electrodes up to 18 Atm in nitrogen in an axial magnetic field (Adams, 1967). The effect of a small axial air flow between brass co-axial electrodes in an axial magnetic field was to reduce the arc velocity by approximately a half.

The effect therefore of operating the discharge at atmospheric pressure without an axial gas flow is likely to assist the formation of a diffuse discharge.

Initially the use of an iron cored magnet was considered in which the arc rotated in a region between two pole-pieces and between two concentric electrodes with their axis parallel to the magnetic field. It was important that the pole pieces should not interfere with the arc behaviour and also that optical observation of the rotating arc could be made. As a result the separation of the pole pieces was several cms and it was necessary to bore holes

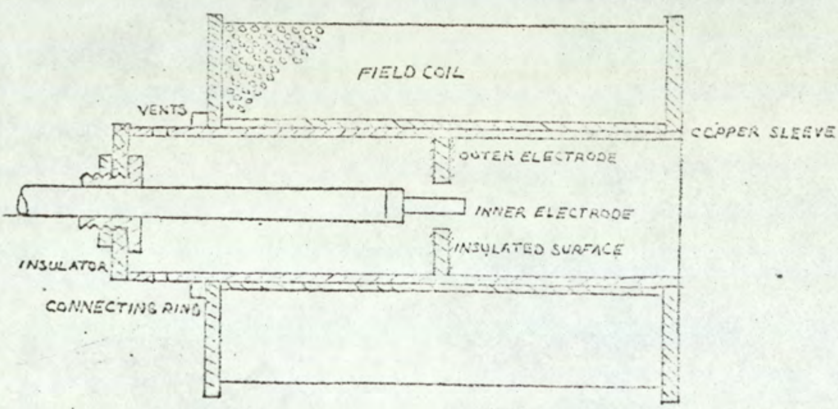


Iron Cored Magnet.

Figure 5.1.

in them for a lens system to enable the arc to be observed. The magnet was constructed and tested and is shown in Fig. 5.1. The large air gap required and the increase in leakage flux caused by holes in the pole-pieces reduced the efficiency of the system and it was decided to use an air cored pulsed field coil.

The field coil used had a bore diameter of 5 cm and a length of 13 cm. A flux density of 2 Wb/m^2 could be obtained for times of up to 2 seconds at field currents of about 400A.



Air Cored Field Coil and Electrode Assembly.

Figure 5.2.

The electrode configuration used is shown in Fig. 5.2.

The copper electrodes were mounted in the centre of the coil inside a copper tube which served as a connection to the outer electrode and protected the coil former from the arc. Three connections separated by 120° were made to a heavy copper ring fastened on to the end of the tube projecting out of the coil and

were connected together some distance from the coil to assist a uniform current distribution in the tube. The central electrode was 0.48 cm diameter and fitted into the end of a brass tube. This diameter was found in practice to be the smallest diameter that could be used without excessive melting of the central electrode occurring during a 10 millisecond pulse at the highest values of arc current envisaged viz. about 2,000A. The electrode separation was 0.8 cm, the same as the smallest value used by Mayo and Davis. The sides of the outer electrode were coated with refractory cement providing an insulating layer and confining the arc to the inside edge of the electrode.

5.1.2. The Power Supplies.

An arc current of more than 2,000A at a voltage of 400V was required to obtain results under similar conditions to those of Mayo and Davis. A continuous supply at this output was not available and even at low power inputs would not have been feasible due to the high level of energy dissipation inside the relatively small volume in the bore of the coil.

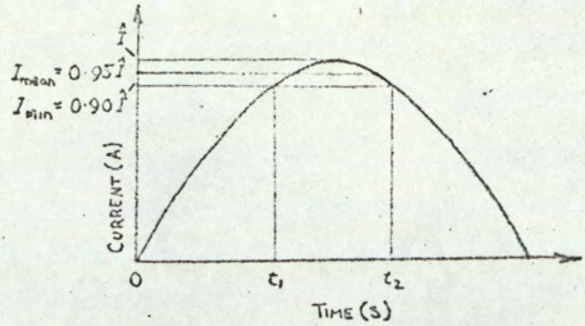
Equilibrium conditions are obtained in the arc root regions in about 60 microseconds (Froome, 1946) and in the arc column in less than 1 millisecond (Witte, 1934, (See also 2.3.). A pulsed discharge system may therefore be used to investigate many arc parameters if the pulse length is longer than 1 millisecond.

Several possible energy storage systems were considered. Inductive storage systems are suitable normally for very rapid pulses of considerably less than 1 microsecond duration. Capacitive storage enables longer pulses to be obtained but are normally bulky and the exponential decay in current makes the effective arc current difficult to assess. Rotary generator systems relying on the mechanical inertia of the rotor enable high peak currents to be obtained but are costly and cumbersome.

Synchronous switches relying on the stability of the mains supply have been used (Goldschmidt, 1943, Spink & Guile, 1965), but due to the mechanical inertia of the operating mechanism require accurately controlled timing mechanisms, and contact bounce causes the time of switching to be poorly defined. If the mechanical switch is replaced with a thyristor the timing of operation can be controlled very accurately. In addition, as in this case, if it is required to switch only one half cycle intermittently the operating current can be more than twenty times the continuous current rating.

The duration of half a cycle of mains frequency is sufficient for many arc investigations to be carried out if the arc is initiated near the beginning of the cycle. The variation of the arc current may be assumed to be sinusoidal (which is a close approximation in most cases).

Half a cycle of a sinusoidal waveform is shown in Fig. 5. 3.



One Half Cycle at 50Hz Showing Region over which Constant Current Measurements were Obtained.

Figure 5. 3.

The current

$$i = \hat{I} \sin \omega t \qquad (5.3)$$

where i = instantaneous current. (A)

$\hat{I}$ = peak current. (A)

ω = angular frequency. (rad)

t = time. (s)

The current is at 90% of its peak value when

$$0.9 = \sin \omega t \qquad (5.4)$$

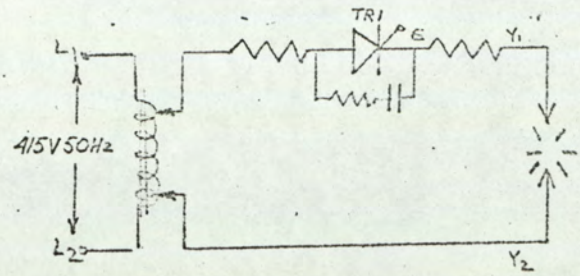
When the frequency is 50 Hz

ωt = 3. 6 milliseconds and 6. 4 milliseconds

corresponding to t_1 and t_2 in Fig. 5. 3.

The total time during which the current is within $\pm$ 5% of 95% of the peak value is 2. 8 milliseconds. This is sufficient time for the arc to reach an equilibrium condition and for measurements to be made of the arc current, voltage and rotational frequency.

The thyristor was connected to a 415V 50 Hz a.c. supply and was triggered from a specially constructed pulse unit. The thyristor and arc supply circuit are shown in Fig. 5.4.



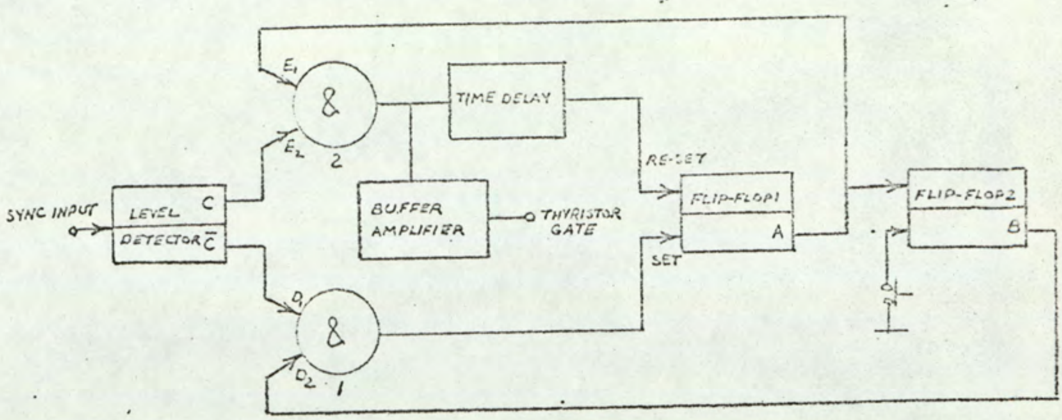
Arc Power Supply.

Figure 5.4.

The pulse unit was synchronised to the supply voltage waveform with a step down transformer. The trigger circuit was designed so that the following requirements were met.

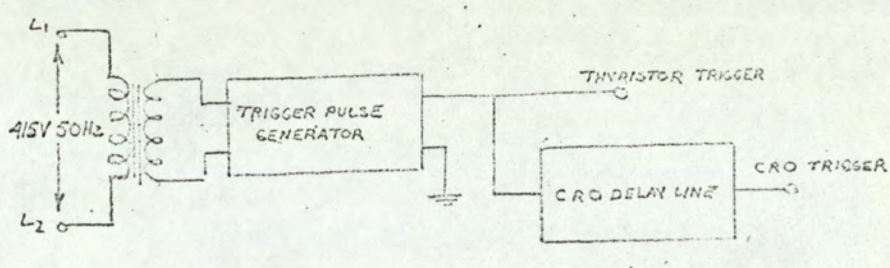
1. The triggering point on the voltage waveform could be accurately pre-set at a chosen part of the waveform of the supply voltage.
2. The trigger unit provided only one pulse when a re-set button was pressed and did not operate again until it was re-set.
3. The trigger pulse occurred at the pre-set point on the voltage waveform after voltage zero independently of when the re-set button was pressed.

The logic diagram which satisfies these requirements is shown in Fig. 5. 5. and the circuit diagram is shown in Fig.5. 6.

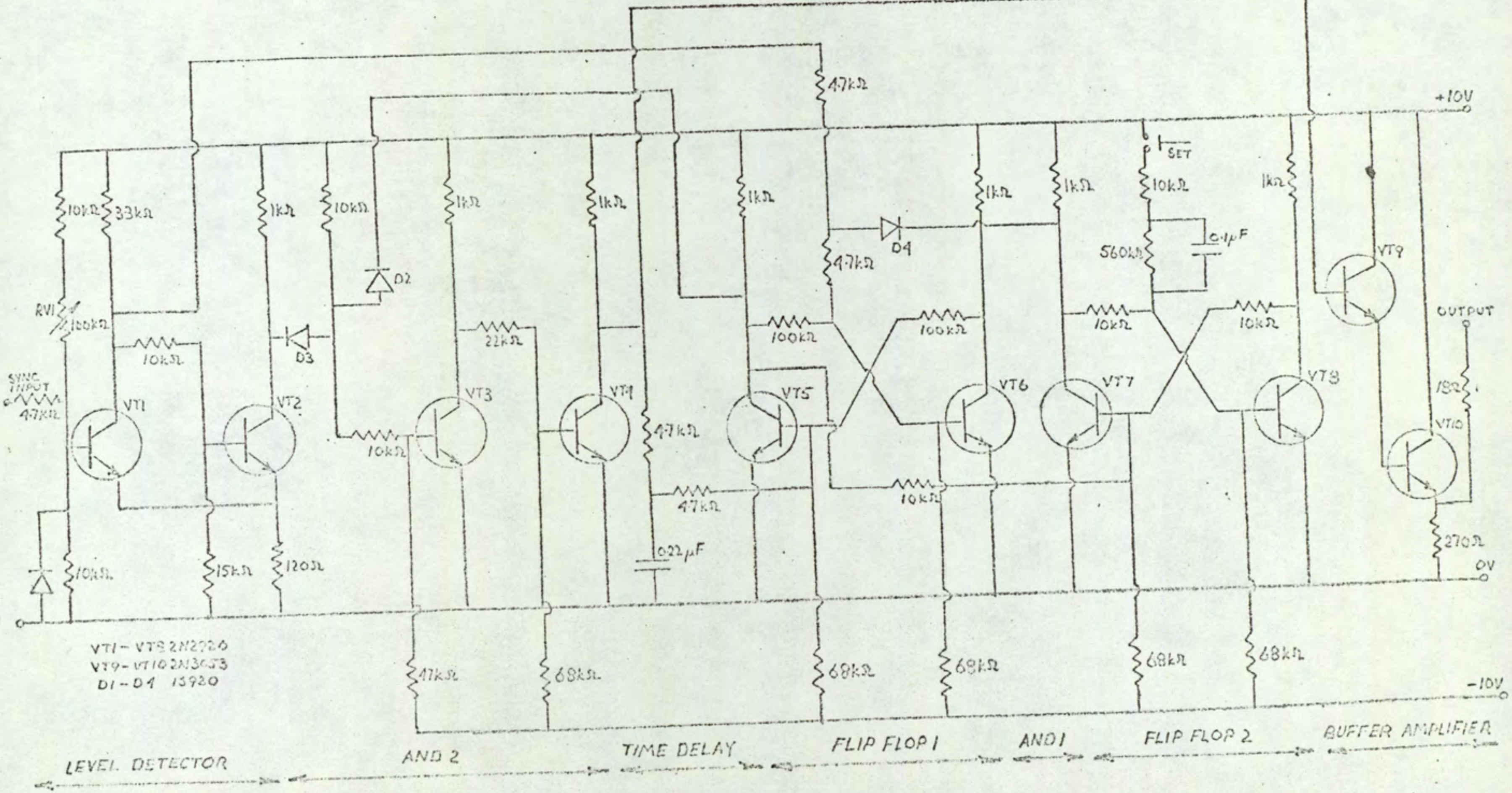


The Logic Diagram of the Thyristor Trigger Pulse Generator.
Figure 5. 5.

The same pulse that was used to trigger the thyristor triggered the delayed time-base of the oscilloscope used to examine the arc voltage, current, and output waveforms of the probes. Enlargement of the waveform over the range of maximum current was obtained in this way enabling accurate measurements of the rotational frequency to be made. A block diagram of the control circuit used is shown in Fig. 5. 7.



Block Diagram of Control Circuit.
Figure 5. 7.

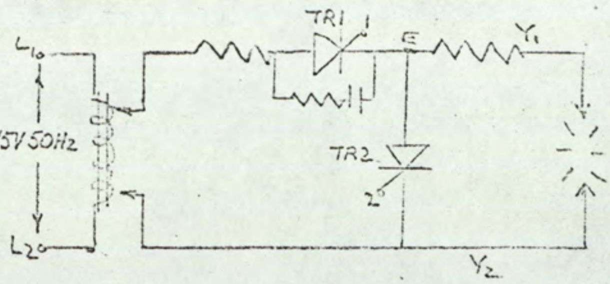


CIRCUIT OF THYRISTOR TRIGGER PULSE GENERATOR

FIGURE 5.6

The persistence of arc luminosity was measured by extinguishing the arc abruptly at a well defined point on the arc waveform so that the time at which the arc is extinguished is accurately known.

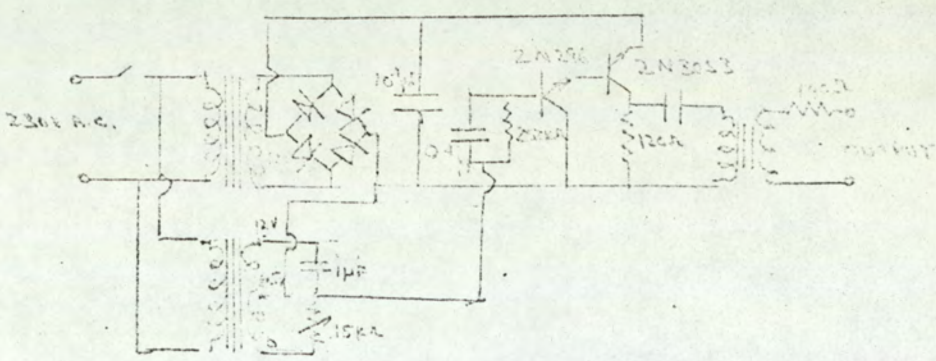
A second thyristor TR2 was connected in parallel with



Power Supply and Diverter Circuit.

Figure 5.8.

the arc as shown in Fig. 5. 8 so that when TR2 was triggered the arc current was diverted through it . The second thyristor was triggered from a free running trigger pulse unit synchronised to



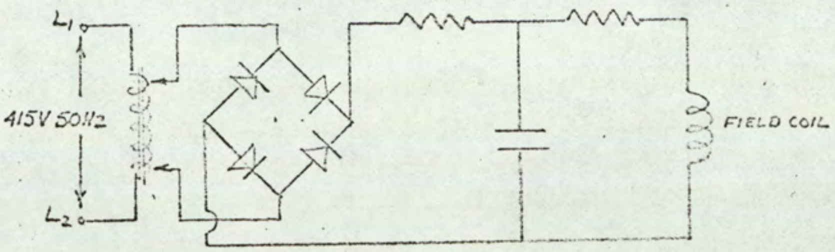
Free Running Pulse Generator for Diverter Thyristor.

Figure 5.9.

the supply frequency but with variable phase- shift. The circuit diagram of the free running trigger pulse unit is shown in Fig. 5.9.

The divertor thyristor is triggered on each half cycle but conducts only for part of the half cycle that TR1 is triggered.

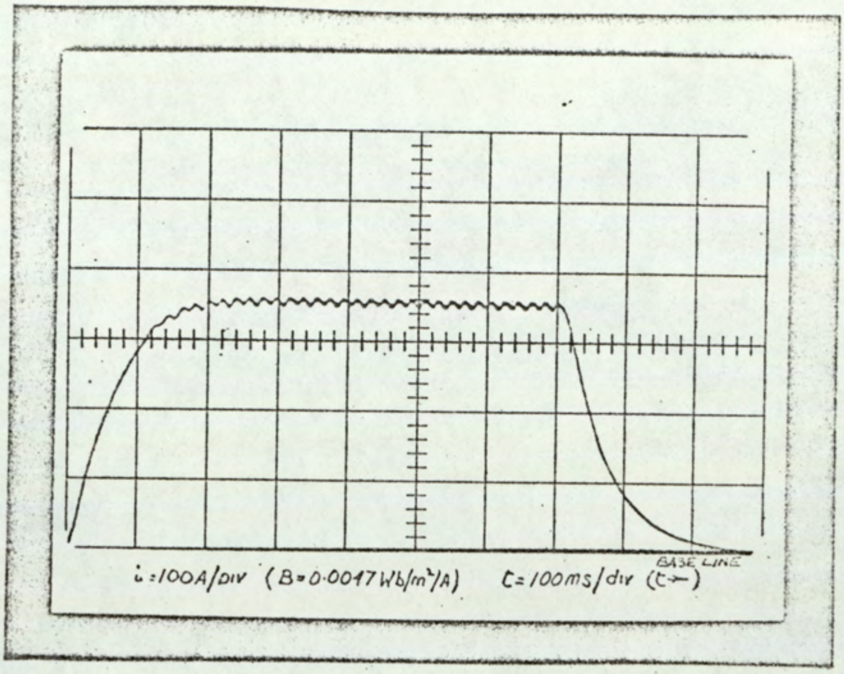
The field coil was supplied from a rectified and smoothed a.c. supply with a contactor and timing circuit in the a.c. input circuit shown in Fig. 5.10 The pulse duration could be varied from about 0.2s to 20s.



Field Coil Power Supply.

Figure 5.10.

The ripple voltage across the coil at maximum field strength was less than 3% of the mean d.c. voltage and is shown in Fig. 5.11. The flux distribution in the bore of the coil was measured with a miniature Hall effect probe using a battery to supply the coil at constant current. The flux density was within 3% in the region of the arc gap of the value measured at the centre of the coil.



Field Current Waveform at 1.8 Wb/m^2.

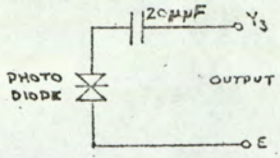
Figure 5.11.

5.1.3. Measurement of Arc Voltage, Current and Velocity.

The main evidence for a diffuse arc has been obtained by high speed photography. Mayo and Davis examined the behaviour of the rotating discharge with a high speed framing camera at 7,800 frames/sec. with an exposure time of 43 μsec. A low speed framing camera at 64 frames/sec. with a Kerr cell shutter was used to give exposure times of 0.1 micro-seconds. An apparently diffuse discharge filling the entire arc gap was observed in both cases.

Initial observations made here were with a high speed framing camera at 6,000 frames/sec. and an exposure of 33 micro-seconds. Results similar to those of Mayo and Davis were obtained in which the entire annular gap appears to be filled with a diffuse discharge. (See also 5.1.4., Fig. 5.17). The luminosity in the arc gap varied appreciably around it however when the camera lens was stopped down. Even when neutral density filters were used no apparently constricted arc structure was observed.

There are other possible reasons for the luminosity of the arc gap, apart from the arc becoming diffuse, which are discussed in the following section. Consequently an alternative means of distinguishing whether the arc was diffuse was required. Photo-electric devices such as photo-voltaic diodes used considerably below saturation might distinguish the arc column if it is appreciably brighter than the luminous vapour. The optical probe shown in Fig. 5.12 using a photo-voltaic diode with a frequency response up to 150 kHz was constructed. The optical probe enabled measurements of rotational frequency to be made up to about 20,000 r/s.



Circuit of Optical Probe.

Figure 5.12.

Above this the noise level made the output corresponding to the arc passing the probe difficult to distinguish. Since this occurred at magnetic flux densities of the order of 1 Wb/m^2 at which Mayo and Davis obtained a diffuse arc a more reliable method of investigating the arc behaviour at these frequencies was required.

A magnetic probe mounted so as to pick up the magnetic field due to the arc current would not be affected by luminosity or ionised gas outside the arc column. If the arc became diffuse the local magnetic flux density associated with it would be altered and could be detected. Since small Hall probes were available these were considered first. The voltage output of the Hall probe will be proportional to the magnetic field due to the arc current.

i.e. $$V_h \propto I \qquad (5.5)$$

where V_h = voltage output from Hall probe.

I = arc current.

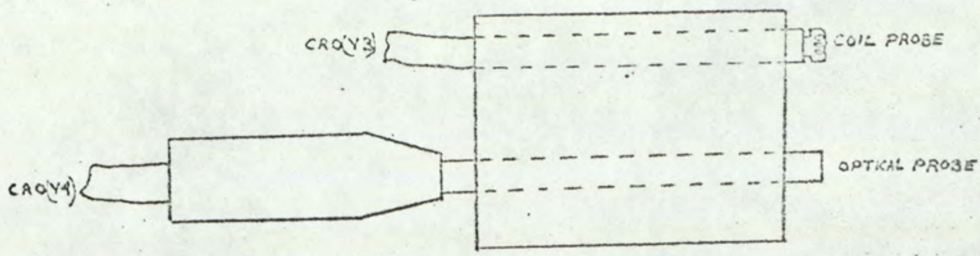
If the Hall probe is situated so that the magnetic field of the arc is perpendicular to the Hall element a fluctuation in the output voltage of the probe should be obtained each time a constricted arc passes it. If the arc became diffuse the magnetic field associated with the discharge should be constant and a constant output from the Hall probe would be obtained.

Initial calculations showed that a magnetic flux density of about 2.10^{-3} Wb/m^2 existed 1 cm from a conductor carrying a current of 100A. The maximum voltage output obtainable from the Hall probes at this value of magnetic flux density was about 0.5 mV. When a Hall probe was used the fluctuation in output voltage was comparable with the noise level. Hall probes were therefore rejected although with more time available this technique may have been improved on.

Search coil probes were a possible alternative method of detecting the magnetic field of the arc current. An output voltage from a coil probe will be obtained as the arc passes it but the amplitude will also increase with arc velocity. If the arc becomes diffuse no output voltage will be obtained.

The first coil was wound by hand on a bakelite former and was relatively bulky. The output voltage measured was very small and again of the order of the noise level from the system. A smaller coil was obtained from a sub-minature intermediate frequency transformer. The coil consisted of 86 turns of 42 s.w.g. wire on a ferrite former 1.8 mm diameter and 2 mm long and enabled a much greater signal to noise ratio to be obtained.

Connections were made to the coil with a co-axial lead secured in a tube shown in Fig. 5.13, which fitted into the bore of the magnet coil. The axis of the search coil was mid-way between and tangential to the two electrode surfaces, separated from the arc gap by a wooden spacer enabling the probe to be repeatedly placed in the same position. The radial position of the coil probe



Method of Mounting Coil and Optical Probes.

Figure 5.13.

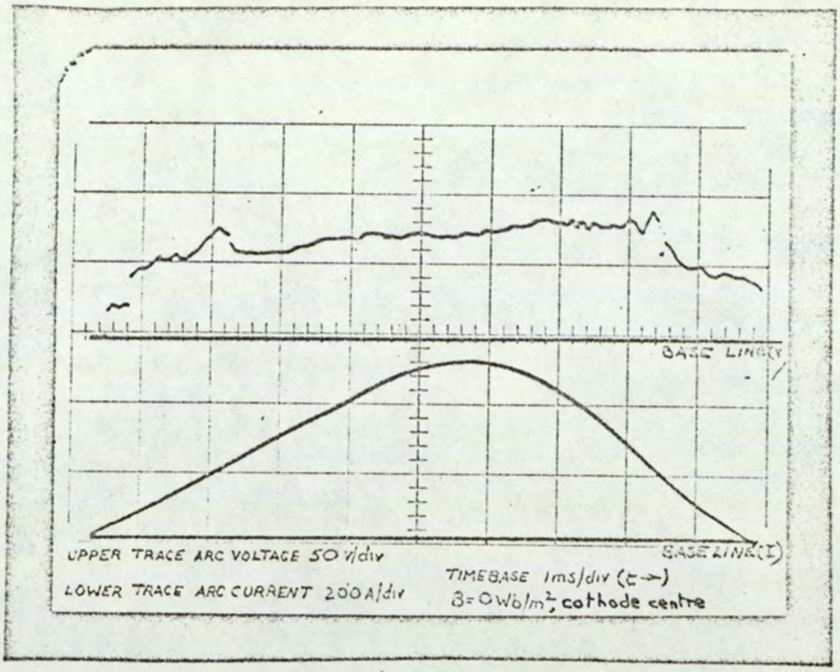
had little effect on the output but no signal output was obtained when it was rotated through 90^o and flux linkage with the rotating arc was a minimum. The optical probe was also mounted in the same tube separated by 120^o and a disc of mica approximately 0.02 cm thick was used to prevent the arc from touching and damaging the probes which were at earth potential. Subsequent tests showed that this had no apparent affect on the arc behaviour or measurements made. The coil probe was covered with a cap of boron nitride as additional protection in the case of failure of the mica. The tubular holder containing the probes was prevented from moving axially. Since both ends of the tube inside the field coil were now blocked it was necessary to drill three holes at the end of the tube which projected from the coil to allow for the sudden explosive expansion of the gas in the tube when the arc was ignited.

The probe outputs were connected to the inputs of a four channel oscilloscope amplifier the other two channels were used for the measurement of arc voltage and current. The pulse used to trigger the thyristor in the arc supply circuit was delayed by the second time-base of the oscilloscope. The delayed pulse was used to trigger the main time-base so that the region around maximum current could be examined in detail.

The voltage and current waveforms over a complete half cycle are shown in Fig. 5.14. The initial delay caused by the time required to vapourise the aluminium foil between the electrodes is shown by the low voltage at the beginning of the half cycle. Delayed and expanded waveforms of arc voltage, current and the outputs from the optical and coil probes are shown in Fig. 5.15. For clarity the oscilloscope graticule has been removed.

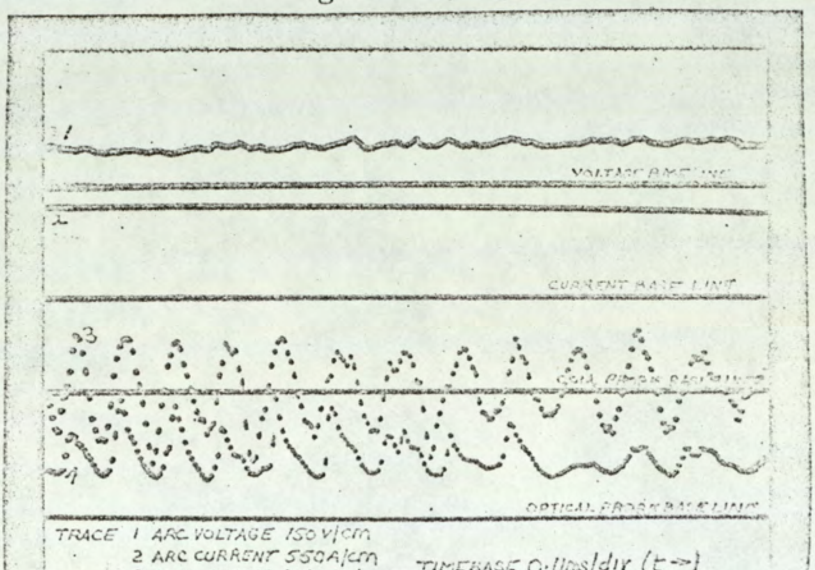
The oscilloscope was calibrated before use to an accuracy of $\pm$ 3%. Close agreement between the rotational frequencies measured with the optical probe and the coil probe was obtained but at rotational velocities above about 20,000 r/s the output of the optical probe was obscured by a high noise level and only the results of the coil probe were used.

The output of the coil probe became modulated with a high frequency voltage of about 100 kHz due to self resonance at high rotational velocities. To reduce this an active filter with a variable cut off frequency was connected in the



Waveforms of Arc Voltage and Current over Half a Cycle.

Figure 5.14.



Expanded Waveforms of Arc Voltage, Current and Probe Outputs with Delayed Trigger.

Figure 5.15.

output circuit of the search coil. This was set as a low pass filter with a cut-off frequency of 50 kHz at which an attenuation of 3dB was obtained. The output of the coil probe alone was amplified by connecting the output from the coil probe to a second oscilloscope with a more sensitive single channel amplifier triggered by the output of the delayed trigger signal obtained from the first oscilloscope.

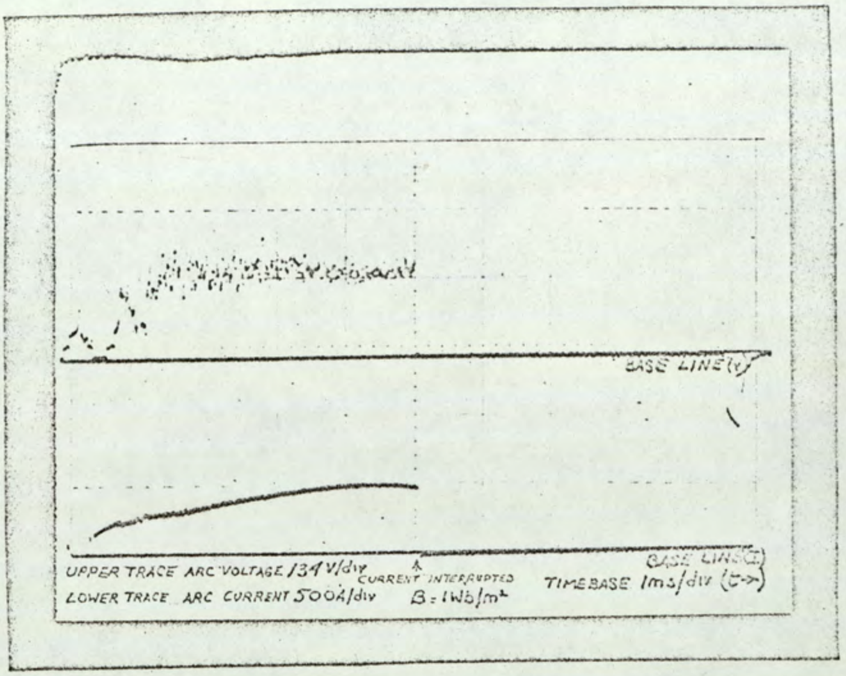
Measurements up to a magnetic flux density of 1.7 Wb/m^2 at constant arc currents ($\pm$ 10%) of 200A and 500A with the electrodes connected alternatively as anode and cathode and at 2,200A and 1.7 Wb/m^2 were made.

5.1.4. The Measurement of Persistence of the Luminosity in an Arc Gap.

The absence of a regular signal output from the optical probe at rotational velocities measured with the magnetic probe above about 20,000 r/s was thought to be due to the persistence of luminosity in the arc gap.

To obtain some information on the persistence of the luminosity of medium current arcs at 1 Atm in air some measurements were made on a static 60A d.c. arc between graphite electrodes using the thyristor diverter and control circuit shown in Fig. 5.8. The arc current could be interrupted in this way in less than 0.1 ms. The arc was photographed at 6,000 frames/s. and the arc current waveform and timing marks at 1 millisecond intervals were superimposed on the film. The thyristor trigger unit was operated from the camera control unit so that the film could be brought up nearly to full speed before the arc was extinguished. The luminosity of the arc gap persisted for about 10 milliseconds after arc extinction and the ends of the electrode remained luminous for considerably longer.

Since these results were not directly applicable to the present investigation although of more general value, a similar test was also carried out on the rotating arc discharge using the

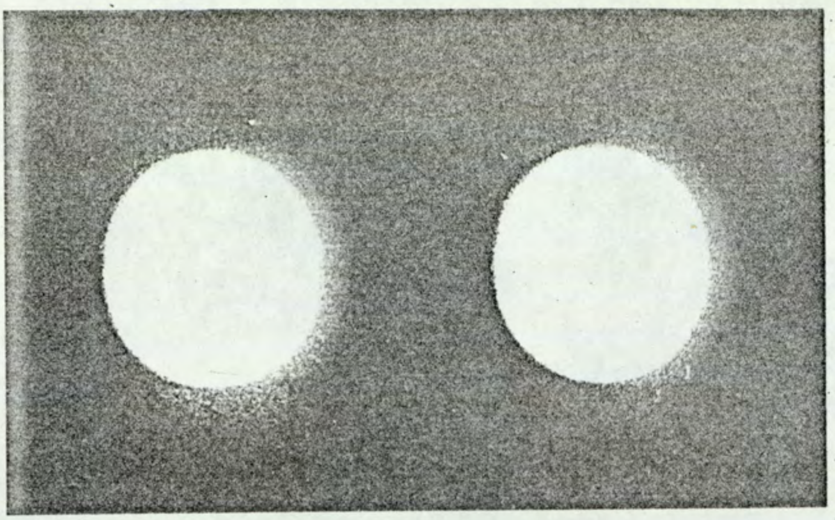


Waveforms of Arc Voltage and Current Interrupted by the Thyristor Diverter.

Figure 5.16.

thyristor switch as before with the diverter connected in parallel with the electrodes. Waveforms of the arc voltage and current are shown in Fig. 5.16. A framing speed of 6,750 frames/s. with an exposure of 27 microseconds at f.2. on Kodak Tri-X film was used.

Single frames of the film immediately before and during arc extinction and 3.9 milliseconds after are shown in Fig. 5.17. The current waveform is shown as a continuous horizontal line visible after arc extinction. The entire cross section of the bore of the coil was shown to be luminous even 5.3 milliseconds after arc extinction and traces of luminosity were visible more than 19 milliseconds after the arc was extinguished.



Annular Gap During Arc Extinction (Arc Current is extinguished during second frame, indicated by horizontal line at the bottom right-hand corner).

Cathode Centre. Magnetic Flux Density 1.0 Wb/m^2.
Arc Current 500A.
6, 750 frames/s.
Exposure 27 microseconds.

Annular Gap 3.9 Milli-seconds After Arc Extinction.

Electrode Gap Before and After Arc Extinction.

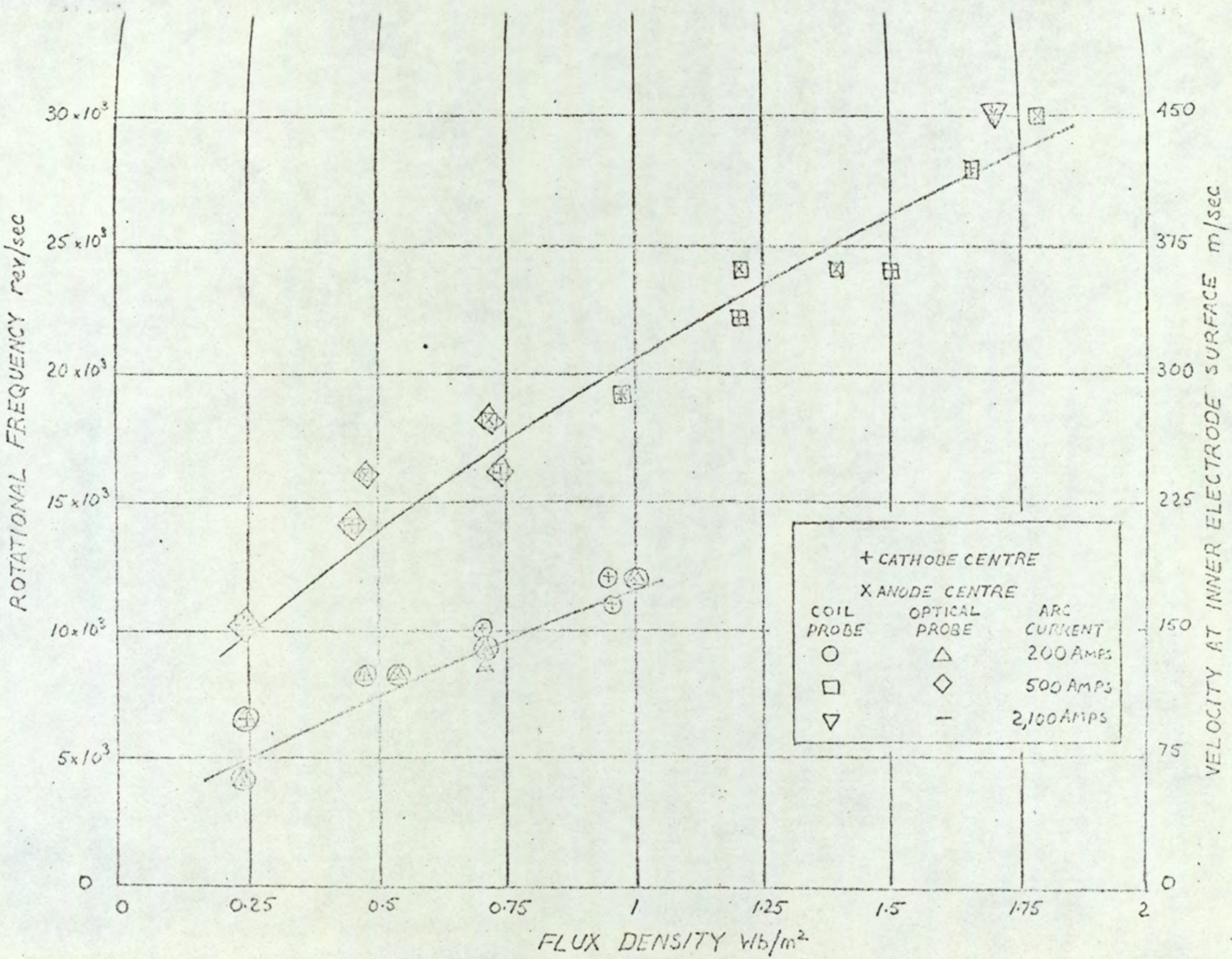
Figure 5.17.

The effect of decreasing the lens aperture and using optical filters would be to decrease the apparent persistence but at high values of rotational frequency the slow decay of luminescence will still prevent the arc from being distinguished.

5.1.5. Discussion of Results from the Measurement of Arc Velocity and Voltage.

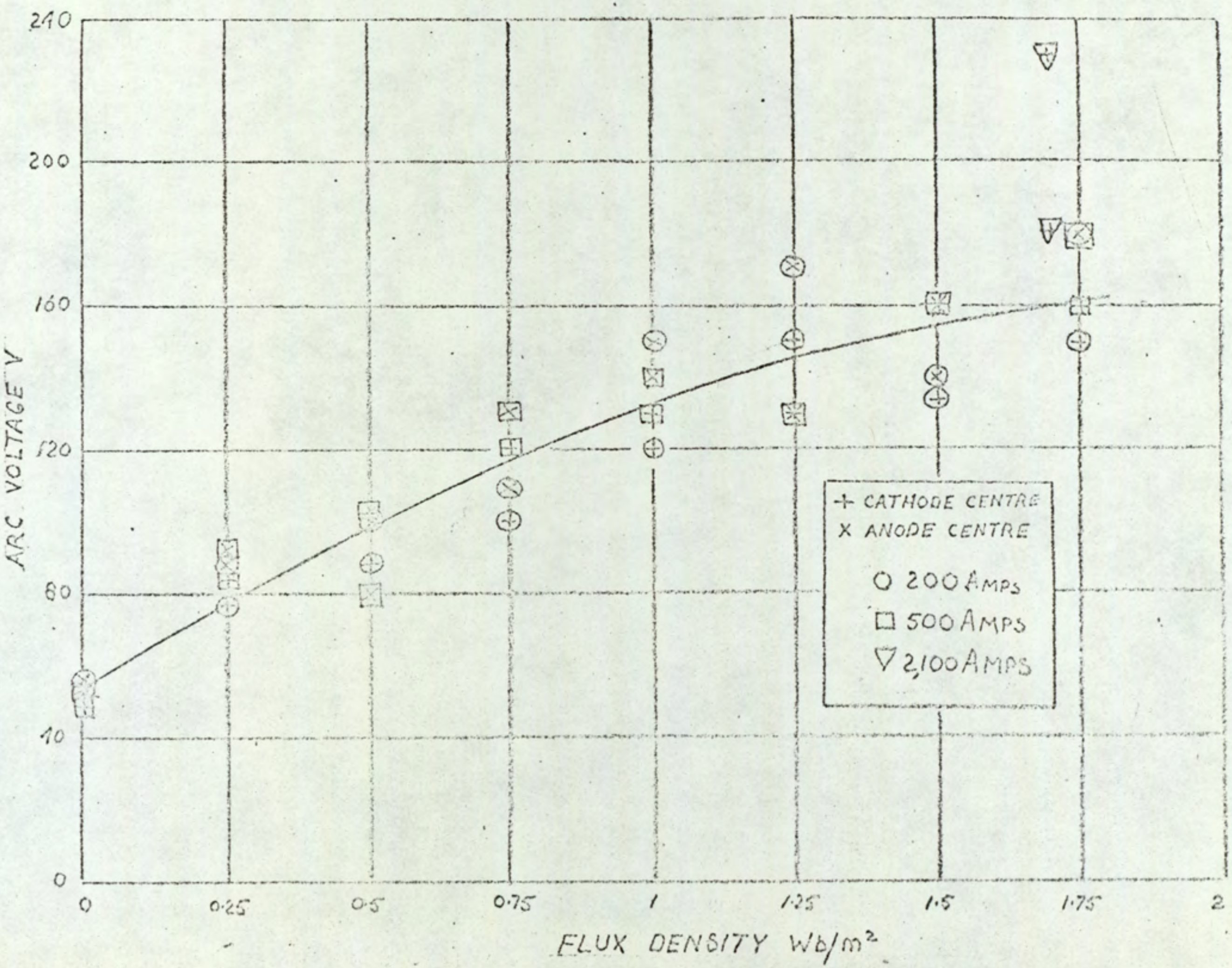
The evidence for the existence of a constricted arc as opposed to an arc diffused around the annular gap is considerable. The variation of the rotational frequency of the arc with magnetic flux density is shown in Fig. 5.18. Regular fluctuations in the voltage output of the coil probe with the frequency continuously increasing with magnetic flux density up to 1.7 Wb/m^2 have been obtained at arc currents of 500A with electrodes of either polarity. Regular fluctuations were also observed at arc currents of 2,100A and at magnetic flux densities of 1.7 Wb/m^2. Good agreement was obtained with results from the optical probe up to magnetic flux densities of 1 Wb/m^2 corresponding to rotational frequencies of about 21,000 r/s. A unique velocity of a rotating arc cannot be determined but it is normally taken as the cathode root velocity where the cathode is the inner electrode. The velocity at the inner electrode has been used for both methods of connection. The values obtained shown in Fig. 5.18 are in good agreement indicating as is to be expected at these high velocities that the arc is column dominated rather than affected by the velocity at the cathode root.

No discontinuity in the variation of either velocity or arc voltage with the magnetic flux density, shown in Figs. 5.18 and 5.19., was observed which might be expected to occur if the arc changed from being concentrated to diffused through the arc gap.



VARIATION OF ROTATIONAL FREQUENCY AND ARC VELOCITY WITH MAGNETIC FLUX DENSITY

FIGURE 5.18



VARIATION OF ARC VOLTAGE WITH MAGNETIC FLUX DENSITY

FIGURE 5.19

At magnetic flux densities of 1 Wb/m^2 and above when the central electrode was made anode the output signals from both the optical probe and the coil probe became irregular. This occurred at rotational frequencies of 10,000 r/s and above and arc currents of 200A and 500A but was not apparent at 2,100A and 1.7 Wb/m^2. At currents of 200A the output waveform from the coil probe above 1 Wb/m^2 became so poorly defined that it was not possible to make measurements of the rotational frequency. Irregular fluctuations in the output waveforms from the probes still however indicated the existence of a constricted arc.

A possible explanation of this behaviour is discontinuous motion at the arc root causing the arc to move in an irregular fashion. Discontinuous tracks from arc roots have been observed on parallel rail electrodes in air at currents up to 600A (Secker & Guile, 1959), but continuous tracks were found at higher currents up to 20,000A under similar conditions (Spink & Guile, 1965). Discontinuous movement of arcs at currents up to 500A driven by their self-magnetic field between parallel brass cylindrical rod electrodes up to 5 mm apart in air at 1 Atm has been observed (Hamilton, 1968).

The reasons for the discontinuous motion at medium currents are not known but may be connected with the division of the cathode spot on cold cathode electrodes which is believed to occur over this range of arc current. If the cathode root is unstable, repeatedly dividing individual roots being created and extinguished, the arc velocity although column dominated may be influenced. At high arc currents the nett effect of root splitting will be proportionately less. (See also 2.1.1.). Under these circumstances the velocity at the cathode root might be affected by the fluctuations in current at the arc roots.

The variation of arc velocity with magnetic flux density and arc current can be expressed by

$$U \propto B^p I^q \qquad (2.12)$$

where U = arc velocity

B = magnetic flux density

and for arcs in air at 1 Atm

$$0.55 < p < 0.65 \qquad (2.13)$$

$$0.4 < q < 0.5 \qquad (2.14)$$

(Myers & Roman, 1967)

The variation of U with B is shown in Fig. 5.20 with log scales

$$p = 0.60 \text{ at } 200\text{A} \qquad (5.7)$$

$$p = 0.54 \text{ at } 500\text{A} \qquad (5.8)$$

Insufficient variation in current was obtained to enable q to be determined accurately.

The variation of voltage gradient in the arc column with magnetic flux density and arc current is given by

$$E \propto B^r I^s \qquad (2.18)$$

where E = voltage gradient in the arc column.

The variation of V with B is shown in Fig. 5.21 with log scales giving

$$r = 0.4 \text{ at } 200\text{A to } 500\text{A} \qquad (5.9)$$

$$s = 0 \text{ at } 200\text{A to } 500\text{A} \qquad (5.10)$$

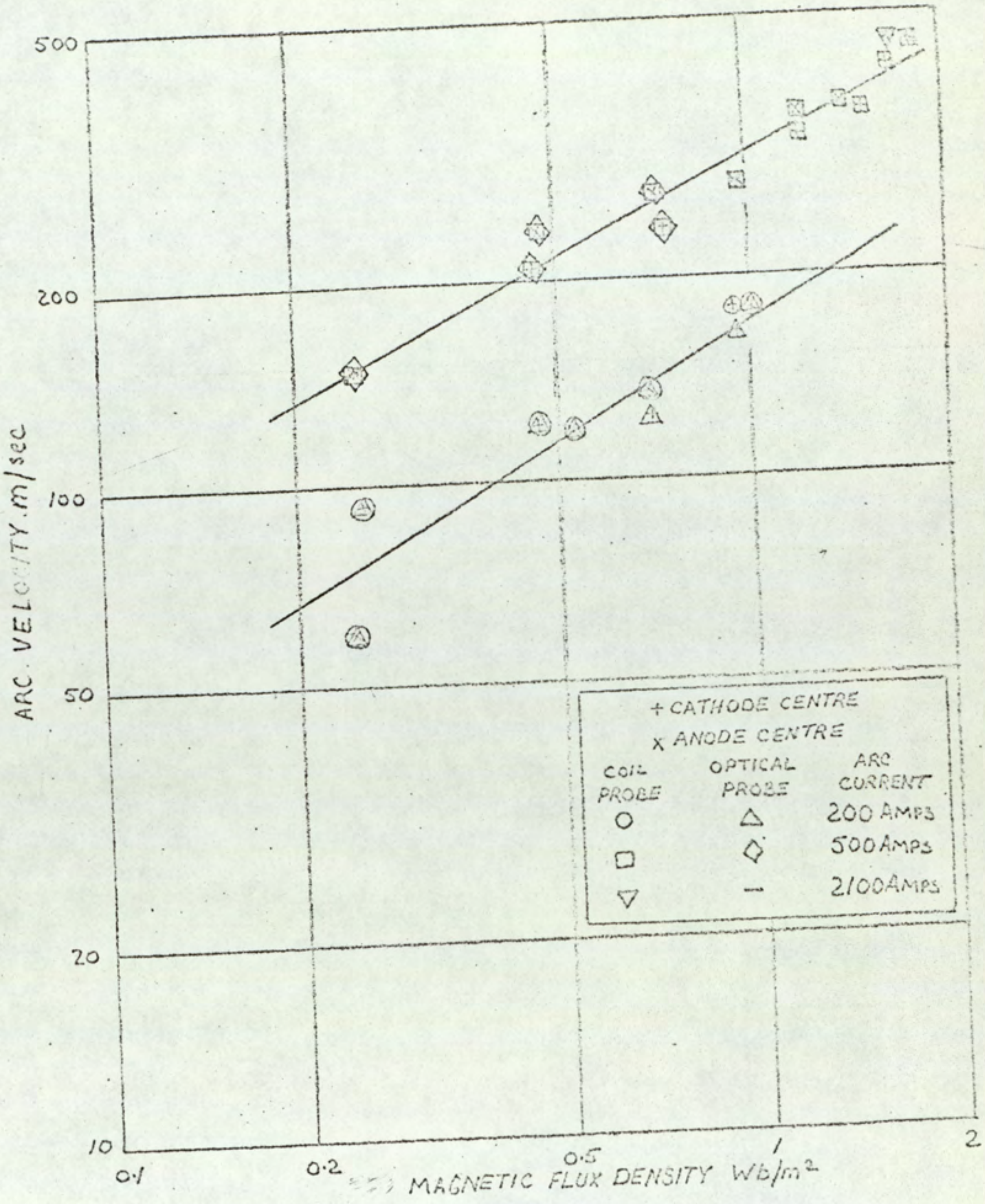
This is not identical with the variation of E with B as the length of the arc may vary with the arc velocity. Results obtained for parallel brass rail electrodes give

$$0.3 < r < 0.4 \qquad (2.20 \;\&\; 2.21.)$$

and for co-axial graphite electrodes

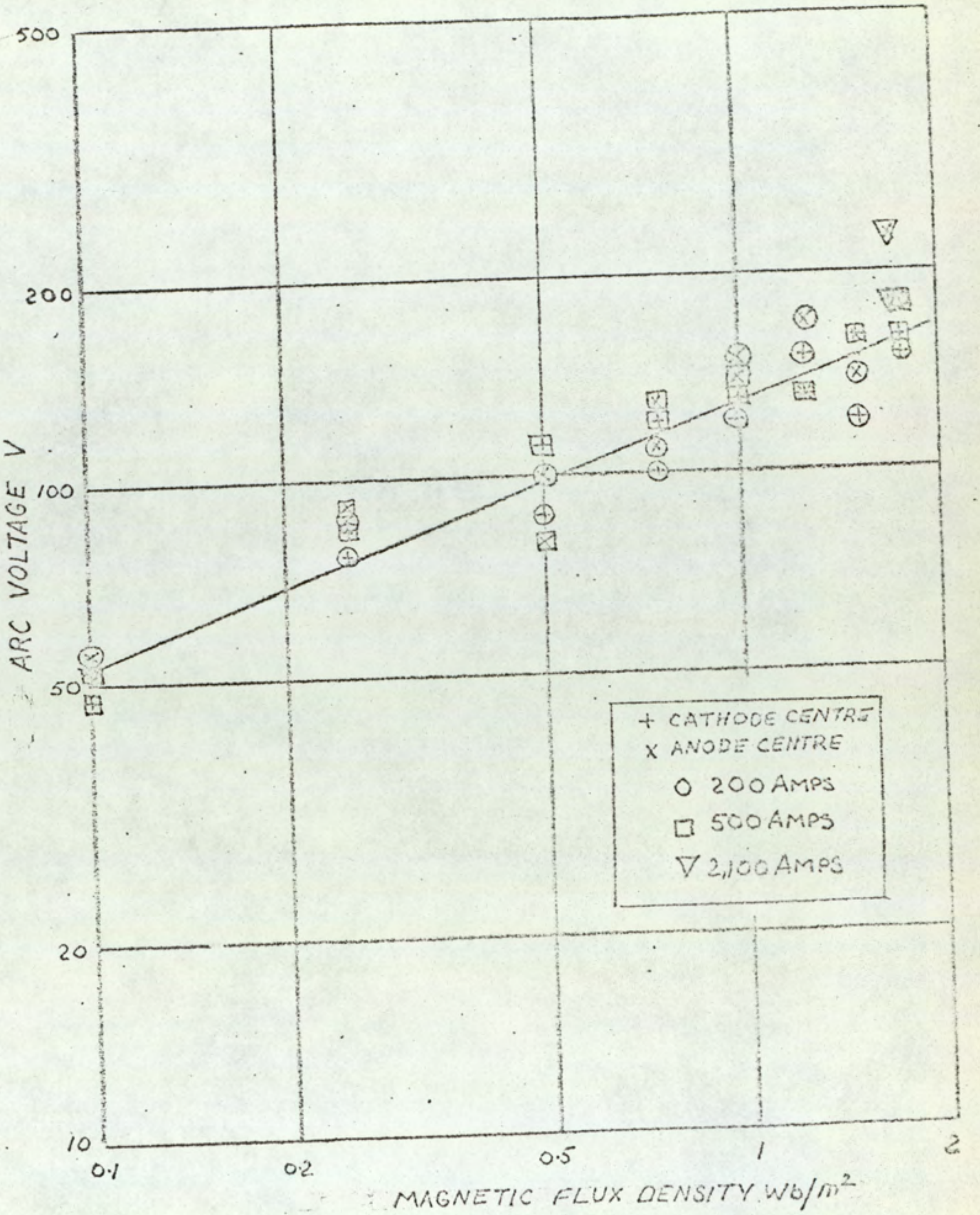
$$r \doteqdot 0.27 \qquad (2.22)$$

In all cases $s \doteqdot 0$.



VARIATION OF ARC VELOCITY WITH MAGNETIC FLUX DENSITY

FIGURE 5.20



VARIATION OF ARC VOLTAGE WITH MAGNETIC FLUX DENSITY

FIGURE 5.21

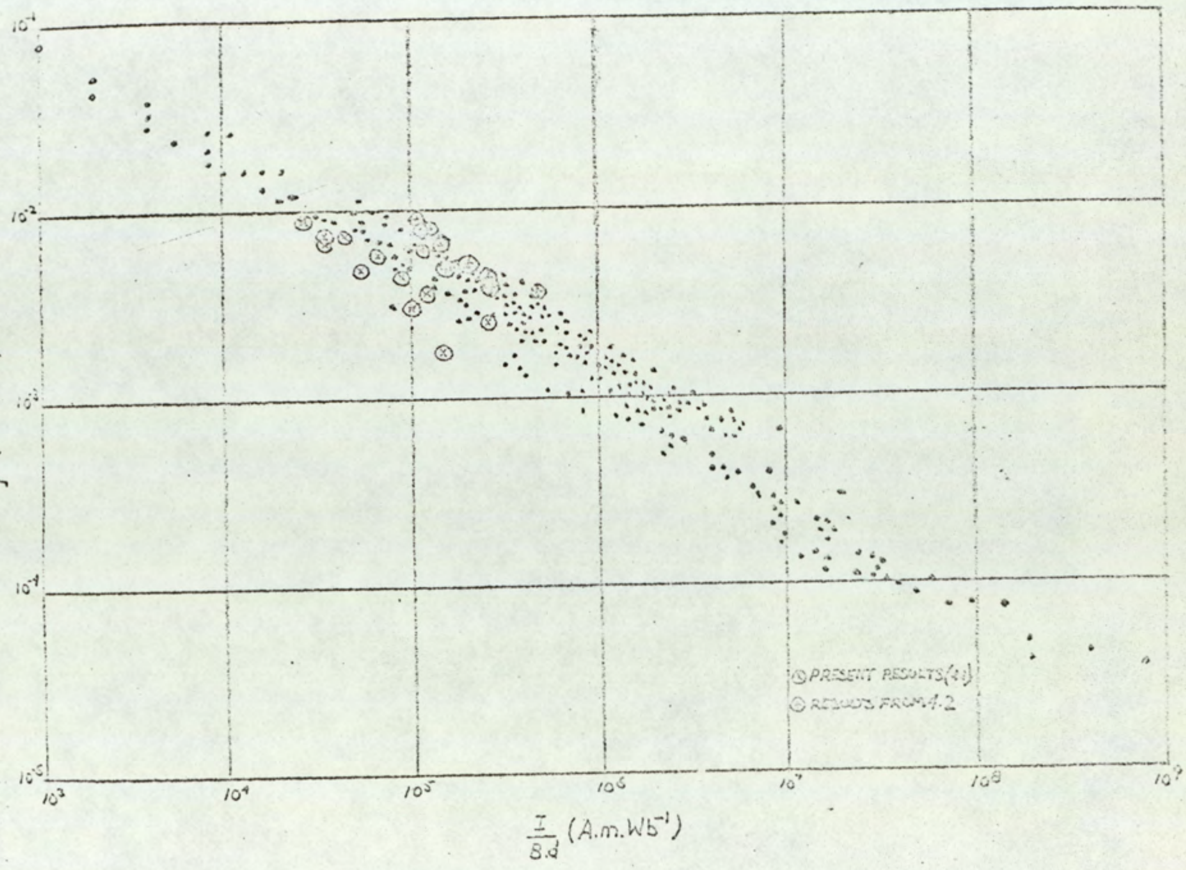
The results obtained here have been plotted in the generalised form suggested by Dautov & Zhukov, (1965) with the results correlated over the range of 3A to 20,000A, 1.3 m/s to 900 m/s, 0.003 Wb/m^2 to 1.0 Wb/m^2 and 0.001m to 0.1 m electrode spacing. (Adams et al, 1967) shown in Fig. 5.22. The results show no significant deviation from the behaviour of the other results which were known to be for constricted arcs.

The apparent change of the dynamic resistance of the arc from negative to positive observed by Mayo and Davis is not necessarily due to the discharge becoming diffuse. The arc voltage is approximately independent of the arc current at high currents but the arc velocity continues to increase with the arc current. Since the voltage

$$V = f(B) \tag{5.11}$$

∴ the change may be due to the increase in voltage with arc velocity at high arc currents which may be greater than the decrease in the voltage resulting from a negative characteristic. This is implied by the present results obtained at 2,200A and 500A. Positive arc characteristics have in any case been obtained previously for static arcs in air (King, 1961) and are indicated by the results for self driven arcs between parallel rail electrodes in air at high currents (Spink & Guile, 1965).

The measurements of erosion rate reported by Mayo and Davis are expressed as percentage contamination of the heated gas. The minimum erosion rate may be calculated from the contamination level and flow-rate by assuming the highest current was used at the highest gas flow-rate which gives an erosion rate of 28×10^{-6} g/coulomb. This is an order of magnitude higher than the results obtained in the erosion measurements described in 5.2. where the



CORRELATION OF VELOCITY MEASUREMENTS WITH MAGNETIC CHARACTERISTIC OBTAINED FOR CONSTRICTED ARCS BY ADAMS ET AL 1967.

FIGURE 5.22

arc was constricted at all times and therefore cannot be attributed only to the arc becoming diffuse. The decrease in erosion rate compared with other arc heaters observed is more likely due to the increased arc velocity at the higher magnetic field used and the differences in electrode geometry.

5.1.6. The Persistence of Luminosity in an Arc Gap.

The main evidence for the existence of diffuse arc discharges is the uniform luminosity of the entire annular electrode separation. The results obtained here indicate that although the arc may appear to be diffuse a constricted arc is still present. Measurements of the persistence of the luminosity of an arc after current interruption indicated that the luminosity persisted for several milliseconds.

The cause of the luminosity is not clear but there are several possible explanations other than the existence of a diffuse discharge.

The decay of light output from spark discharges with electrode separations of a few millimetres has been observed with a photo-multiplier (Johnson & Jones, 1952) in various gases and liquids including air at 1 Atm. A rapid initial decay of 1×10^{-5} of the peak value was obtained in the first 300 microseconds after which the light output decayed by only 1×10^{-2} of the peak value in the subsequent 300 μsec. It was later shown that the slow decay of the apparent luminosity was due to phosphorescence of the glass in the optical system used (Guile, 1967).

Phosphorescence is unlikely to have caused the luminosity observed here or in the observations of Mayo and Davis. If the lens of the high speed camera becomes phosphorescent the entire lens will be affected since the lens aperture is situated behind the lens. As a result the entire film frame would be fogged, which did not occur. The optical probe from which the results were obtained used a quartz window for which the phosphorescence is very much less than that of glass.

Luminescence due to persistence of ionised gas may occur. At arc currents up to 25A in air at atmospheric pressure the temperature of the arc column measured acoustically between copper electrodes 2 mm apart decays from about 6,000°K to 4,000°K in the first 100 microseconds after current interruption (Edels & Holme, 1966). The decrease in conductance during this time for a similar arc was about an order of magnitude (Kimblin & Edels, 1966). Increase in arc current and electrode separation should decrease the rate of decay as the cooling effect of the electrodes is reduced and the volume of the discharge increases.

The luminosity of an arc of several thousand amps in air at 1 Atm persisted for more than 1 second after the current had been interrupted (Forrest, 1950). The luminosity was attributed to the presence of ionised gas but may be due to vapour from the electrodes or the fuse used to establish the arc.

The persistence of luminosity observed by Mayo and Davis and by Forrest may be due to active nitrogen. The slow decay of active nitrogen from its excited state or the process by which it is produced have not been agreed on. It has been mainly investigated at low gas pressures in high purity nitrogen but it has been shown to exist in air at atmospheric pressure for times long enough to enable visual observation of its characteristic yellow after-glow obtained on de-excitation (Strutt, 1916). Active nitrogen can be produced at atmospheric pressure by an arc discharge (Stanley, 1954). At low pressures de-excitation has been observed after half an hour (Strutt, 1916), but at atmospheric pressure with oxygen and moisture present its lifetime will be greatly reduced. The period of rotation corresponding to the region at which the output from the optical probes became unreliable was about 50 microseconds and it is possible that the persistence of illumination observed during this time may be due to the presence of active nitrogen. Other results where long jets of luminous gas have been observed (Moss & Young, 1964, Thorpe, 1966), may also be explained by this mechanism (see also section 4.1.5.).

The overall results indicate that the observation of arc behaviour, particularly when moving at high velocities between co-axial electrodes, may give misleading results due to the slow decay of luminosity in the electrode gap. No evidence of a diffuse discharge has been obtained over the range of arc current and magnetic flux density investigated. It is believed that the apparently diffuse discharge that has been observed previously was due to persistence of luminosity due either to hot electrode vapour or the persistence of metastable states of excited gas molecules.

The results of this section have been incorporated in "Concentrated or Diffused Arcs", Harry J. E., Guile A. E. which has been accepted (March 1968) for publication in Proc. I. E. E.

5.2. The Measurement of the Erosion Rate at the Electrodes of an Arc Rotated by a Transverse Magnetic Field.

The tests described in the preceding section 5.1. indicated that under the conditions investigated a diffuse arc discharge was not obtained up to magnetic flux densities of 1.7 Wb/m^2. The reduced erosion reported by Mayo and Davis was not therefore a result of the arc becoming diffuse, for which they suggested magnetic flux densities of the order of 1 Wb/m^2 were required, but was more likely to be due to the high arc velocity at these values of magnetic flux density. The term erosion is used here in the sense it is normally used to include both loss of material caused by the evaporation of electrode material by physical processes and chemical combination with the ambient gas, since it is difficult to estimate the two effects separately. The various erosion processes have been discussed in 2.1.4.

The power input to a field coil increases with the square of the magnetic flux density. At high magnetic fields the power losses in the field coil may become comparable with the power losses in the plasma torch. The progressive increase in the magnetic flux density that had been previously carried out (see also 3.5) cannot be continued indefinitely for a rotating arc. The electrode erosion rate will depend on both the arc velocity and rotational frequency.

The variation of electrode erosion rate as a function of arc velocity, rotational frequency and hence magnetic flux density is an important parameter of a plasma torch. It was possible that very little if any advantage would be obtained above a critical value of arc velocity affected by the rate of thermal diffusion in the arc electrodes and the period of rotation. The rate of thermal diffusion may be expressed in terms of the depth of thermal diffusion which is a measure of the penetration of the heat pulse at the arc root during the period of rotation of the arc

$$\delta = (\alpha \tau)^{\frac{1}{2}} \qquad (5.12)$$

where δ = diffusion depth (cm)

τ = time between the heat pulse (s)

α = thermal diffusivity of electrode material(cm. s)

where $\alpha = \frac{k}{\rho c_p}$ (5.13)

k = thermal conductivity (w. cm. /cm^2 ^{o}k)

ρ = density (g/ml)

C_p = specific heat (J/g ^{o}c)

When $\delta \rightarrow 0$ little further decrease in evaporation rate may be expected to occur.

The effect of cooling water flow-rate and electrode wall thickness were also of interest. The general tendency has been to use high pressure water supplies at high velocity in order to obtain a high heat transfer coefficient at the copper water interface. Thin wall electrodes have been regarded as necessary in order to minimise electrode vaporisation (Winkler et al, 1964, Phillips, 1964). The electrode wall thickness cannot be decreased indefinitely and will have an optimum value determined by the rate of evaporation, rate of thermal diffusion, and wall thickness.

Qualitative results from a wide range of sources (see also 3. 5) for varying electrode geometries indicate that the electrode erosion is small at magnetic flux densities of 0. 1 Wb/m^2, and arc velocities of about 300 m/s. The erosion at the arc anode is normally assumed to be less than that at the arc cathode for reasons that have been discussed in 2. 1. 4. It was therefore decided to confine the investigations mainly to the measurement of cathode erosion, increasing the magnetic flux density from about 0.1 Wb/m^2 corresponding to arc velocities of about 100 m/s for the electrode configuration used.

5.2.1. The Electrode System.

Electrode erosion is dependent on

1. The arc velocity.
2. The electrode material.
3. The ambient gas.
4. The electrode shape, size and separation.
5. The electrode polarity.
6. The electrode cooling.
7. Heat transfer from the arc column.

In addition if the arc rotates between co-axial electrodes it is dependent on the period of rotation as well as the arc velocity.

The variation of the minimum erosion rate with the magnetic flux density was required under conditions comparable with those obtained in a plasma torch rather than a rigorous investigation of erosion under a wide range of conditions. The values obtained in this way could then be used as a reference for comparison with electrode systems which might be influenced by factors other than the electrode erosion rate. The effect of varying the electrode wall thickness and cooling water flow-rate on the erosion rate was also required.

Different ambient gases are likely to have an appreciable effect on the erosion rate due to chemical combination at the electrode surface and differences in physical properties such as the ionisation potential and transport properties. An inert gas would prevent chemical combination of the electrode material occurring but since it was intended to apply the results to a plasma torch working in air it was necessary to make the erosion measurements in air.

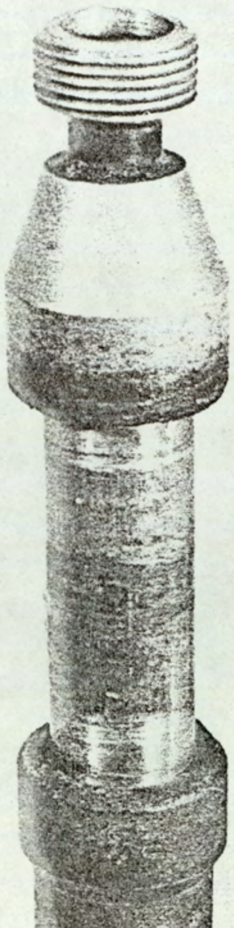
Since the minimum erosion rate was needed it was important to optimise the conditions described in 1 to 7 above for minimum erosion to occur. The most suitable prectical electrode material has already been discussed in section 3.3 and shown to be copper if the melting point is not exceeded, because of its high thermal conductivity. As a result phosphorous de-oxidised copper was used because of its ready availability. The effect of impurities on the thermal and electrical conductivities is small and was not considered to be an important factor affecting electrode erosion (see also 5.2.6).

For efficient electrode cooling the water flow-rate should be sufficient to prevent local boiling, when the heat transfer co-efficient to the water becomes unstable and the overall heat transfer is greatly reduced. The heat transfer at the arc root is localised to a small axial region of the electrode. Very little radial mixing of the heated water may occur in this region and the mean temperature rise of the cooling water should be small. It is difficult to estimate the effect of this, so initially the largest possible flow-rate was used with provision to reduce the flow-rate when required. For maximum heat transfer the Reynolds Number for the water flow should be as high as possible and therefore the water velocity should be high. In practice this was determined by the bore of the electrode and the pressure of the cooling water supply available.

The simplest form of electrode geometry possible comprising two co-axial electrodes with the axis vertical was used. The central electrodes Fig 5.23 had a minimum bore diameter of 0.38 cm with a constant outer diameter of 2.54 cm. This allowed considerable variation in the wall thickness of the central electrode without appreciably altering the maximum water flow-rate through it. The water flow-rate could be maintained at 0.5 l/s at which the mean temperature rise of the cooling water in the central electrode was less than 5^{o}c. The electrode erosion rate will also be dependent on the arc velocity and the period of rotation which is governed by the circumfrential path length. The circumfrential path length at the central electrode was one which could be easily realised in a plasma torch.

The change in weight of the electrode due to erosion was expected to be very small compared with the weight of the electrode and the central electrode was made as light as possible for the first series of tests. The minimum thickness of the electrode walls was limited by mechanical strength to about 0.025 cm. A minimum length of about 7 cm was necessary to ensure that the arc did not touch the end fittings.

The electrode separation used was 0.8 cm, the same as that used in the previous test described in 5.1 so that some consistency was obtained enabling comparison of the results from the two tests where possible to be made. The radial separation of 0.8 cm is such that the cathode and anode fall regions are small compared with the electrode separation. Under these conditions the arc might be expected to behave as a medium length arc if the transition ~~or long arc~~ regions are small and is typical of separations that have been used in the plasma torches described in Chapter 3.



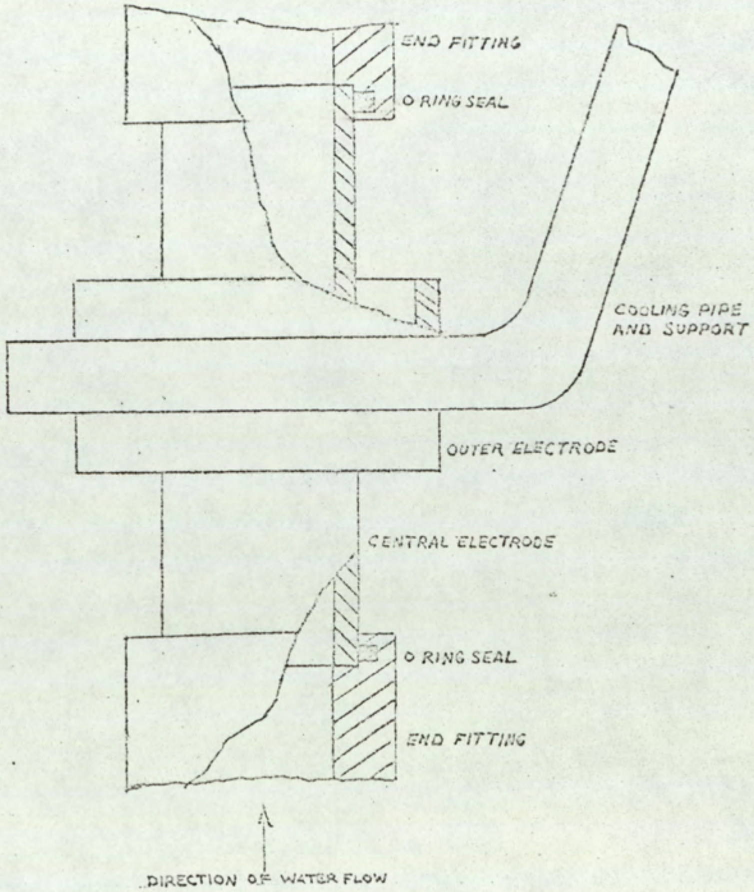
Central Electrode with End Fittings

Figure 5.23.

Previous measurements for the erosion rate of a static arc at 200A between copper electrodes in air (Holm, 1949), indicated an erosion rate of 400×10^{-6} g/Coulomb. The minimum value of erosion rate obtainable postulated by Holm, which might be expected to be approached by an arc moved at a high velocity over water cooled electrodes, was 13.10^{-6} g/Coulomb. Using these values the total erosion after 10 minutes corresponds to 48 g and 1.56 g respectively.

The percentage change in weight of the central electrode due to erosion was expected to be small. It was therefore important to prevent any changes in weight of the electrode that might occur in mounting or demounting the electrode, for example due to wear at screw threads. To reduce this to a minimum the central electrode was held by friction only with O ring seals in two brass end fittings to which electrical and water connections were made. The complete electrode assembly is shown in Fig. 5.24. The end of the central electrode butted on a ridge in each end-piece which ensured good electrical contact to the electrode. The O-rings were used ungreased to prevent grease adhering to the tube and causing errors in measurement of the electrode weight.

The outer electrode was a copper tube cooled by a square copper pipe silver soldered to the outside of the tube. The cooling pipe was also used to support the electrode, and as the electrical connection to it. The length of the tube was made longer than the width of the cooling pipe to prevent the arc from running on the outer surface of the electrode. In addition the outer surface and ends of the electrode were covered with refractory cement to prevent the arc from running on them. In the tests in which a graphite outer



The Complete Electrode Assembly.

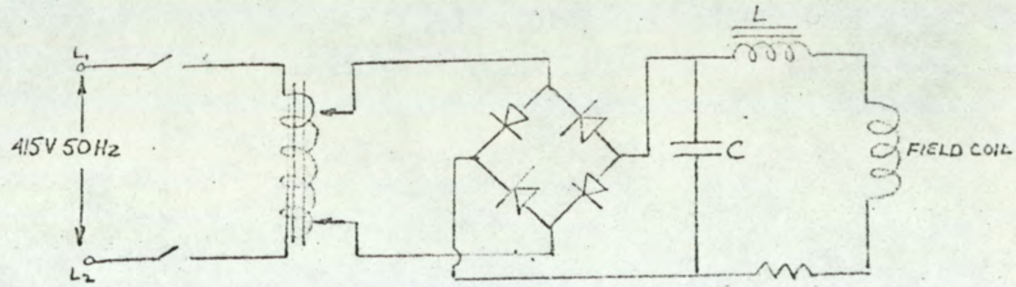
Figure 5.24.

electrode was used the outer electrode was of the same construction but with a larger bore sleeved with a graphite insert so that the electrode separation remained the same.

5.2.2. The Field Coil and Power Supplies.

The field coil used was originally intended for another application in which a continuous magnetic flux density of 0.1 Wb/m^2 was required. It consisted of 225 turns of 2 s.w.g. double cotton insulated wire wound on a former with an internal bore diameter of 18 cm and overall length of 11 cm. It was however possible to obtain flux densities as high as 0.5 Wb/m^2 for more than 1 minute when starting from room temperature, sufficient for measurements of arc voltage and current to be made. Flux densities up to 0.35 Wb/m^2 could be obtained for up to 10 minutes without damage to the coil insulation.

The field coil was supplied from a single phase bridge rectified 50 Hz a.c. supply. The input voltage to the rectifier was controlled by an on-load variable output transformer which enabled



Field Coil Power Supply.

Figure 5.25.

the field current to be held constant to within ± 5%. The field supply circuit is shown in Fig. 5.25.

The rectified output obtained from the power supply was smoothed with a capacitor input L-C filter with an inductance of 2.5 mH and a capacitance of 28.10^3 microfarads. The ripple factor in terms of the field current was less than 2% at a flux density of 0.5 Wb/m^2.

The arc current was supplied from the same d.c. source used for the pulsed field coil described in section 5.1.2. and shown in Fig. 5.10. In addition an inductor of 2.82 mH was connected in series to improve the arc stability. The arc current could be varied between 30A and 280A with a tapped series resistance of total resistance 5 ohms. Connection to the central electrode was made at either end of the electrode each connection having a balancing resistance of 0.05 ohms in series to reduce the effect of the self-magnetic field. The upper limit of current was governed by the maximum possible dissipation of heat in the locality of the resistor rather than by the rating of the power supply itself. The maximum current obtainable was limited by this to 200A for 10 minutes at which about 80 kW was dissipated in the series resistance. The ripple factor in terms of the arc current at 200A was measured and was less than 10% of the mean value of arc current.

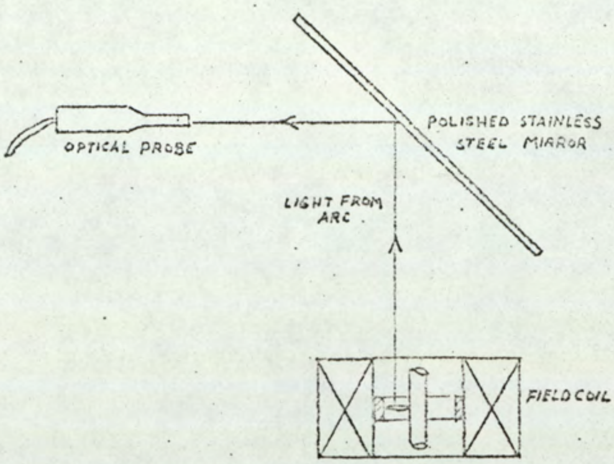
5.2.3. Instrumentation.

The arc current was measured with a moving coil ammeter and normally varied by less than $\pm$ 4%, the mean current varied during a test by an amount smaller than this. The voltage fluctuations about a mean value were greater than $\pm$ 4% and initial measurements were made with a thermo-couple voltmeter in order to damp the more rapid fluctuations so that the mean value averaged over a period of the order of a second was obtained. Less than a fifth of the scale was usable if the open unit arc voltage was within the full scale deflection of the meter resulting in readings of poor accuracy. Protection of the thermo-couple heater with Zener diodes so that the meter could be used on a more sensitive range without damage if the arc was extinguished was attempted, but leakage currents below the Zener breakdown voltage substantially affected the accuracy of meter readings. Finally a moving coil voltmeter with a full scale deflection of about half the open circuit voltage of the power supply was used with fuses in the leads and was switched into circuit only while readings were made. The arc voltage was generally less stable than the arc current but average values could be estimated in this way to within about $\pm$ 10% of the mean value in the worst case and normally to within about $\pm$ 3% when the arc was in a stable mode.

The current in the field coil was obtained from the voltage drop across a series shunt in the field coil supply circuit measured with a digital voltmeter. The magnetic flux density at the centre of the coil was obtained from the coil calibration curve obtained with a Hall probe. The variation of the magnetic flux density in the volume occupied by the electrode gap was also measured at the time of calibration and was within $\pm$ 5% of the value at the centre, the greatest variation occurring in the radial direction.

The rotational frequency of the arc was measured with the optical probe described in section 5.1.3. and shown in Fig. 5.12 which is reliable over the range of frequencies measured here.

The probe was directed at the reflected image of the arc in a



Optical Arrangement for Observation of Arc and Measurement of Arc Velocity.

Figure 5.26.

sheet of polished stainless steel shown in Fig. 5.26 normally used for indirect observation of the arc.

The mass of the electrodes was measured with an analytical beam beam balance to within 0.005 g corresponding to less than 0.025% of the total weight of the electrode. A greater accuracy was obtainable with a 0.001 g rider but was not thought justifiable due to the comparatively large spread in the readings obtained.

The arc was ignited with a small piece of aluminium foil bridging the arc gap which was either ejected on ignition or in some cases vaporised completely. The possible error due to condensation of the aluminium foil on the electrodes is very small since the aluminium foil used weighed less than .01 g.

5.2.4. Observations and Measurements.

The arc rotated between the two electrodes in a stable mode at magnetic flux densities above 0.1 Wb/m^2 and at currents of about 100A and above. At values of magnetic flux density and current below these corresponding to rotational frequencies of less than 1,000 r/s the arc tended to run outside the arc gap on the central electrode in a very unstable mode, extinction usually occurring after a short time.

Reversal of the vertical direction of the magnetic field by changing the polarity of the field coil connections had little or no apparent effect on the arc behaviour apart from changing the direction of rotation. Depending on the axial direction of the magnetic field and the electrode polarity, movement of the arc away from the centre of the coil should be accompanied by either a force directed inward or outward from the centre of the coil. This is due to interaction of the arc current with the non-axial components of the magnetic field away from the coil centre. As the coil was long compared with the possible axial movement of the arc the horizontal component of the magnetic field will be small. The positioning of the electrodes was found to be very critical if the arc was to be run for several minutes. This was probably due to convection effects which although the arc has a high velocity of rotation may cause a slow drift in the axial direction causing instability when the arc runs outside the annular arc gap.

Measurements of the change in weight of the central electrode were made after various running times, drying the electrode in an oven at about 80^{o}c to remove all traces of moisture before weighing it. It was found in some cases that initially, after the first minute or so of running the electrode gained in weight. At the same time black and red scale was apparent on the electrode surface. The increase in weight was thought to be due to the formation of this scale which is probably black cupric and red cuprous oxide.

Appreciable random variations occurred in the erosion rate for the same arc current. These random variations were attributed to the formation of the oxide scale which is only weakly attached to the electrode and may drop off in subsequent tests. Accordingly it was decided to condition new electrodes before making erosion measurements by running the arc on them until the arc path was oxidised and to remove loose scale before each weighing by wiping the electrodes with a soft cloth. The initial conditioning also removed traces of oil or grease remaining from machining, and care was taken not to touch the arc path by hand after conditioning.

The initial measurements of the erosion rate indicated only a very small change in weight occurred and it was therefore desirable to run the arc for as long as possible before measuring the loss in weight. This was limited to about 10 minutes by the power dissipated in the series resistance in the arc supply circuit. If the arc was extinguished during this time the electrode was dried and reweighed but the result was not used, so that the conditions of measurement were the same in each case.

No results were included when the electrode wall was punctured during a test since very rapid erosion occurs under these conditions not typical of the normal erosion rate. Even with these precautions quite considerable fluctuations in the erosion rate of up to 50% were observed and it was decided to obtain several measurements at each value of magnetic flux density used.

The effect of taking more than 1 set of readings is to reduce the overall error by a factor $\left(\frac{1}{N-1}\right)^{\frac{1}{2}}$ (Bell, 1953) where N is the number of sets of readings obtained. In this case 36 sets were obtained at each value of magnetic flux density resulting in an overall error of less than 25%.

The first series of measurements were made on the copper cathode with a wall thickness of 0.025 cm. Since the preparation of the 0.025 cm wall tubing involved an appreciable amount of machining from the available thick walled tube a thinner walled copper tube from a different source requiring less machining was tested. Two electrodes were made from this tubing the first failing on ignition of the arc, the second tube failing on ignition after it had been

and no measurements were obtained.
conditioned This early failure was not observed at any time with any of the electrodes made from the original copper used (11 in all). Failure only occurred due to puncturing of the electrode wall after a considerable running time normally of the order of an hour or more.

To determine the cause of failure the copper used for each electrode was analysed and the results are discussed in 5.2.6. Further tests used the original copper.

The effect of varying the electrode wall thickness and cooling water flow-rate on the rate of erosion was investigated. Two electrodes of wall thickness 0.25 cm and 0.5 cm respectively were tested at the maximum water flow-rate and the electrode with 0.25 cm wall thickness at half the maximum flow-rate at the same arc current and magnetic flux density.

At water flow-rates less than half the maximum flow-rate very rapid electrode failure occurred. When the electrode was replaced with a piece of glass tube it was observed that the tube was no longer completely filled with water, streaming to one side of the tube resulting in poor cooling of the electrode. At higher values of flow-rate the glass tube was entirely filled.

An attempt was made to measure the anode erosion by reversing the polarity of the electrodes. Measurements showed that an appreciable increase in weight of the central electrode had occurred and deposits on the surface of the anode, not present when it was a cathode, were apparent. The increase in weight was attributed to metal transfer by the cathode jet from the less effectively cooled outer electrode which was now the cathode. To reduce the material transferred a series of tests were carried out using a graphite outer electrode with the same electrode separation as before.

The central electrode was connected both as a cathode and as an anode. With the central electrode connected as cathode the erosion rate was identical to that obtained previously for the copper cathode with a copper anode as the outer electrode but when the connections were reversed the erosion rate of the anode was appreciably less.

Erosion measurements were made with a brass cathode of wall thickness 0.25 cm and a copper anode. The brass was a typical leaded brass with a chemical analysis of 57% copper, 2.7% lead and 40.3% zinc. The arc was very stable on the brass cathode keeping to the same path and rapidly eroding a groove in the electrode surface which is shown in Fig. 5.31. The change in weight was very much greater than that measured for the copper electrode and only two measurements of erosion were required to obtain the same order of accuracy since the effect of minor variation was very much less.

5.2.5. The Electrical Characteristics and Velocity Measurements.

The variation of arc voltage with magnetic flux density is shown in Fig. 5.27 at various values of arc current. The arc voltage tends to increase with magnetic flux density and is higher with the anode at the centre.

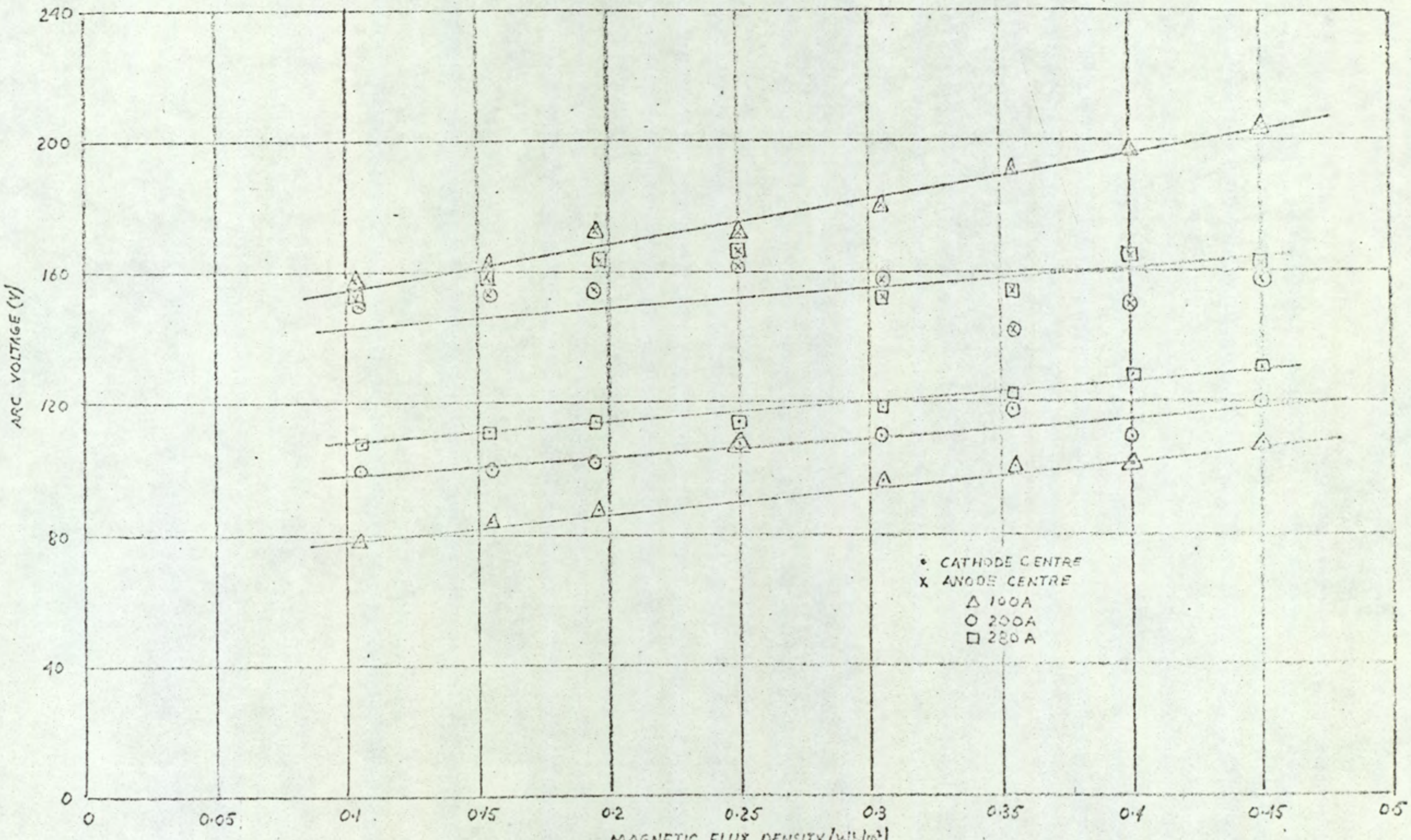
The variation of V with B is shown in Fig. 5.28 with log scales. The variation of arc voltage with magnetic flux density and arc current has been expressed as

$$E \propto B^r I^s \qquad (2.18)$$

here

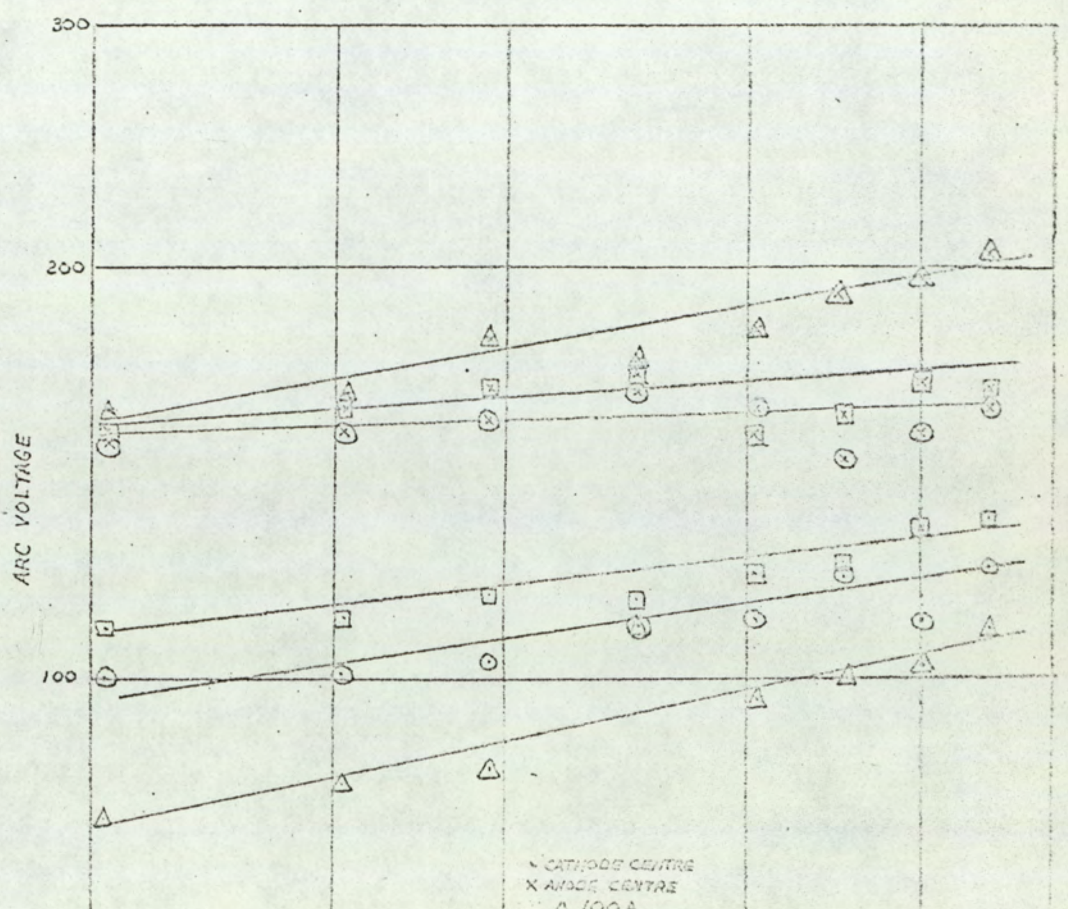
$$r \doteqdot 0.16 \qquad (5.14)$$

This relative independence of the arc voltage from the magnetic flux density where the induced e.m.f. in



VARIATION OF ARC VOLTAGE WITH MAGNETIC FLUX DENSITY

FIGURE 5.27



VARIATION OF ARC VOLTAGE WITH MAGNETIC FLUX DENSITY

FIGURE 5.28

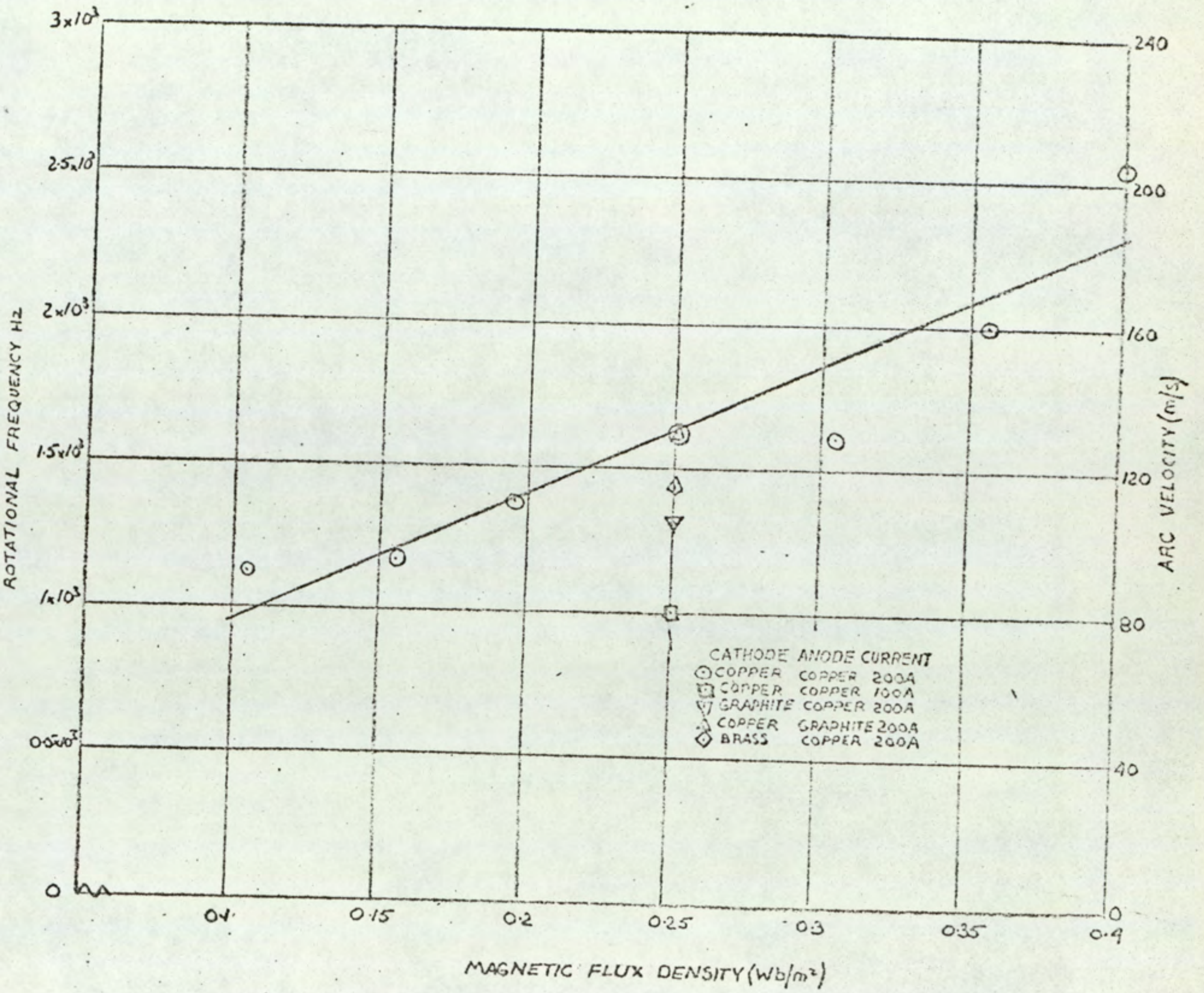
the arc is small compared with the arc voltage has been shown elsewhere and has been discussed in section 2.4.3. The most comparable results are those obtained with co-axial brass electrodes in air at atmospheric pressure for an electrode separation of 1.27 cm and for the same inner electrode diameter that was used here, with the centre electrode as cathode (Adams, 1965). A variation in the voltage gradient in the arc column of about 25% was obtained over a range of magnetic flux density of 0.02 to 0.14 Wb/m^{-2} for a range of arc currents from 200A to 500A corresponding to $\delta = 0.21$.

No results are available to compare the arc voltage measured with the anode as the central electrode which was generally higher than those obtained when the cathode was at the centre, although Adams (1964), found that it was more difficult to obtain steady rotation. The difference in voltage, obtained with reversal of the electrode polarity may be caused by the possible variation in arc length. A rotating arc will tend to take up either a radial or involute shape depending on the arc velocity and electrode separation (Adams, 1964). Observations made with a high speed framing camera showed that the arc was of an approximately involute shape with a characteristically dragging anode root causing shunting of the arc column to take place, and the arc was column dominated. The cathode root leads the arc column even on the outer electrode where the circumfrential path length is about 1.6 times that at the inner electrode. The arc voltage is influenced by the length of the arc column which in turn is affected by shunting of the arc column in particular at the anode root. When the outer electrode is made the anode a concave surface is presented to the dragging arc column encouraging shunting whereas when the anode is the centre electrode the convex surface discourages shunting. As a result the arc voltage tends to be higher when the anode is at the centre.

The more rapid increase in arc voltage obtained as the magnetic flux density is increased at 100A with the anode at the centre is probably due to the increased instability of the arc which was observed at this low value of arc current. The effect of the instability which tends to cause arc extinction results in an increase in the measured mean voltage above that of a stable arc.

The variation of arc voltage with arc current may be seen from the results in Fig. 5.27. These have not been plotted separately as the variation is not sufficient over the small range of arc current used. The values of arc voltage obtained when the cathode is at the centre show the arc voltage increasing with the arc current. The corresponding variation of arc velocity with arc current is about 50% (Fig. 5.29), equivalent to a variation of magnetic flux density at constant current of about 2:1. Again referring to the variation of arc voltage with magnetic flux density indicates that this corresponds to a voltage variation of about 10% similar to that observed.

The results obtained for the central electrode as anode show an appreciable decrease in arc voltage from 100A to 200A implying a negative V-I characteristic, however both the greater



VARIATION OF ARC VELOCITY WITH MAGNETIC FLUX DENSITY

FIGURE 5.29

instability of the arc at the lower value of arc current when the anode is at the centre, and greater arc length could cause this. The small difference obtained in arc voltages measured at 200A and 280A when the arc is more stable is consistent with this explanation. Similarly the lower arc voltages measured with one graphite electrode are likely to be due to the reduced fluctuations in arc movement that were observed since the arc velocity is not substantially different from that measured with two copper electrodes.

The variation of the rotational frequency and velocity of the arc at the surface of the inner electrode shown in Fig. 5.29. show the arc velocity and rotational frequency increasing with the magnetic flux density. Little difference is apparent in the arc velocity measured on copper or graphite electrodes. The velocity was considerably less at 100A. The variation of U with B is shown in Fig. 5.30 with log scales.

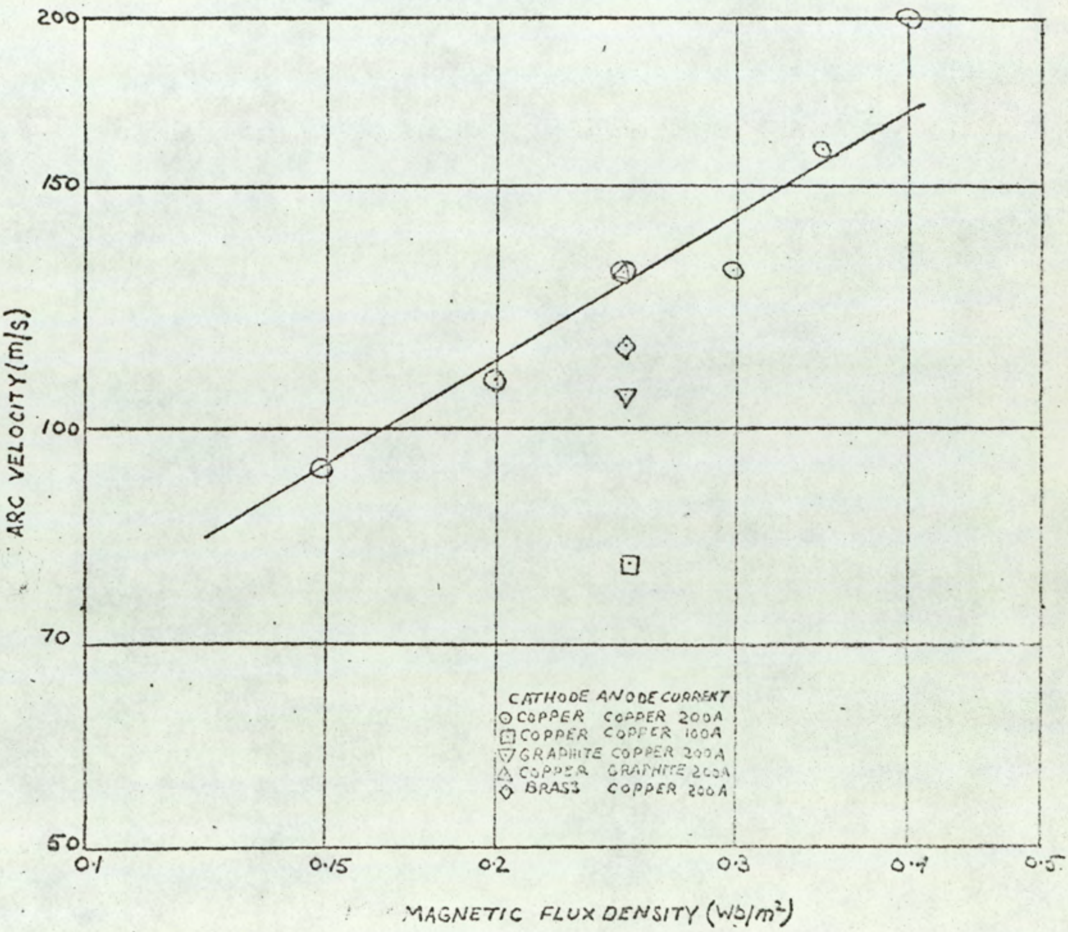
The variation of the arc velocity with magnetic flux density at constant arc current can be expressed as

$$U \propto B^{P} \qquad (2.12)$$

where $0.55 < P < 0.65$ (2.13)

here $p = 0.62$

The velocity measurements have also been plotted in the generalised form suggested by Dautov (1965) (Fig. 5.22) and are consistent with the results correlated by Adams et al, 1967.



VARIATION OF ARC VELOCITY WITH MAGNETIC FLUX DENSITY

FIGURE 5.30.

5.2.6. Discussion of Erosion Measurements.

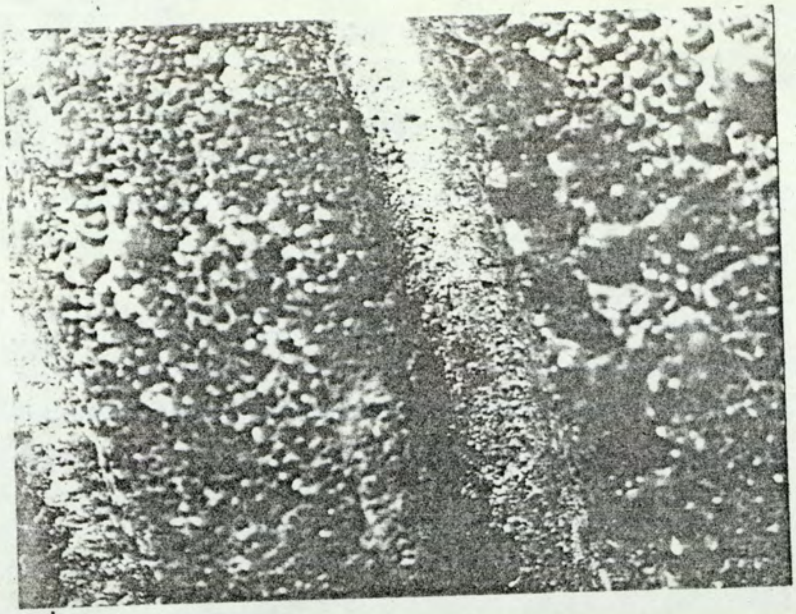
An enlarged photograph of the surface of the brass electrode is shown in Fig. 5.31. No grooves were apparent in the surface of the copper electrode but a deep groove was very rapidly formed on the brass electrode after only one test. The other groove was obtained in the second test on the electrode when the electrode was inverted. The grooves indicate that when a groove is formed and the arc is more stable the arc root is confined to the groove which becomes progressively deeper.

Macro-photographs of the surface of the copper and brass electrodes after several tests are shown in Fig. 5.32. In both cases the arc track differs from the rest of the electrode the preferred path being almost free from asperities. This is particularly evident in the case of the copper electrode where even marks left from machining have been removed on the arc path. The tendency of the arc to rotate around a preferred path in an oxidising gas such as air is in good agreement with results that have shown that the arc velocity increased until an optimum oxide layer is built up (Burkhard, 1966), and tended to travel along the same path at each revolution (Bronfman, 1963).

The results obtained for the measurement of erosion on copper cathodes of the same wall thickness and at the same cooling water flow-rate are shown in Fig. 5.33. The measurements were obtained over the range 0.1 to 0.35 Wb/m^2 at a constant arc current of 200A. The individual points and the curve obtained from the mean value of erosion rate at each value of magnetic flux density are shown. The lower range of magnetic flux density that could be used was limited by instability to about 0.1 Wb/m^2. This has also been observed at arc currents of 1000A and above below about 0.04 Wb/m^2 for a similar configuration (Boldman, 1962). Below this value of magnetic flux density

Surface of Brass Electrode After Two Tests Showing
Grooves Formed at Cathode Root.(X3)

Figure 5.31.

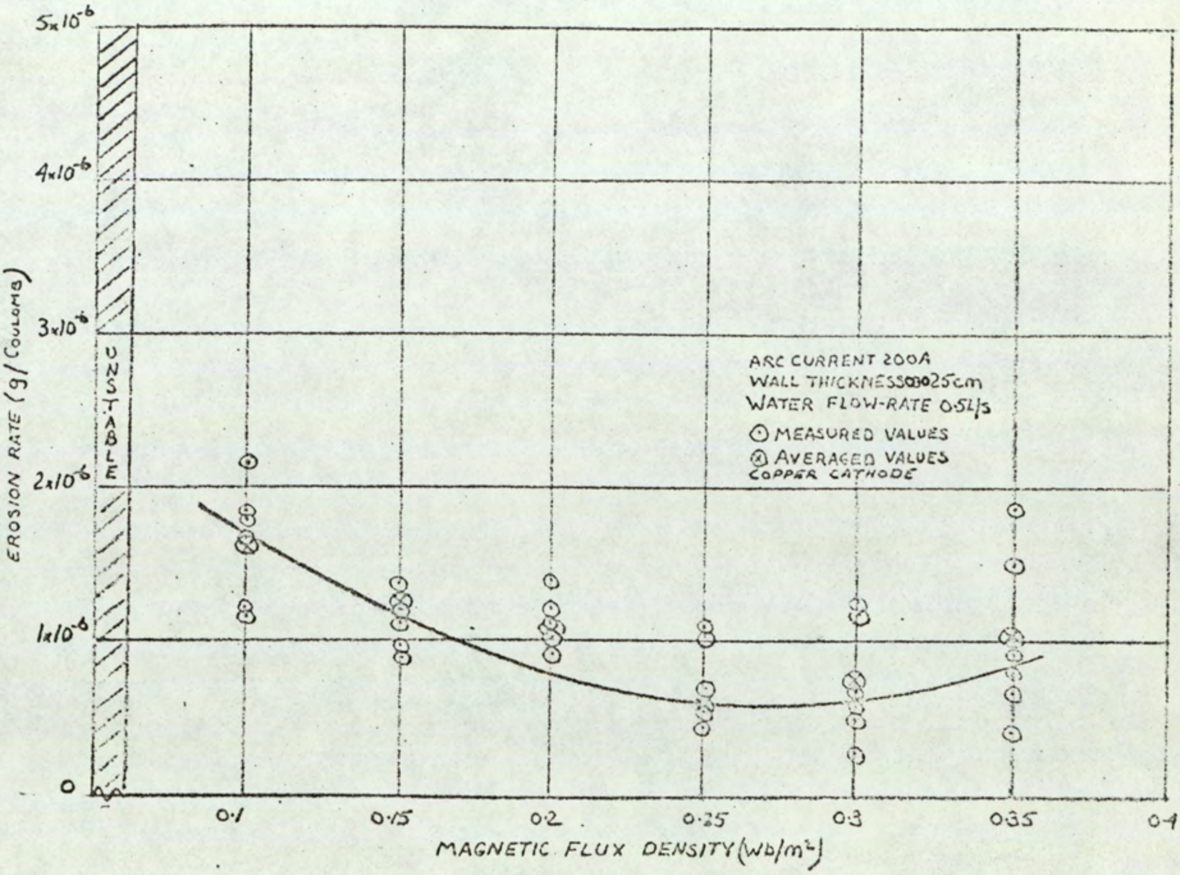


Brass Electrode (X12)

Copper Electrode (X12)

Macrophotographs of Arc Tracks on Surface of Copper and Brass Electrodes after Several Tests.

Figure 5.32.



VARIATION OF EROSION RATE OF THIN WALL CATHODE WITH MAGNETIC FLUX DENSITY

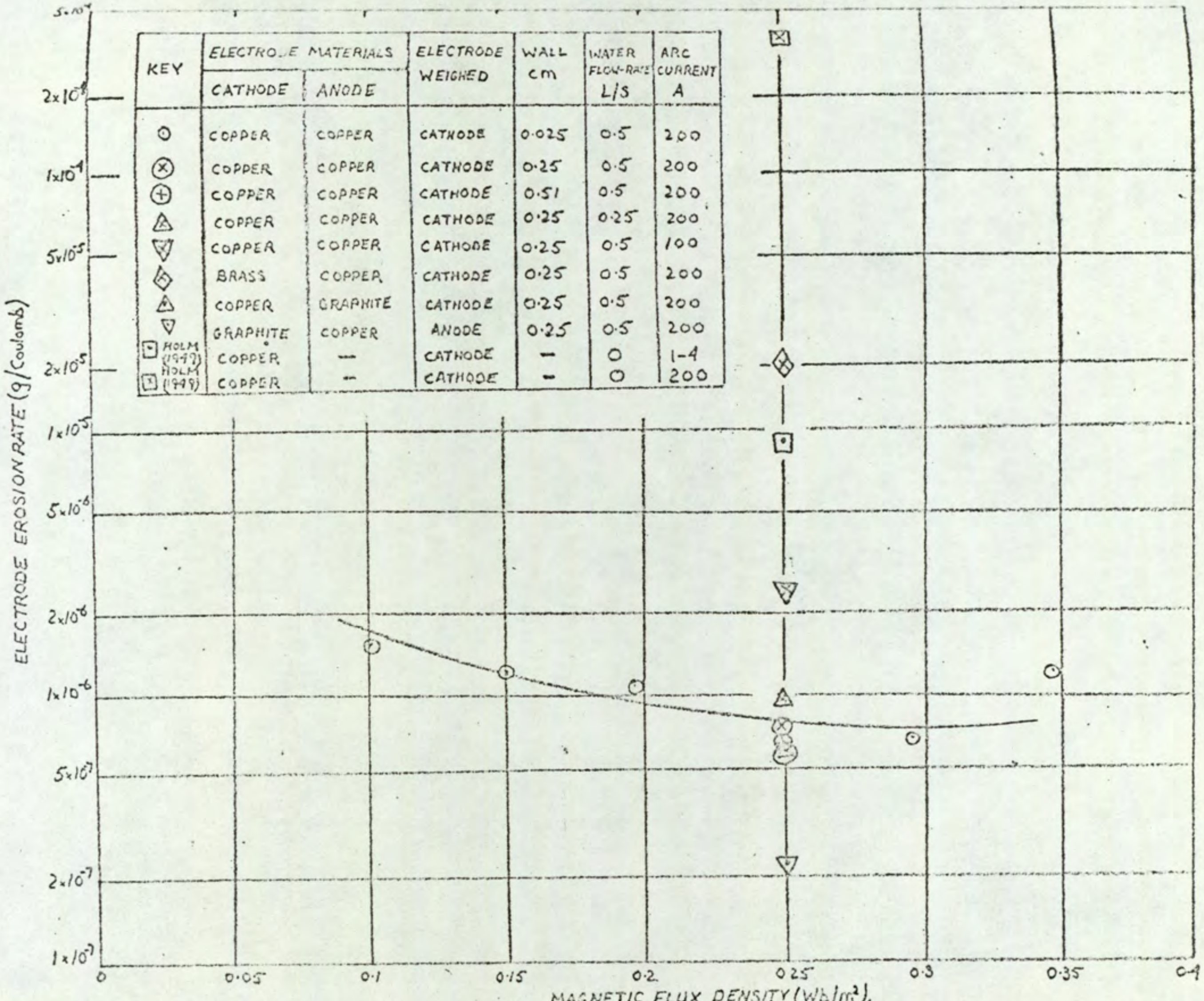
FIGURE 5.33

and corresponding arc velocity the magnetic field has apparently little stabilising influence on the random behaviour of the arc.

The complete series of results including those obtained with different electrode materials and wall thicknesses, arc current, cooling water flow-rate, and electrode polarity are shown in Fig. 5.34. In addition values obtained by Holm (1949) are plotted.

The value of erosion rate obtained for the arc current of 100A with a copper cathode which is greater than that obtained at 200A is at first sight surprising since the mean value obtained from the six tests is outside the range of scatter. The arc velocity at 100A and 0.25 Wb/m^2 shown in Fig. 5.29 is very nearly the same as that at 200A and 0.1 Wb/m^2 at which points the erosion rates are approximately equal. This indicates that the erosion rate is dependent not on the arc current but the mean power density at the cathode root, below a critical velocity. The power density at the arc root is independent of the arc current if the current density at the arc root is constant. The result at 100A also indicates that the erosion rate is still decreasing as shown at 200A with increase in the rotational frequency above 1,100 r/s. At the same time it is not possible to be more conclusive since the reduction in arc current and area may alter the arc root behaviour and the heat transfer by a disproportionate amount.

The presence of voids or porosity will also greatly reduce the effect of conduction of heat away from the arc root. The results of the chemical and metallurgical analysis of the two different samples of copper used are shown in Table 5.1. The only difference apparent is the small increase in phosphorous content in the copper which was eroded rapidly. The effect on the thermal and electrical conductivity of the copper is small and the main factor affecting the heat transfer is the heat transfer coefficient at the copper-water interface. A



VARIATION OF EROSION RATE WITH MAGNETIC FLUX DENSITY, ELECTRODE MATERIAL, WALL THICKNESS, POLARITY AND COOLING WATER FLOW-RATE

FIGURE 5.34

possible explanation of the rapid erosion obtained with one of the samples is the presence of adsorbed gas in the electrode material (Mosley, 1967) which may affect the erosion rate. An alternative but similar explanation is if the metal is porous and voids exist the arc root may cut into the voids where the arc root may be more stable and cause very rapid local evaporation of electrode material.

Table 5.1.

Analysis of Copper Used for Cathode.

Spectrographic Analysis		
Nickel	0.007 - 0.01%	1* & 2*
Arsenic	0.001%	1* & 2*
Iron	0.005 - 0.007%	1* & 2*
Tin	0.001 - 0.003%	1* & 2*
Chemical Analysis		
Phosphorous	0.034%	1.
	0.045%	2.
Metalurgical Analysis	-	
Hardness	120 Vickers. (Same degree of cold working)	1 & 2.
Grain size -	fine	1 & 2.
Electrical Conductivity from Phosphorous Content	80% I.A.C.S.	1.
Thermal Conductivity 0.94 x I.A.C.S.	74% I.A.C.S.	2.

*1 refers to the satisfactory electrode material 2 to the electrodes that failed rapidly.

No other source of quantitative measurement of arc erosion for a rotating arc is known. The only values of erosion rate reported have been measured on circuit breakers involving repeated making and breaking of the contacts (Holm, 1949, Wilson, 1955, etc.).

Holm considered the thermal transfer at the cathode root and equated the input power from the cathode fall region to the electrode losses by conduction through the electrode from the arc root and evaporation of electrode material.

$$V_c I = W_c + W_e \tag{5.15}$$

where V_c = cathode fall voltage

I = arc current

W_c = power dissipated by conduction

W_e = power dissipated by evaporation

The electrical conductance of a circular contact on a semi-infinite surface is 4 ak (Holm, 1967) (5.16)

where a = radius of contact area

k = conductivity

The thermal conductance will be the same giving

$$W_c = 4\,akT \tag{5.17}$$

and

$$W_e = Hx \tag{5.18}$$

where T = melting point of electrode material.

x = mass of electrode material evaporated per second.

H = latent heat of evaporation.

Since

$$I = \pi a^2 J \tag{5.19}$$

$$W_c \propto \sqrt{I} \tag{5.20}$$

Using this equation he deduced that a minimum level of erosion existed at arc currents where conduction was sufficient to dissipate the power input to the cathode root without melting of the electrode surface occurring. This occurred at currents below about 5A on copper electrodes at which the measured erosion rate was of the order of 13.10^{-6} g/Coulomb. As the current was increased above 5A conduction alone was insufficient to dissipate the heat input to the cathode and evaporation of the cathode occurred. At high currents the main method of energy dissipation was by evaporation.

The measured value of the erosion rate for the rotating arc between copper electrodes was less than 1.10^{-6} g/Coulomb at an arc current of 200A, which is more than an order of magnitude less than the minimum level of evaporation postulated by Holm. The corresponding erosion rate obtained by Holm for a static arc at 200A is 400.10^{-6} g/Coulomb. These values are shown plotted in Fig. 5.34 together with the measured values.

As the measured values of erosion rate are substantially less than the minimum theoretical and measured values it is of particular interest to look for possible causes of the reduced erosion.

One possible cause of the low erosion rate may be by material transfer from the anode to the cathode. No significant change in the erosion rate of the cathode occurred when a graphite anode was used which to some extent implies that metal transfer from anode to cathode was not significant since deposition of un-oxidised carbon is unlikely to occur. At the same time the anode root behaviour on a carbon anode is likely to vary considerably from that on a copper anode and the variation in for example the anode jet may affect the cathode jet behaviour so that the results are not necessarily exactly comparable.

Gain in weight of the cathode may occur by oxidation of the cathode. That this occurs initially was shown by the change in colour of the electrode surface. The results for the electrode with a wall thickness of 0.25 cms were obtained over a period of 1 hour 40 minutes. No significant change in the erosion rate was observed from that when the electrode was new (after conditioning) and at the end of the series of tests. If oxidation was occurring the electrode might be expected to oxidise rapidly at first, the rate of oxidation decreasing as the region near the arc track became covered until a layer of optimum thickness was built up (Burkhard, 1966). This apparently occurred in the first few minutes during which the electrode was conditioned no further increase in weight occurring after this. It therefore seems unlikely that progressive oxidation of the electrodes after conditioning should explain the low values of erosion rate observed. The other compound likely to form on the electrode is copper nitrate but the low melting point (115°c), and low density make it unlikely that this should be formed in any significant quantity.

The limiting value of erosion rate in air may be due to chemical combination rather than physical processes. This is indicated by the higher erosion rate obtained with the brass electrode where compounds such as zinc nitrate and lead oxides which melt below the melting point of copper may form. Another possibility in the case of the brass electrode is the selective removal of lead (m. pt 327°c) or zinc (m. pt 420°c) from the brass eutectic at the arc root assisting the formation of voids and more rapid erosion.

The measurements made for different conditions are all mutually consistent and there is no apparent source of error sufficient to result in a decrease of erosion rate by an order of magnitude. It was therefore concluded that lower rates of electrode erosion than those postulated by Holm as being the minimum level possible due to effects similar to sputtering, are obtainable. The results used by Holm were obtained from tests on arcs in switchgear. The measurements were of the loss of material obtained from many operations and the arc duration was normally of only a few milli-seconds

Bridging of the contacts with molten metal leading to rapid deterioration of the switch contacts (Betteridge & Laird, 1938), may also occur. Such measurements may be highly influenced by ignition and extinction phenomena whereas the present erosion measurements are for an arc running for 10 minutes with only one ignition and extinction.

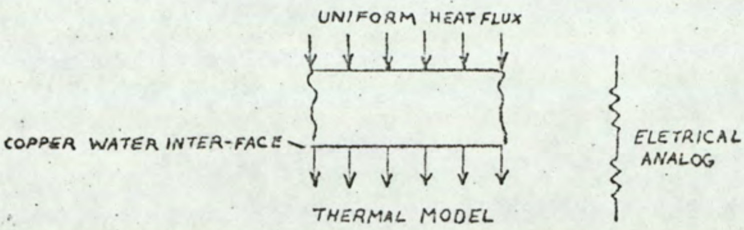
The sputtering process suggested by Holm may be considered more generally in the light of subsequent work (Knacke & Stranski, 1956, von Engel & Arnold, 1960), to include energy transfer not involving classical thermo-dynamic processes. Such processes involve the transfer of kinetic or potential energy from the cathode fall region to the electrode material. These effects might be supposed to be independent of a transverse velocity component however the effect of decreasing the angle of incidence of particles impinging at the cathode surface at high arc velocities may be appreciable (Wehner, 1954). Adams (1964) showed that if a rotating arc is a radial or an involute shape the region of the cathode root is approximately normal to the cathode surface. The electrode erosion due to non classical processes might therefore be expected to be largely independent of the arc velocity, if this is true of the region immediately in front of the cathode.

The variation of the erosion rate with the magnetic flux density with a copper cathode (Fig. 5.33,) shows that the erosion rate is still decreasing at magnetic flux densities of up to 0.25 Wb/m^2 corresponding to velocities of about 130 m/s. The rate of decrease is however small at 0.25 Wb/m^2 and a minimum level corresponding to that due to sputtering may be approached, but is lower than that obtained by Holm. The increase in the erosion rate that apparently occurs at flux densities of 0.35 Wb/m^2 is not considered to be significant and is within the limits of experimental error. Even at these low values of erosion rate the loss of cathode material in terms of the number of atoms is of the order of 10^{16} atoms/Coulomb, so that on an atomic scale the erosion rate is still considerable.

Suits (1935) showed that as little as one part in a million of copper vapour in air will provide electrons to carry 97% of the current so that no significant change in the overall behaviour of the arc at these low erosion rates might be expected.

5.2.7. Analysis of the Heat Transfer at the Arc Roots .

The conditions at the arc root of a rotating arc can be analysed in terms of transient, periodic and steady state solutions (Phillips, 1964). Phillips considered the one dimensional model shown in Fig. 535depicting the electrode as a slab thickness b .



Thermal Model used by Phillips(1964)

Figure 5.35.

receiving a pulse of heat Q on one side at x = o and cooled by forced convection at x = b on the opposite surface. The two other sides were assumed to be adiabatic surfaces. Thefrequency of the heat pulses was $\frac{1}{\tau}$ and the duration of each pulse was $c\tau$ where c is the ratio of the radius of the arc root a to the electrode circumfrence.

Using this modeltransient, periodic and steady state solutions for the conditions at the arc root were derived. The transient solution is required when the diffusion depth is comparable with the electrode wall thickness. The diffusion depth is a measure of the depth of penetration of the heat pulse into the electrode and is given by

$$\delta = (\alpha \tau)^{\frac{1}{2}} \qquad (5.12)$$

For an electrode wall thickness of 0.025 cm and when τ = 1mS and for copper α = 1.14cm/s the diffusion depth δ = 0.035 cm is greater than the wall thickness of the electrode.

The maximum periodic temperature is given by

$$T_{MAX} = 2Q'b \sum_{n=1}^{\infty} a_n \left(\frac{1 - \exp\left(\frac{-\alpha c \tau \beta_n^2}{b^2}\right)}{1 - \exp\left(\frac{-\alpha \tau \beta_n^2}{b^2}\right)} \right) \qquad (5.24)$$

$$a_n = \frac{(\beta_n^2 + (h'b)^2)}{\beta_n^2 (\beta_n^2 + h'b(1 + h'b))} \qquad (5.22)$$

$$\beta_n \tan \beta_n = h'b \qquad (5.23)$$

$$Q' = \frac{Q}{k} \qquad (5.24)$$

$$h' = \frac{h}{k} \qquad (5.25)$$

T_{max} = maximum temperature(^oC)

Q = magnitude of heat pulse (W)

b = electrode wall thickness (cm)

α = thermal diffusivity (cm. s)

τ = period of heat pulse (s)

$c\tau$ = duration of heat pulse (s)

h = heat transfer coefficient ($W/cm^2\ {}^oC$)

k = thermal conductivity ($W\ cm/cm^2\ {}^oK$)

The heat transfer coefficient is obtained from the Nusseldt number

$$N_u = \frac{h D_E}{k} \qquad (5.26)$$

where N_u = Nusseldt number

D_E = Hydrodynamic diameter of cooling channel

For a round pipe De = 1

The Nusseldt number is obtained from the relation

$$Nu = 0.023\,(P_r)^{0.4}\,(R_e)^{0.8} \quad \text{(McAdams, 1954).} \quad (5.27)$$

where P_r = Prandtl Number

R_e = Reynold's Number

Equation 5.24 has been solved for these conditions but a considerable number of approximations are necessary and it is more useful to consider the thin walled electrode in the light of the steady state solution.

When $\delta \ll b$

Phillips showed that a steady state solution could be obtained which reduced to

$$(T_c - T_o) = QcA\left(\frac{b}{k} + \frac{1}{h}\right) \qquad (5.28)$$

where T_c = temperature at cathode root

T_o = initial temperature of cathode surface

A = effective cross-sectional area over which heat transfer occurs.

The thermal conductivity term $\frac{b}{k}$ and the heat transfer coeffecient term $\frac{1}{h}$ have been calculated for the various conditions obtained in the test and are shown in Table 5.2.

Table 5.2.

Heat Transfer Coefficient and Conductivity Terms for the Range of Conditions Investigated.

b cm	$\frac{1}{h}$ $(W/cm^2\,°C)^{-1}$ Water Flow-rate L = 250 ml/s	L = 500 ml/s	$\frac{b}{k}$ Copper (700°C)	$\frac{b}{k}$ Brass (300°C)
0.025	7.64	4.29	0.007	-
0.25	5.11	3.06	0.073	0.223
0.50	3.06	1.76	0.365	-

The results indicate that an increase of more than 4 times in the heat transfer coefficient term $\frac{1}{h}$, from 1.76 to 7.64 and a variation in the conductivity term $\frac{b}{k}$ for the copper electrode of 50 times has no apparent effect on the electrode erosion rate. The heat transfer coefficient term for the conditions investigated varies from 3 to 100 times the conductivity term, and may therefore be taken as the dominant factor affecting the electrode cooling.

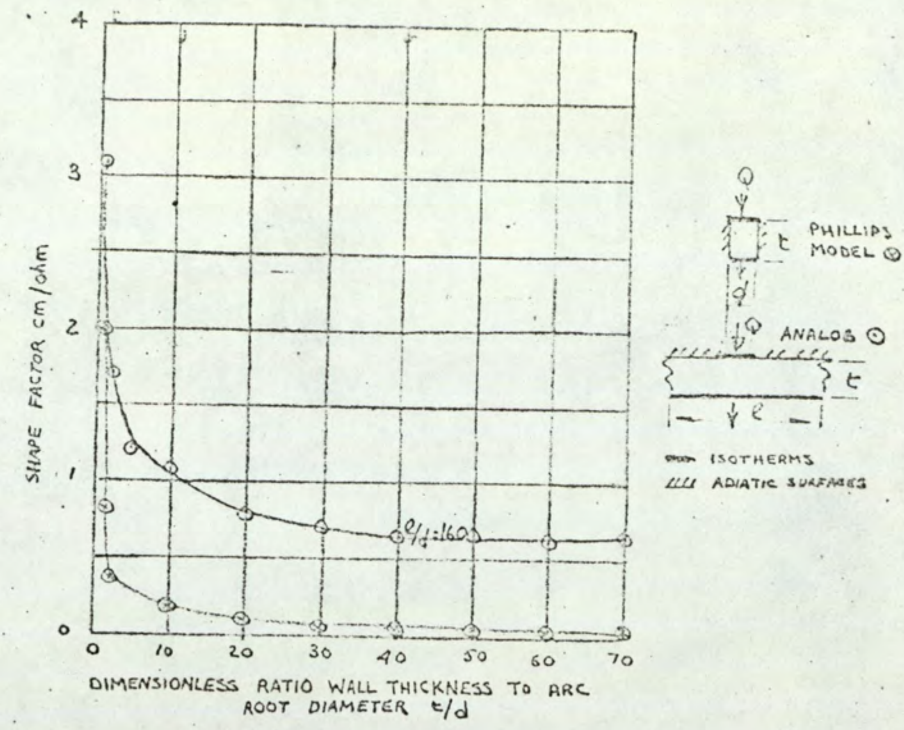
The model used by Phillips does not take into account the non uniform thermal distribution which occurs. The effect of this may be included in a shape factor terms to give

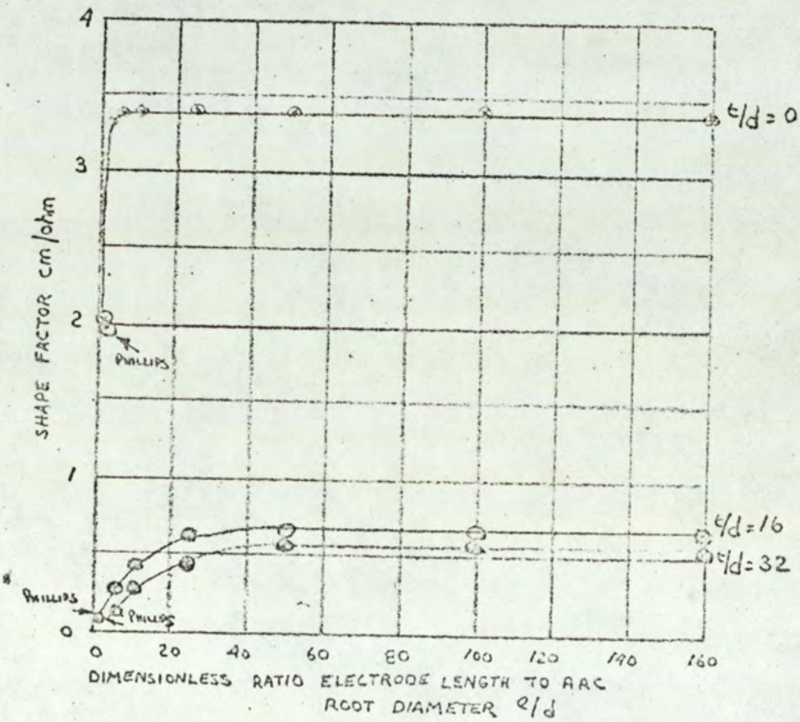
$$(T_c - T_o) \doteqdot Q\left(\frac{1}{kS\pi d} + \frac{1}{hA'}\right) \qquad (5.29)$$

where A' = effective interval surface area of electrode over which heat transfer occurs at the copper water inter-face.

The shape factor has been evaluated with a resistance analog for a wide range of electrode dimensions normalised in terms of the diameter of the arc root. The results are shown in Figs. 5.36 together with those obtained assuming the model used by Phillips. The thermal conductance is considerably greater than that obtained by using Phillips model. As a result the effective heat transfer at the inner surface and the overall transfer will be higher than that obtained with Phillips model.

The inside water cooled surface of the electrode is assumed to be an isothermal which was assumed in the derivation of the shape factor. This is a reasonable approximation in the derivation of the shape factors where the temperature at the inner surface $T_1 \ll T_c$, but is not necessarily true for the heat transfer coefficient h where $T_o < T_1$. The minimum value of A' will be equal to the area of the





VARIATION OF SHAPE FACTOR WITH ELECTRODE DIMENSIONS NORMALISED IN TERMS OF THE ARC ROOT DIAMETER

FIGURE 5.36

track of the arc root. The maximum possible value will be equal to the inside surface area of the electrode . If it is assumed that all the power dissipated in the cathode fall region is transferred to the electrode, the total heat transfer at the cathode root is given by

$$Q = V_c I \qquad (5.30)$$

$$T_c - T_o = \frac{V_c I}{\pi D}\left(\frac{1}{kS} + \frac{1}{hg}\right) \qquad (5.31)$$

and where $g = \dfrac{A'}{\pi D}$

Typical values for the copper electrodes used in this test are

$V_c = 15V$

$k' = 4W/cm^2\ ^oK$

$S \doteqdot 0.7 - 3.4$ cm/ohm.

$h = 0.13 - 0.57\ \omega/cm^2.s.^oc.$

and where $g_{min} = 16.10^{-3}$ cm at 200A and $J = 10^6 A/cm^2$

$g_{max} = 169$ cm.

The effective area over which heat transfer to the cooling water at the inside surface of the electrode is difficult to estimate. An order of magnitude may be evaluated from the variation of the shape factor with the normalised electrode length. This indicates that more than 70% of the conduction occurs within an axial region 20 times the arc root diameter. The effect of the remaining area on the heat transfer coefficient will be small.

i.e. $\quad g \doteqdot 3.2.10^{-1}_{cm}$ at 200A. $\qquad (5.32)$

This value will tend to be higher than the actual value since the internal surface of the electrode is not exactly an isothermal surface.

From this it can be seen that the dominant factor affecting the temperature at the electrode surface is the heat transfer coefficient h and little if any advantage is obtained by reducing the electrode wall thickness of a high conductivity material such as copper.

The steady state condition is the condition reached when no melting occurs and further increase in arc velocity has little effect. This will depend not only on the arc velocity but on the diameter of the arc electrode. In order to optimise the magnetic flux density required the minimum magnetic field consistent with the lowest value of erosion is needed. It is interesting therefore to consider the minimum conditions for the surface of the electrode to be maintained below the melting point of the electrode material.

The thermal conditions at the arc root are difficult to analyse due to the non-uniform temperature and energy distribution in the region of the arc root. The arc root region is considered as a rectangular region of width equal to the arc diameter on the circumfrence of the electrode which is assumed to be of large dimensions compared with the width of the arc track, and the arc continually traverses the same path (Bronfman, 1963).

Holm (1967) assumed a hemispherical equipotential equivalent to the equipotential at the arc root and showed that the constriction resistance was equivalent to a circular contact of diameter $\frac{\pi d}{2}$. It is assumed here for simplicity that the region within the semicircular region below the arc root is at the same potential at the arc root. At distances further than this the potential rapidly decreases. If the temperature gradient is now substituted for voltage gradient and applied to the two dimensional model here, to a first approximation no further decrease in temperature will occur at the cathode root.

when $\delta \doteq d$

where $\delta = (\alpha\tau)^{\frac{1}{2}}$ (5.12)

$d = \left(\frac{4I}{\pi J}\right)^{\frac{1}{2}}$ (5.9)

and where δ = diffusion depth

d = width of arc root

δ = thermal diffusivity

τ = period of arc rotation

I = arc current

J = current density at arc root.

For copper α = 1.14 cm.s. at 20°c.

$J = 10^6$ A/cm^2

The same model is used to determine whether melting can be prevented.

If the total power input at the surface of the arc track is sufficient to melt the semicircular region below the arc track, melting of the electrode surface when $\delta \doteq d$ ~~melting~~ cannot be prevented.

The heat transfer at the semicircular region below the arc track below the melting point of the electrode material is given by

$$W_c = \Delta T c_p \rho \left(\frac{\pi d^2}{8} \times \pi D\right) \qquad (5.30)$$

where
$$W_c = V_c I = V_c \frac{\pi d^2}{4} J \qquad (5.31)$$

and where W_c = power input from cathode fall region

ΔT = rise in temperature of electrode material

c_p = specific heat of electrode material

ρ = density of electrode

D = diameter of electrode

V_c = cathode fall voltage

I = arc current

For copper c_p = 0.382 J/g/^{o}c

ρ = 8.93 g/cm^3

V_c = 15 V.

Equations(5.30)&(5.31) show that within the limit of the assumptions made the rise in temperature ΔT is independent of the arc diameter or current and depends on the electrode diameter. i.e. The thermal flux density at the arc root is constant.

The rotational frequency at which the diffusion depth is equal to the radius of the arc root, optimum frequency and the minimum electrode diameter required for the melting point of the electrode material not to be exceeded, have been obtained and are plotted in Fig. 5.37. as a function of arc current.

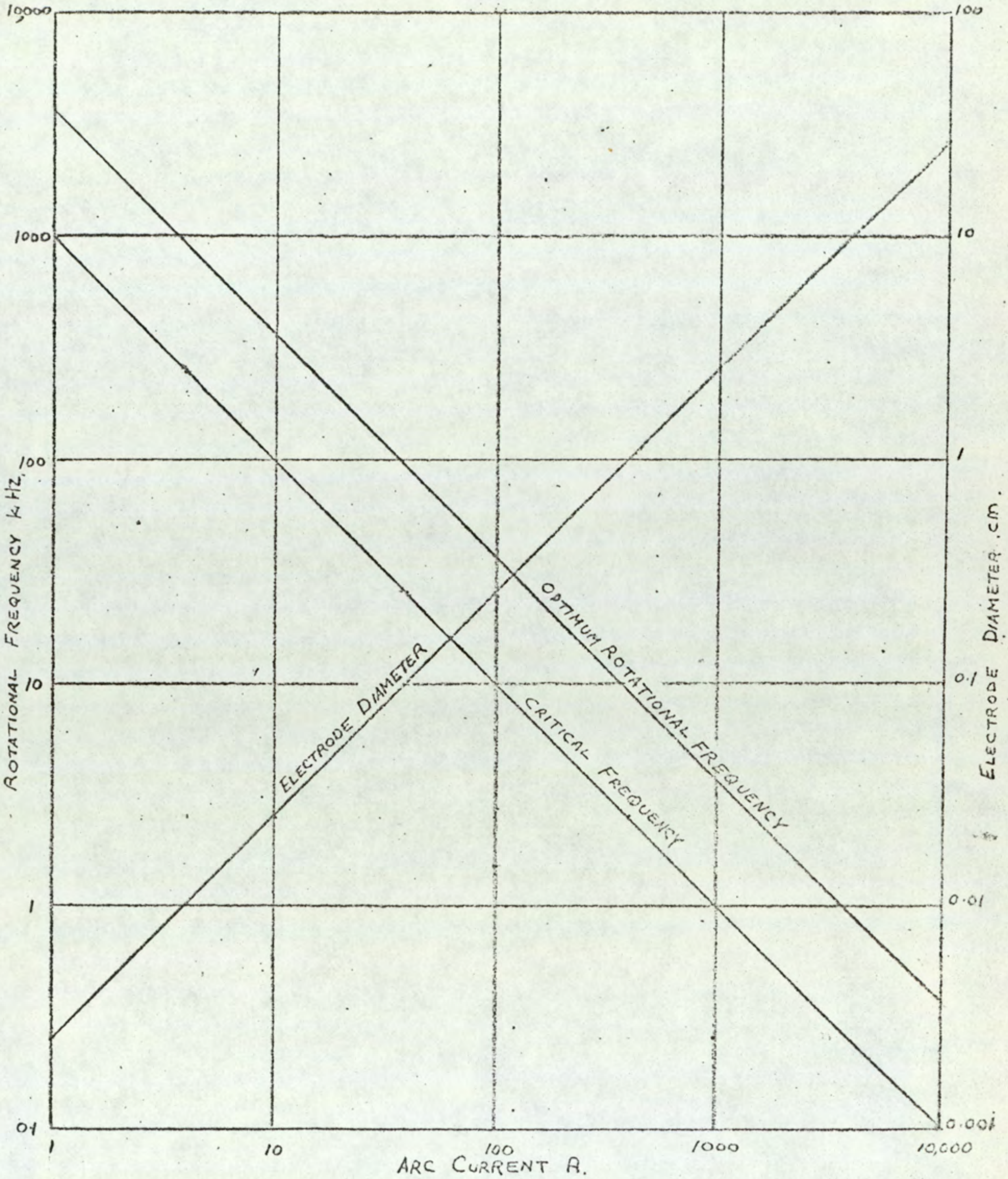
The minimum arc velocity required to maintain the surface of the arc electrode below the melting point of the electrode material can be deduced in the same way (critical velocity).

$$\frac{W_c d}{f_c \pi d} = \Delta T c_p \rho \left(\frac{\pi d^2}{8} \times d \right) \qquad (5.30(a))$$

This represents the energy input over a length of the arc track measured in the circumfrential direction equal to the diameter of the arc root. Clearly this is an over-simplification but is true for

$$x \rightarrow 0$$

where x is a point on the radius of the arc root.



VARIATION OF CRITICAL FREQUENCY AND MINIMUM ELECTRODE DIAMETER WITH ARC CURRENT

FIGURE 5.37

Substituting values for an arc on a copper cathode equation reduces to

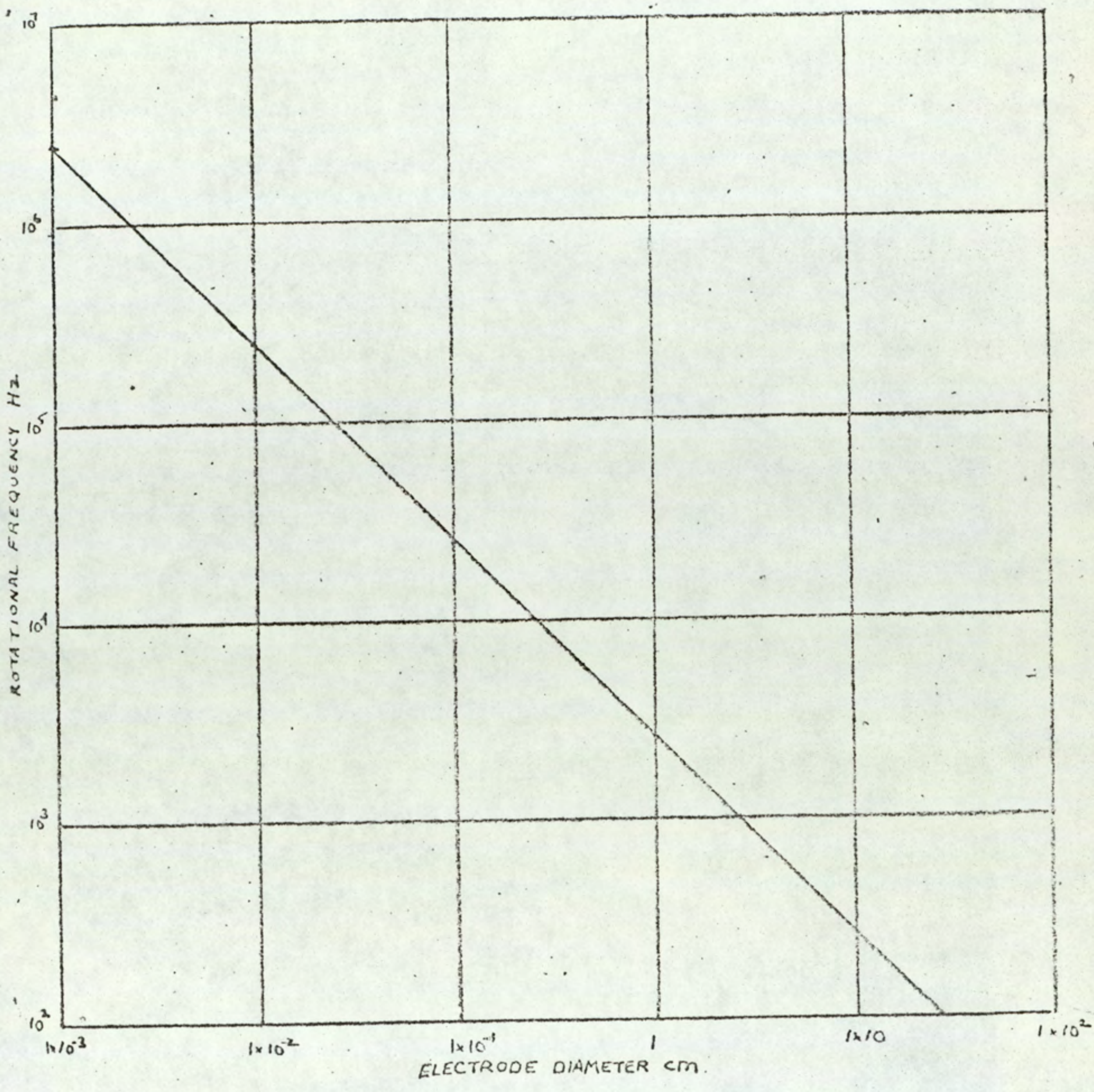
$$f_c D = 2,640 \qquad (5.32)$$

or
$$U_c = 83 \text{ m/s} \qquad (5.33)$$

At velocities below this value melting of the electrode material will occur. The critical frequency is also shown in figure 5.37. The minimum electrode diameter is frequently greater than the minimum value defined by the conditions for minimum erosion for example by mechanical considerations. The critical frequency as a function of electrode diameter is shown in Fig. 5.38.

From these results the order of magnitude of the minimum conditions required to prevent melting of the arc electrodes can be deduced. In the test described here the electrode diameter (2.54 cm) was above the minimum diameter required for copper at 200 Amps The critical frequency is therefore less than that at the minimum electrode diameter. The rotational frequency at 0.25 Wb/m^2 was 1,500 r/s which is greater than the critical frequency required for this value of electrode diameter. The erosion measurements for the copper cathode indicate that no further significant decrease in erosion occurs at higher magnetic fields and hence arc velocities, and are in good agreement with the thermal model used.

It is appreciated that the assumptions made about the thermal processes occurring at the arc root are greatly simplified. More detailed analysis is not justified as the conditions at the cathode root (in particular the cathode fall voltage) and current density (which may be non-uniform) at the arc root, are not accurately known. The results may nevertheless be used to define the minimum conditions required to minimise electrode erosion.



VARIATION OF CRITICAL FREQUENCY WITH ELECTRODE DIAMETER

FIGURE 5 38

5.3. Summary of Results and their Application to the Plasma Torch.

It has been shown conclusively that over the practical range of operation of a plasma torch, for arc currents up to 2,200A in transverse magnetic fields up to 1.7 Wb/m^2 in air at atmospheric pressure, a diffuse arc cannot be obtained. The results indicate that optical observation of an arc rotating at high speed may be misleading. Further evidence of the presence of active nitrogen at atmospheric pressure which is believed to have caused some of the effects observed with the plasma torches described in Chapters 3 & 4 has been obtained. The improved stability, higher arc voltage, increase in voltage with arc current and lower erosion rate claimed to be obtained with a diffuse arc are likely to result from the higher magnetic field strengths used; not from the arc becoming diffuse.

An erosion rate an order of magnitude less than the minimum value previously believed to be obtainable has been measured for a rotating arc. Little further decrease in erosion occurred at magnetic flux densities above about 0.25 Wb/m^2 corresponding to an arc velocity of 120 m/sec and a rotational frequency of 1,500 revs/sec. Under these conditions the effect of variations in the electrode wall thickness and cooling water flow-rate are small and the system may be represented by a steady state model. The model has been extended to take into account the non-uniform conditions at the electrode below the arc root. If the mean temperature of the electrode surface at the arc root is below the melting point of the electrode material it is unnecessary to use high pressure water supplies or thin walled electrodes. This has previously been believed to be required to minimise erosion but will only be necessary if other losses, for example due to containment are high.

The minimum conditions for the electrode surface temperature to be maintained below the melting point of the electrode material in terms of the diameter of the inner electrode and the frequency of rotation have also been obtained. The results obtained in this way are in good agreement with measured values. The results may be used to determine the order of magnitude of the electrode diameter and arc velocity required to minimise the electrode erosion.This has important application in the design and operation of a plasma torch.

CHAPTER 6.

The Second A. C. Plasma Torch.

The results from the preceding chapters are used to design an a. c. plasma torch. The tests carried out on the plasma torch to determine its efficiency and electrical parameters as a function of gas flow-rate are described.

6.1. Summary of the Results of the Previous Tests and their Applications to the Plasma Torch.

The tests described in Chapters 4 and 5 provide information on technological problems in the design of an a.c. plasma torch and basic data where required on arc behaviour. The results of these investigations are embodied in the final version of the a.c. plasma torch which is described in this chapter.

The preliminary work carried out on the various nozzle shapes described in Chapter 4 indicated that the conversion efficiency was reduced by the constriction in the nozzle. The stabilising effect of the constriction of the arc column in the nozzle was not a necessary condition for an arc to be maintained between non-refractory electrodes in an axial or transverse gas flow. As a result a greater flexibility was obtainable in electrode design enabling electrode losses due to the arc column touching the nozzles walls and conduction and convection from the arc and heated gas to be reduced.

The use of a high frequency high voltage auxillary ignition source to initiate the arc and assist in re-igniting the arc at each half cycle after current zero, enabled the arc to operate from lower voltage supplies and at higher power factors than previous a.c. torches described in Chapter 3.

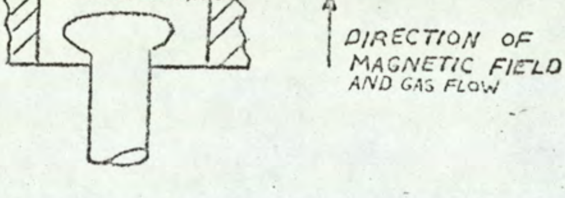
The use of an ignition electrode which is described in Chapter 4, enabled ignition voltages considerably less than those required by the main arc gap to be used.

The investigations described in Chapter 5 indicated that a diffuse discharge was not obtainable in a plasma torch operating at atmospheric pressure. The magnetic field used to rotate the arc was found to result in an improvement in arc stability at magnetic flux densities above about 0.1 Wb/m^2, below which the arc was very unstable. Little if any decrease in the erosion rate of the arc electrodes occurred above magnetic flux densities of about 0.25 Wb/m^2, corresponding to an arc velocity of 130 m/s and a rotational frequency of 1,600 r/s. The erosion rate was found to be constant over a wide range of the water flow-rate and electrode wall thickness. The minimum conditions in terms of the electrode diameter and a critical velocity required to maintain the surface of the electrode below the melting point have been obtained.

6.1.1. The Plasma Torch Electrode Configuration.

The preliminary tests described in Chapter 4 indicated that the electrode losses decreased substantially as the containment of the arc in the plasma torch nozzle was reduced. Whilst this may be intuitively deduced it had not been shown conclusively before as conflicting results had been obtained for the effect of constriction of the arc on the overall efficiency. These have been discussed in Chapter 3.

The electrode arrangement satisfying the requirements of minimum containment is a co-axial configuration allowing minimum axial movement of the arc roots. This configuration (Fig.6.1)



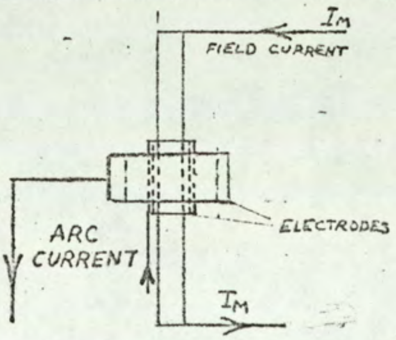
Electrode Configuration Used by Grear (1960)

Figure 6.1.

has been used with d.c. but the arc was found to be highly unstable.

(Greer, 1960). The reason for the instability was not given but some of the earlier work described in Chapter 4 and work elsewhere (Guile, 1967), indicates that an arc root may move away from the point of minimum separation on cold cathode materials under the influence of plasma jets, non axial components of the external magnetic field, and arc column movement due to convective effects. The arc length may fluctuate by an appreciable amount for a given electrode separation leading to a highly unstable arc.

Insulation of the electrode surfaces with refractory materials is ineffective for continuous operation at high values of arc current as the insulation is rapidly vapourised. Axial movement of the arc column due to instability and the axial gas flow may be reduced with a suitable magnetic field, in addition to the axial magnetic field used to rotate the arc. (Roman & Myers, 1967).
If the arc is assumed to be radial at electrode separations less than 2 cms (Adams, 1964) a circumfrential magnetic field is required. This has been used in the electrode configuration shown in Fig. 6. 2. in which a central electrode passed through the inner electrode so



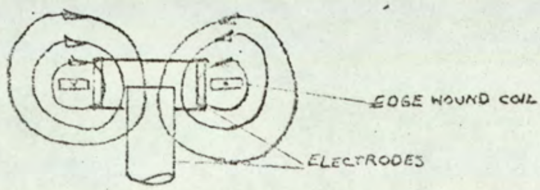
Stabilisation of Axial Position of Radial Arc with Circumfrential Magnetic Field.

Figure 6. 2.

that connections could be made to either end, and a separate field current isolated from the arc current was passed along it. (Mosley, 1967). This method is not feasible with the blunt ended electrode which does not pass through the nozzle used here which is required to obtain a high efficiency in order to reduce the area of cooled copper surfaces exposed to the heated gas stream.

Preliminary observations using high speed photography at 6,000 frames/s of the arc between co-axial copper electrodes, an electrode separation of 0.8 cms, and an inner electrode diameter of 2.5 cms, showed that the arc took up an approximately involute shape. The lower mean arc velocity was 200 m/s compared with about 110 m/s for the same electrode separation with carbon electrodes used by Adams at which a radial arc was obtained. The factors affecting the production of a radial or involute arc have been discussed in 2.4.4.

An involute arc shape results in a component of arc current tangential to the circumference of the annular electrode gap. (Fig. 6.3). The possibility of controlling the arc position with



Stabilisation of Axial Position of Involute Shaped Arc with a Radial Magnetic Field.

Figure 6.3.

a radial component of magnetic field from a conductor wound on edge around the outside of the nozzle was considered. This particular type of construction results in a current distribution varying inversely with the coil radius and high magnetic fields are obtained in this way. (See also Appendix 1).

Some estimate of the order of magnitude of the required radial component of magnetic field may be made from a knowledge of the maximum velocity of the gas in the arc gap. At a gas velocity of say 100 m/s during the period of one half cycle the gas will have moved 1 metre. If the axial gas velocity is assumed to be equal to the axial arc velocity as a first approximation a transverse magnetic flux density of the order of 0.1 Wb/m^2 would be required to hold the arc stationary. Mechanical limitations on the size of the field coil and the high current required to obtain this field with a single layer coil (which is the most effective method) made the application impractical. Similarly modification of the field coil, for example by using a trapezoidal construction or by mounting the electrodes at the end of a uniform field coil, result in a considerable reduction in the magnitude of the axial magnetic flux density. (See also 6.1.4.).

A method of confining the arc roots to the inner walls of the tubular nozzle is to electrically isolate the ends of the nozzle from the walls so that the arc root cannot run on the end faces of the electrodes. In practice this was obtained with the calorimeter used in the energy balance tests, described in section 6.1.5 which was electrically isolated from the nozzle with a layer of refractory insulation between the calorimeter and nozzle end faces. (In this position the insulation is very effectively cooled and lasts almost indefinitely). A nozzle used without a calorimeter could have an isolated end section incorporated.

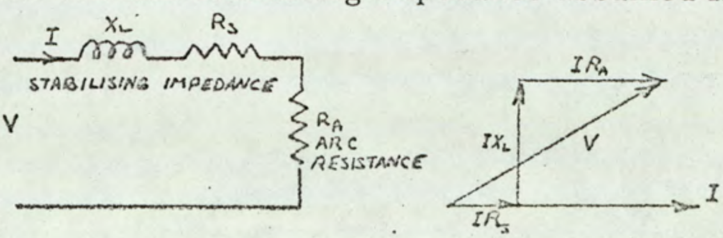
6.1.2. Electrode Dimensions and Separation.

The optimum electrode separation will depend on

1. The power input.
2. The efficiency.
3. Gas flow-rates required.
4. The temperature of the heated gas.
5. Acceptable level of stability.

Normally the gas-flow-rate and specific enthalpy required would be specified enabling the power input necessary to be estimated from a knowledge of the expected conversion efficiency. Here the range of operation is limited only by the maximum available power input.

The power input is governed by the supply voltage, the series impedance and the effective arc impedance. The equivalent circuit of the arc and stabilising impedance assumed is shown in



Equivalent Circuit of Arc and Stabilising Impedance.

Figure 6.4.

Fig. 6.4. This is a reasonable approximation for enabling the arc current and power input to be estimated if the stabilising impedance is considerably greater than the impedance of the supply.

The maximum power input is obtained when

$$\frac{dW}{dR_{ARC}} = 0 \qquad (6.1)$$

i.e. where

$$R_{ARC} = (X_L^2 + R_S^2)^{1/2} \qquad (6.2)$$

and

$$I = \frac{V}{\sqrt{2X_L^2 + 2R_S^2 + 2R_S(X_L^2 + R_S^2)^{1/2}}} \qquad (6.3)$$

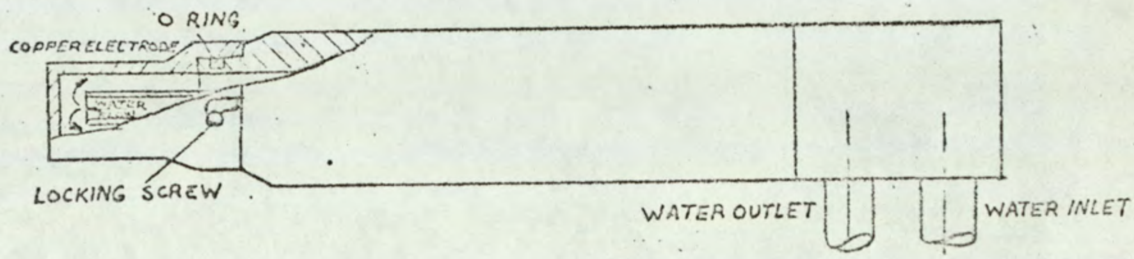
At a supply voltage of 415V, when

$R_S = 0 \qquad I = 235A$

$W = 98\ kW$

The highest gas flow-rate will be needed at the lowest temperature required (1,000°c) at which the highest efficiency will normally be obtained. If a conversion efficiency of 100% is assumed the corresponding maximum gas flow-rate required at 1,000°c and 100 kW is 83.4 g/s. To obtain this flow-rate with a sub-sonic nozzle a minimum cross-sectional area of 2.2 cm^2 is required.

The electrode configuration used was similar to that used in the erosion measurement. The minimum outer diameter of the inner electrode was primarily governed by the necessity to provide a co-axial inlet and outlet for the cooling water. This limited the minimum bore size of the outer tube to about 1.9 cm. The provision of a groove for the O ring seal resulted in an overall outer diameter of 3.2 cm but the stepped construction shown in Fig. 6.5 enabled the



Central Electrode.

Figure 6.5.

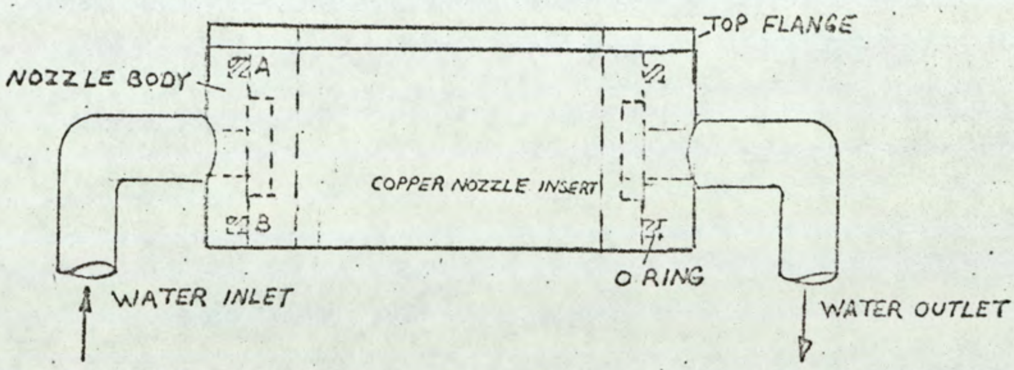
diameter of the electrode to be reduced to 2.5 cm without reducing the water flow.

The minimum electrode separation required to obtain a sub sonic gas flow-rate of 83 g/s with an inner electrode diameter of 2.5 cm is 0.25 cm. An electrode separation of this size is of the order of the diameter of the arc column. Under these conditions only a small arc voltage will be obtained comparable with the sum of the electrode fall voltage and losses due to containment will be high. The condition to obtain the maximum gas flow-rate is easily satisfied in this case. An electrode separation of 0.8 cm was chosen so that the results of the erosion test could be utilised as a design basis to enable the arc voltage and input power to be predicted.

The diameter of the inner electrode is greater than the minimum diameter required at 500A (Fig. 5.37) for gross melting to be prevented. The corresponding minimum rotational frequency required is about 1,000 r/s (Fig. 5.38.) which was obtained at 0.1 Wb/m^2 (Fig. 5.29.). The effect of a small axial gas flow of about 6 g/s results in a decrease in arc velocity of about a half (Adams, 1967) but no further significant decrease occurred as the gas flow was increased (see also 2.4.2.).

The mangetic flux density at 2,000 r/s was about 0.35 Wb/m^2. A range of operation of 0.1 Wb/m^2 to 0.4 Wb/m^2, the same as in the erosion test was chosen. The effect of increase in arc current above 200A would result in a small increase in arc velocity but have little effect if any on the erosion rate since the power density at the arc root is approximately independent of the arc current.

Over this range of magnetic flux density at 200A the arc voltage (Fig. 5.27), varied between 120V to 160V with an electrode separation of 0.8cm for the same diameter of inner electrode. The corresponding velocity of the arc varied from 90 m/s to 200 m/s. In a plasma torch the axial gas flow through the nozzle will also tend to constrict and lengthen the arc. The maximum gas velocity with the given electrode separation is 50 m/s and the effect of the gas flow on increasing the arc voltage is likely therefore to be less than the magnetic flux density and the electrode separation.

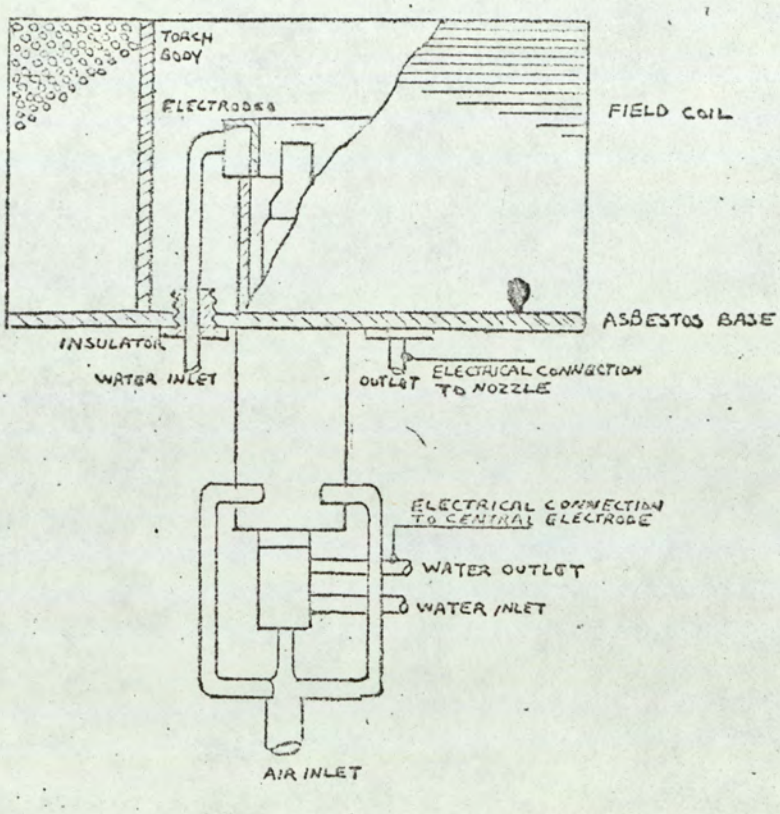


Plasma Torch Nozzle.

Figure 6. 6.

The nozzle is shown in Fig. 6. 6. The length was mainly governed by the width of the channel required for water cooling and the dimensions of the O rings used to seal it which compress on the surfaces at A and B. The upper O ring is protected by the copper flange which acts as a heat sink on the uncooled side of the O ring preventing overheating.

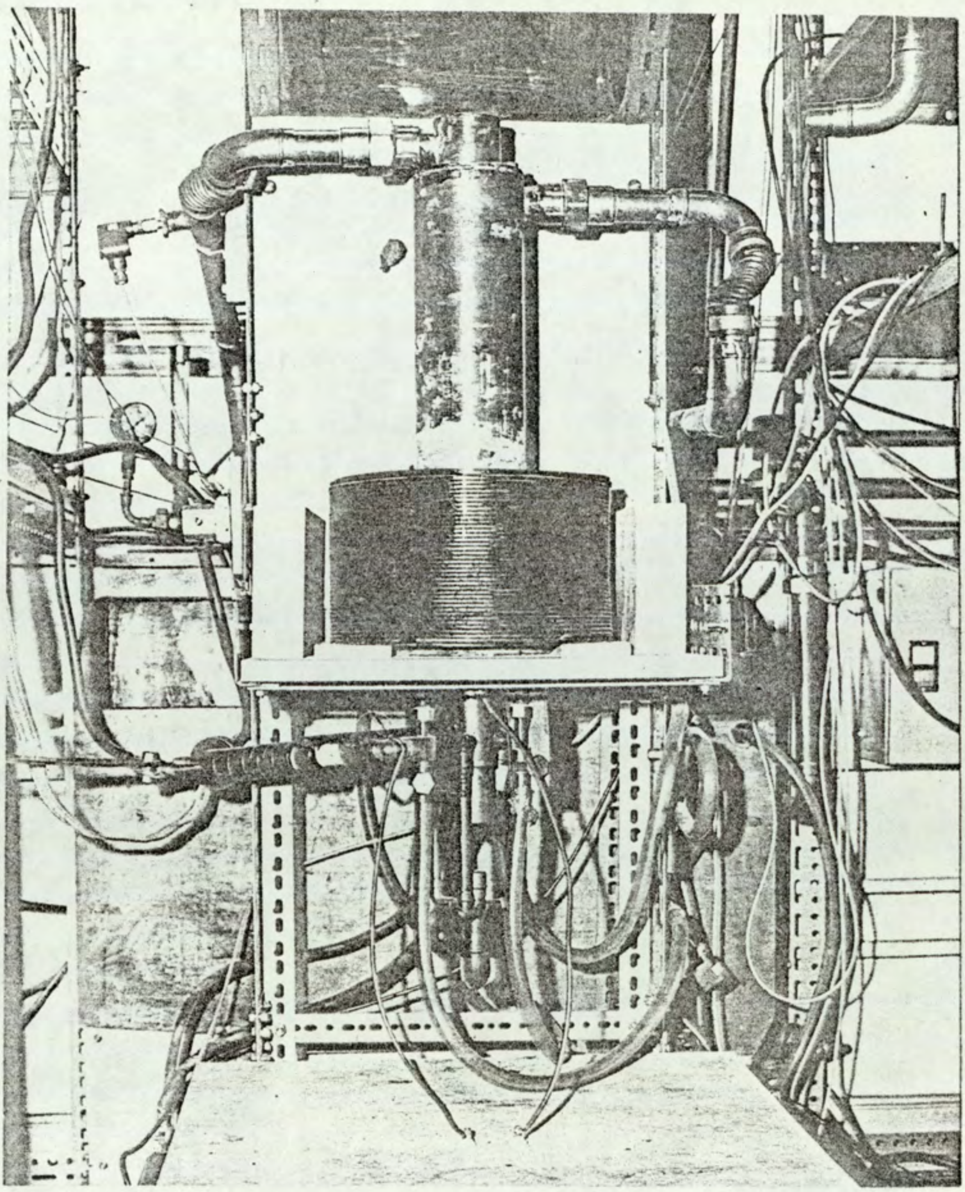
The plasma torch, partly sectioned, is shown in Fig. 6. 7. and the plasma torch with calorimeter in position is shown in Fig. 6. 8.



Complete Plasma Torch.

Figure 6. 7.

The gas flow is introduced via a tube co-axial with the central electrode, at three inlets. The gas is directed into the main gap and prevented from passing outside the nozzle by the asbestos tube which also serves to prevent the arc from running down the nozzle cooling pipes and on the underside at low gas flow-rates. The outer pipe is located in a brass bush fastened to the end of the torch which is asbestos and assists in locating the nozzle cooling pipes which pass through boron nitride sleeves. This rather unusual design was chosen in order to



Plasma Torch with Calorimeter and Field Coil
in Position.
Figure 6.8.

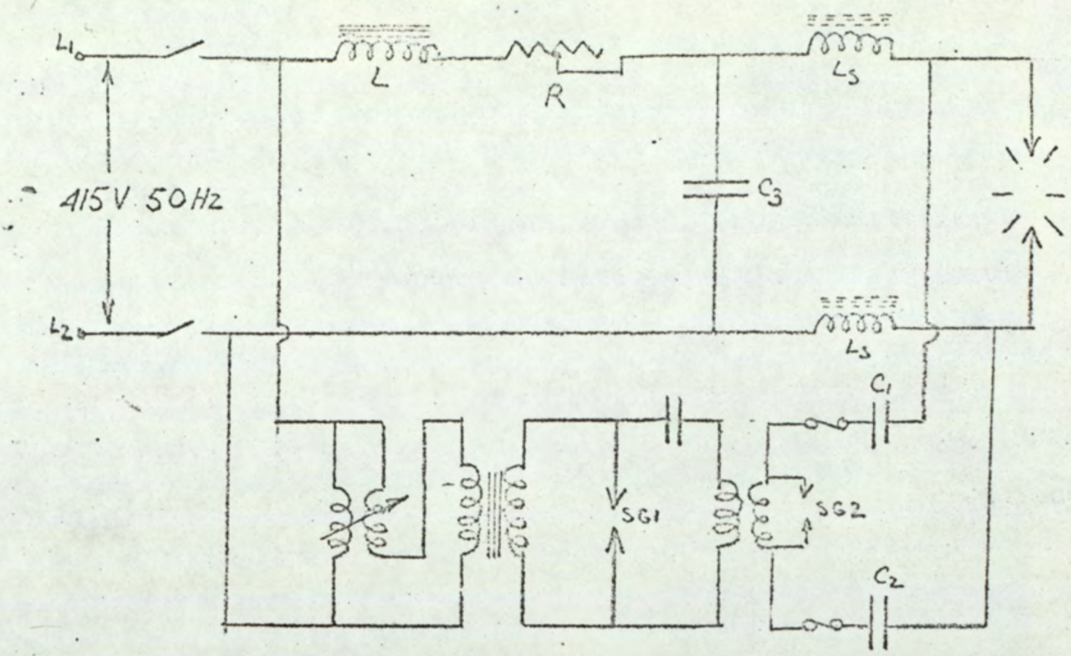
prevent breakdown to a metallic torch body. In addition the asbestos base supports the field coil. The joints in the asbestos were made gas tight with refractory cement.

The end of the central electrode was normally positioned at the bottom of the nozzle so that the arc was contained within the nozzle.

6.1.3. Power Supplies.

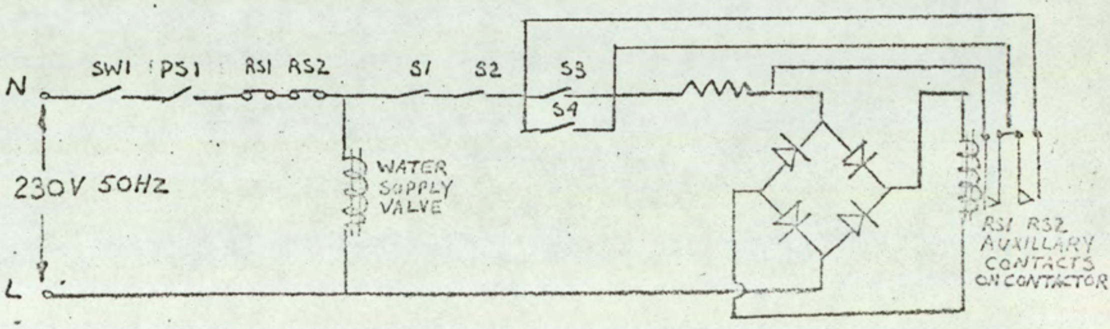
A diagram of the main power supply circuit and ignition unit is shown in Fig. 6.9. and the control circuit in Fig. 6.10. The control circuit of the main contactor S. W. 1. was interlinked with a pressure switch in the water cooling circuit so that the contactor could not be closed unless the cooling water supply was turned on. The solenoid operated valve in the main water supply enabled rapid cut off of the water supply in the event of electrode failure. A fused circuit breaker and a magnetically tripped circuit breaker in the substation provided additional overload and short circuit protection.

The ignition source is unusual in that is is connected in parallel with the main arc current supply so that the secondary of the high voltage output transformer does not carry the main arc current. Better coupling between the primary and secondary windings and a higher turns ratio is obtained since the physical size of the winding is no longer governed by the main arc current. This is of particular importance at high arc currents where the dimensions of the transformer windings would preclude the possibility of a series connected transformer.



ARC POWER SUPPLY AND IGNITION CIRCUIT

FIGURE 6.9



KEY	OPERATION
SW1	OFF LOAD ISOLATOR
PS1	WATER SUPPLY PRESSURE SWITCH
RS1	EMERGENCY STOP STATION
RS2	EMERGENCY STOP STATION
S1	CONTROL PANEL STOP BUTTON
S2	REMOTE STOP BUTTON
S3	CONTROL PANEL START BUTTON
S4	REMOTE START BUTTON
RS1	HOLD CONTACTS
RS2	BREAK CONTACTS

MAIN CONTACTOR CONTROL CIRCUIT

FIGURE 6.10

The spark discharge unit of the original high frequency supply used in the tests described in section 4.2. was used with a re-wound output transformer enabling pulsed ignition voltages of up to 30 kV at frequencies of about 1 MHz to be obtained. Isolation of the ignition supply circuit from the main supply is obtained with the capacitors C_1, C_2 connected in series with the fused output of the ignition unit. A spark gap S.G. 2. was provided to protect the secondary of the high voltage transformer in the event of the connecting leads to the main arc gap becoming disconnected. The ignition current is blocked by the inductance L_s of the connections to the electrodes which are increased by covering the leads with ferrite torroids. The ferrite torroids saturate when the arc is ignited and the ignition source is then shunted by the capacitor C_3.

A disadvantage associated with this method of producing a high voltage high frequency supply is radio frequency interference. This can affect instrument readings particularly thermo-couple instruments. The interference is greatly reduced with parallel connection since after the arc is ignited, the arc is shunted by the capacitor C_3. Other ways of switching the high voltage were also considered using triggertrons or thyristors. Considerable difficulty was encountered in obtaining a suitable triggertron whilst the relatively low operating voltage and slow turn off time make thyristors even when connected in series unsuitable for this purpose.

The phase angle of the ignition voltage was varied with respect to the arc voltage with a phase shifting transformer. Since several ignition pulses are obtained during each half cycle at mains frequency the phase shift was not critical. The field coil power supply that was used in the measurement of electrode erosion (Fig. 5.25) with additional protection including series fuses in each lead and a parallel spark gap was used to protect the field coil in the event of breakdown from the main arc supply circuit.

6.1.4. The Field Coil.

The previous tests described in Chapter 5 indicated that a magnetic flux density above about 0.1 Wb/m^2 was required in order to obtain a stable arc. Little if any further decrease in erosion occurred above about 0.4 Wb/m^2 so that an operating range of 0.1 Wb/m^2 to 0.4 Wb/m^2 was chosen. (See also 6.1.2.). The coil used in the erosion measurement was however unsuitable as the bore was too small to contain the plasma torch.

The possibility of water cooling the coil was considered but rejected since operationformore than half an hour was possible at flux densities of 0.25 Wb/m^2 without overheating occurring. This was sufficient for the tests envisaged. Operation of the coil from an a.c. supply was also considered, but the difficulty of synchronising a power load of this order (up to 6.5 kW) with the arc current other than by connecting it in series with the arc supply appeared at this stage to be insuperable. Series connection was undesirable since the effect of varying the magnetic flux density could no longer be investigated as a separate parameter.

The field coils used up to now had been designed on the basis of the field at the centre of a short single layer coil. This is only approximately true for multi-layer coils, and as the bore diameter and flux density required increase, the error involved becomes significant. In addition it is difficult to obtain the optimum dimensions for a given coil and to match the coil with the power supply which at high values of power input becomes important.

Normalised equations relating the dimensions of the field coil to the effectiveness in terms of a geometry factor have been obtained (Montgomery & Terrell, 1961), derived from Biot-Savart's law for a wide variety of coil construction and shapes. Coil design considerations are discussed in Appendix 1 and the computer program used to determine the geometry factors and other data for two different methods of coil construction shown in Appendix 2.

The results showed the significant decrease in volume of copper required, obtainable with only a small reduction in the geometry factor G.

Dimensions and Characteristics of the Field Coil.

Bore Radius cm	Outer Radius cm	Length cm	G	Resistance (Cold) ohms	Wb/A. m^2	Weight kg	No. of turns	Inductance Henrys
8.6	14.6	16.5	0.15	0.43	4.27×10^{-3}	66	546	0.014

Table 6.1.

The dimensions and characteristics of the coil finally constructed are shown in table 6.1. A constant current density winding was used since the increase in G obtained with the current density varying inversely with coil radius was small compared with the difficulties of construction.

The constructed coil met the design requirement of a flux density of 0.5 Wb/m^2 being obtainable at maximum power input starting from cold with the power supply available.

The field coil was initially calibrated with a Hall effect probe at the centre of the coil in terms of the variation of the flux density with field current. The variation of the axial magnetic field over the region of the annular arc gap was within $\pm$ 2% of the value at the centre.

6.1.5. Instrumentation.

Provision was made for a wide variety of different methods of measuring the arc voltage, current and power. Potential and current transformers were used to isolate the measuring circuit from the line voltage. Indicating instruments could be plugged in on the control panel enabling changes of meters to be easily made.

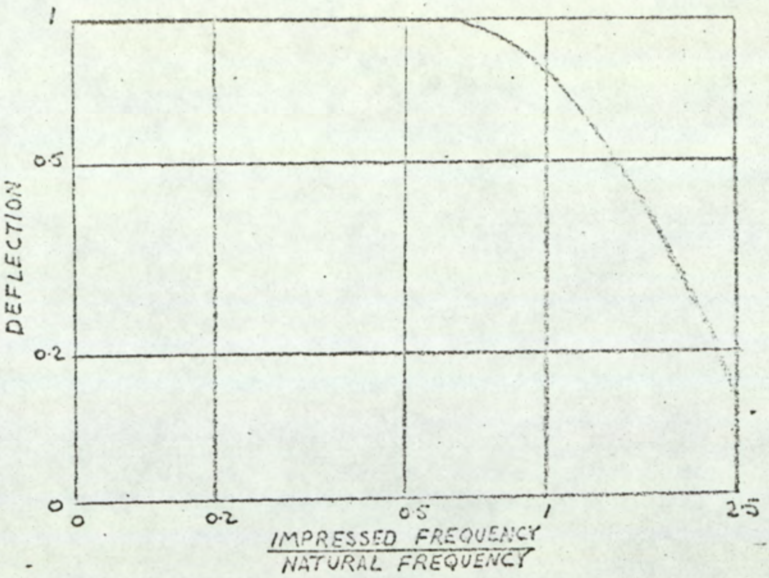
The electrical parameters of most interest are mean values by which the torch current may be characterised e.g. arc voltage, current and power which may be used in assessing the operating conditions. The true mean power is also required for the energy balance measurements. Previous measurements of a.c. arc parameters as described in 4.2.4 & 5 indicated that errors in measurements were caused by fluctuations in the arc parameters particularly the effect of ignition and extinction transients on arc voltage. It was shown that a more meaningful value of arc voltage could be derived from stable readings of arc current and power.

Thermo-couple instruments have already been shown to give substantial errors due to the variation in response time of the thermo-couple element and heater during increasing and decreasing fluctuations in current. (See also 4.2.5.). These errors affect most of the measurements of arc voltage due to the high ignition and extinction peaks which have an appreciable influence on the measured r.m.s. value (Fig. 4.27).

Electromechanical indicating instruments are also affected. The deflection is no longer governed by the steady state equation and the response of the meter circuit and inertia of the movement affect the accuracy of measurement.

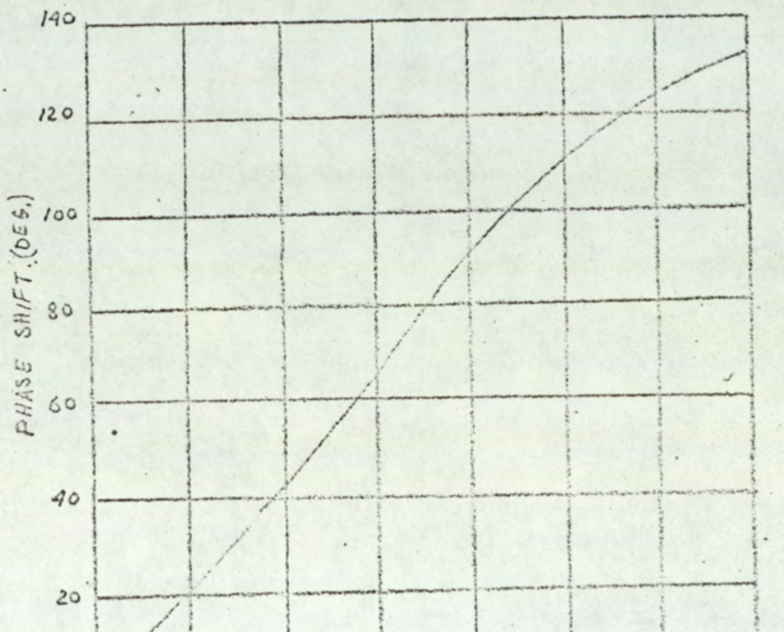
Vibration galvanometers may be used to indicate instantaneous values of arc voltage, current, and power if the frequency response is sufficient. Both the amplitude and phase shift of the galvanometer are frequency dependent and are plotted for critically damped second order systems in Figs. 6.11. and 6.12. in terms of the impressed frequency normalised with respect to the natural frequency of the galvanometer.

The effect of phase shift is most severe and in order to reduce the maximum phase shift to about 10° the natural galvanometer frequency should be of the order of 10 times the maximum applied frequency. The arc has a wide frequency spectrum and the voltage of an a.c. arc will contain high frequency components of appreciable amplitudes due to the ignition and extinction peaks. The variations in amplitude and phase shift are obtained for continuous waveforms. In practice this is not achieved with an a.c. arc due to random fluctuation in arc parameters at each half cycle. As a result a further error exists which is influenced by the stability of the arc.



CRITICALLY DAMPED AMPLITUDE RESPONSE

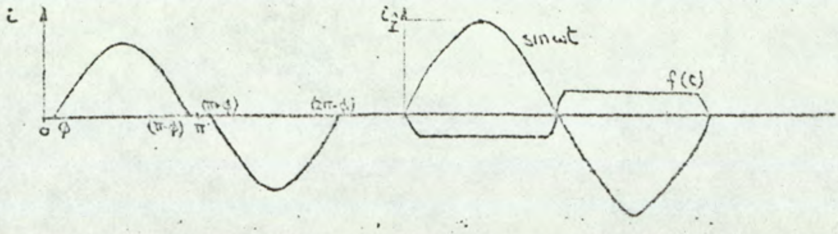
FIGURE 6.11



CRITICALLY DAMPED FREQUENCY RESPONSE

FIGURE 6.12

The arc current waveform is not normally subjected to large random fluctuations if the fluctuations in arc voltage are of a shorter duration than the time constant of the arc column. The arc current is similar to the truncated sinusoidal waveform



Current Waveform and Equivalent Continuous Waveform.

Figure 6.13.

in the period between ignition and extinction of the arc shown in Fig. 6.13. The Fourier analysis of the waveform gives

$$i = \hat{I}\ \mathrm{Sin}\ \omega t + f(t) \tag{6.4}$$

where 2ϕ = duration of arc extinction

(typically $\phi < \frac{\pi}{8}$ rad)

and $f(t)$ = represents higher frequency components.

If the higher frequency components are ignored the arc current can be expressed in terms of a continuous sine wave of the same amplitude as the discontinuous arc current waveform.

The error involved in this approximation depends on the duration of arc extinction and the type of indicating instrument used. For a moving coil vibration galvanometer or rectified meter

$$\xi \propto \lim_{T \to \infty} \left(\frac{1}{T} \int_0^T i \, dt \right) \tag{6.5}$$

and the percentage error reduces to

$$e = (1 - \cos \phi) \times 100\% \tag{6.6}$$

where Θ = deflection

i = instantaneous current

t = time

ξ = fractional error.

The deflection of a moving iron ammeter is given by

$$\theta \propto \lim_{T \to \infty} \left(\frac{1}{T} \int_0^T i^2 \, dt \right) \qquad (6.7)$$

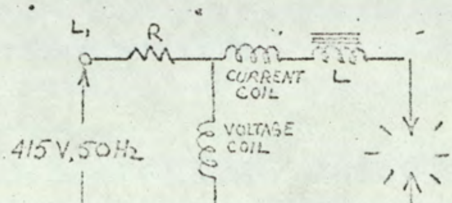
and the percentage error

$$\varepsilon = 1 - \left(\frac{\frac{\pi}{2} - \frac{\sin 2\theta}{2} - \theta}{\pi} \right)^{1/2} \times 100\,\% \qquad (6.8)$$

The variation of the percentage error with ϕ is shown in Fig.6. 14. which indicated that the error for a moving coil instrument is less for the same period of arc extinction than a moving iron instrument.

Measurements of instantaneous arc voltage and current only were obtained with an oscilloscope and a chart recorder. The field current was measured with the current shunt and digital voltmeter used in the erosion test.

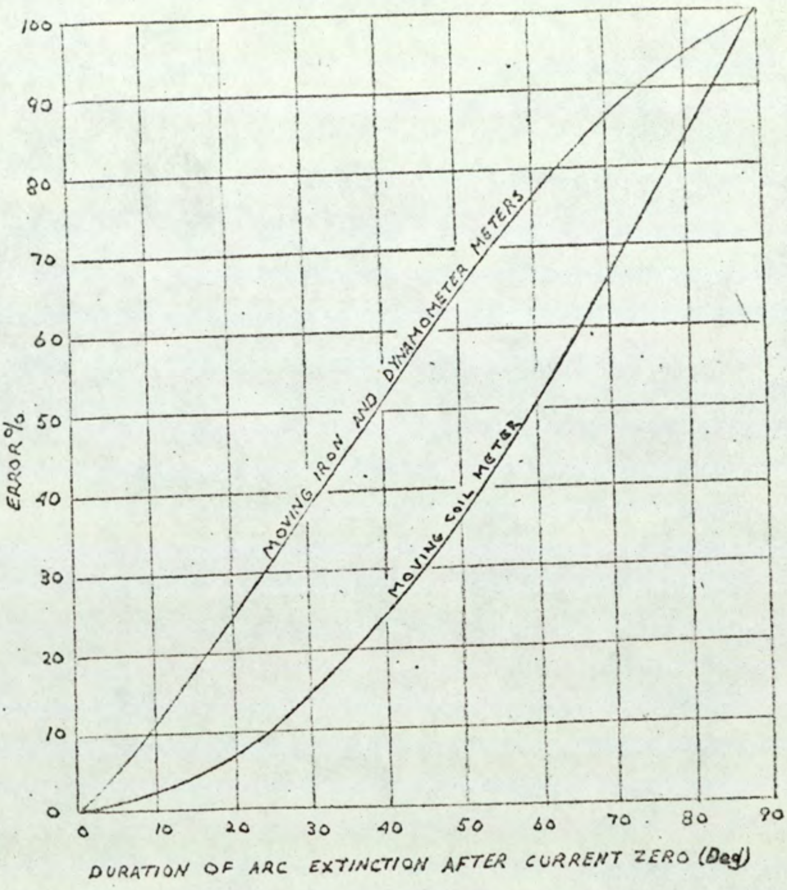
The mean power input was measured with a dynamometer wattmeter. Fluctuations in readings were reduced by connecting the voltage coil to the input of the stabilising inductance as shown in Fig. 6. 15.



Connection of Wattmeter in Arc Circuit.

Figure 6. 15.

In this way the fluctuations in arc voltage are reduced by the effect of the stored energy in the series inductance. The decreased power factor unless very small (e. g. less than 0. 1) does not affect the power readings. If the resistance of the inductance is small (in this case it was less than 0·005Ω) negligible error is introduced by connecting the wattmeter in this



VARIATION OF PERCENTAGE ERROR DUE TO ARC EXTINCTION AT CURRENT ZERO WITH DURATION OF ARC EXTINCTION

FIGURE 6.14

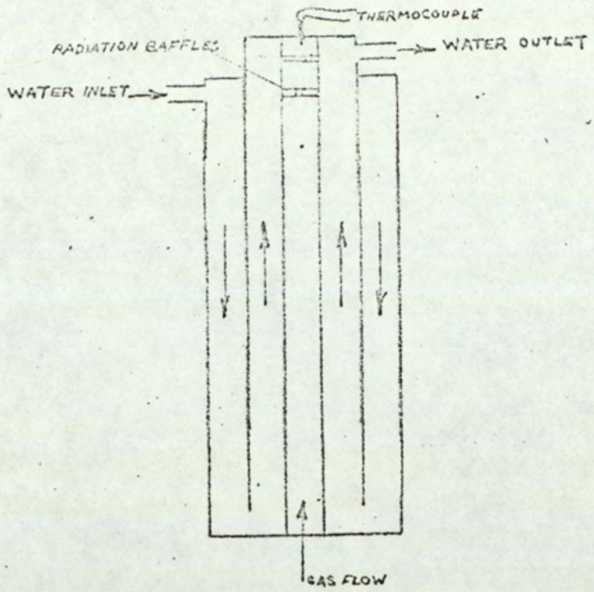
way.

The rotational frequency of the arc was measured with the optical probe shown in Fig. 5.12. In this case since the arc current is continuously varying and as the rotational frequency is relatively low compared with supply frequency it is not possible to obtain measurements as a function of arc current and mean values were used. This is a reasonable approximation as the arc velocity is approximately indepentend of arc current (2.4.2).

Gas flow measurements were made as before with variable area gas flow-meters, three in all being required to cover the range 0 - 56 g/s of air. Corrections were made for variation in the gas pressure with gas flow-rate.

Cooling water temperatures were measured at the inlet to the torch, the outlets of both electrodes and at the outlet of the calorimeter with platinum resistance elements connected to a single indicator using a low resistance multi-position switch designed for this purpose. Accuracy of temperature measurement was $\pm$ 0.5°C. The water flow rate was measured by the time taken to fill a 5 litre flask as in the test on erosion measurement.

The calorimeter used in the energy balance measurements shown in Fig. 6.16 was of the self jacketed typeto minimise conduction and radiation losses. The temperature of the gas at the outlet was measured with a thermo-couple probe mounted in the gas stream. Radiation baffles were used to prevent direct radiation from the arc falling directly on the probe and causing high readings.



Calorimeter used in Energy Balance Measurements.

Figure 6.16.

Heat losses from the calorimeter other than to the cooling water were minimised by keeping the temperature rise of the cooling water as low as possible consistent with the accurate measurement of the rise in temperature of the cooling water.

6.2. Discussion of Results.

Preliminary tests with the high voltage ignition unit showed that at magnetic flux densities above about 0.25 Wb/m^2 the ignition unit failed to ignite the arc. This increase in the breakdown strength of the arc gap with magnetic flux density has been observed at low gas pressures (Llewellyn-Jones, 1966), but no mention of it has been found at atmospheric pressure. It has been explained by the increased transverse movement of charged particles crossing the arc gap causing the ignition discharge to become more diffuse and is less effective in breaking down the gap. It was overcome by increasing the voltage and power output of the ignition unit.

At 140A the arc was relatively stable, shown by waveforms of arc voltage and current the stability improving with increase in the magnetic flux density and decreasing with increase in the gas flow-rate. As the arc current was increased the arc became less stable. The decrease in stability may be due to the reduction in series resistance necessary to obtain the higher arc current which effectively increase the time constant L/R of the supply so that it responds less rapidly to sudden changes in arc voltage. It was not possible to increase the arc current by increasing the supply voltage leaving the stabilising impedance constant.

The interaction of an unstable arc with the supply circuit is highly complex but the behaviour of the arc can be illustrated in terms of a fictitious circuit time constant $\frac{L}{R}$ which includes the effect of the arc resistance. If the time constant of the arc circuit is comparable with the time required to establish equilibrium in the arc column which is normally taken as about 1 millisecond (see also 2.3.), the fluctuation in arc voltage and induced e.m.f. will be restored to the equilibrium value at about the same time. If however the circuit time constant is considerably longer, when equilibrium is obtained in the arc the arc voltage is still affected by the transient and is governed by the induced e.m.f. in the stabilising impedance. This is an unstable state and the arc current will fluctuate.

If an approximate mean value for the equivalent resistance of the arc equal to the minimum arc voltage (Fig. 6.20.) divided by the r.m.s. arc current (Fig. 6.22.) is assumed, the time constant may be calculated.

At 130A τ = 0.821 ms

450A τ = 7.11 ms

At 130A the time constant is comparable with the equilibrium time of the arc column but at 450A is 8.6 times as long and may account for the instability at the higher current.

Stable readings of input power $\pm 3\%$ were measured at 130A with the voltage coil connected to the input side of the stabilising impedance. At the higher value of current the fluctuations in the arc current and power input were appreciable and the measurements of power were less accurate. The time constant of the arc stabilising circuit is longer and rapid fluctuations in the arc current cause fluctuations in arc voltage which are still present on the input side of the stabilising impedance.

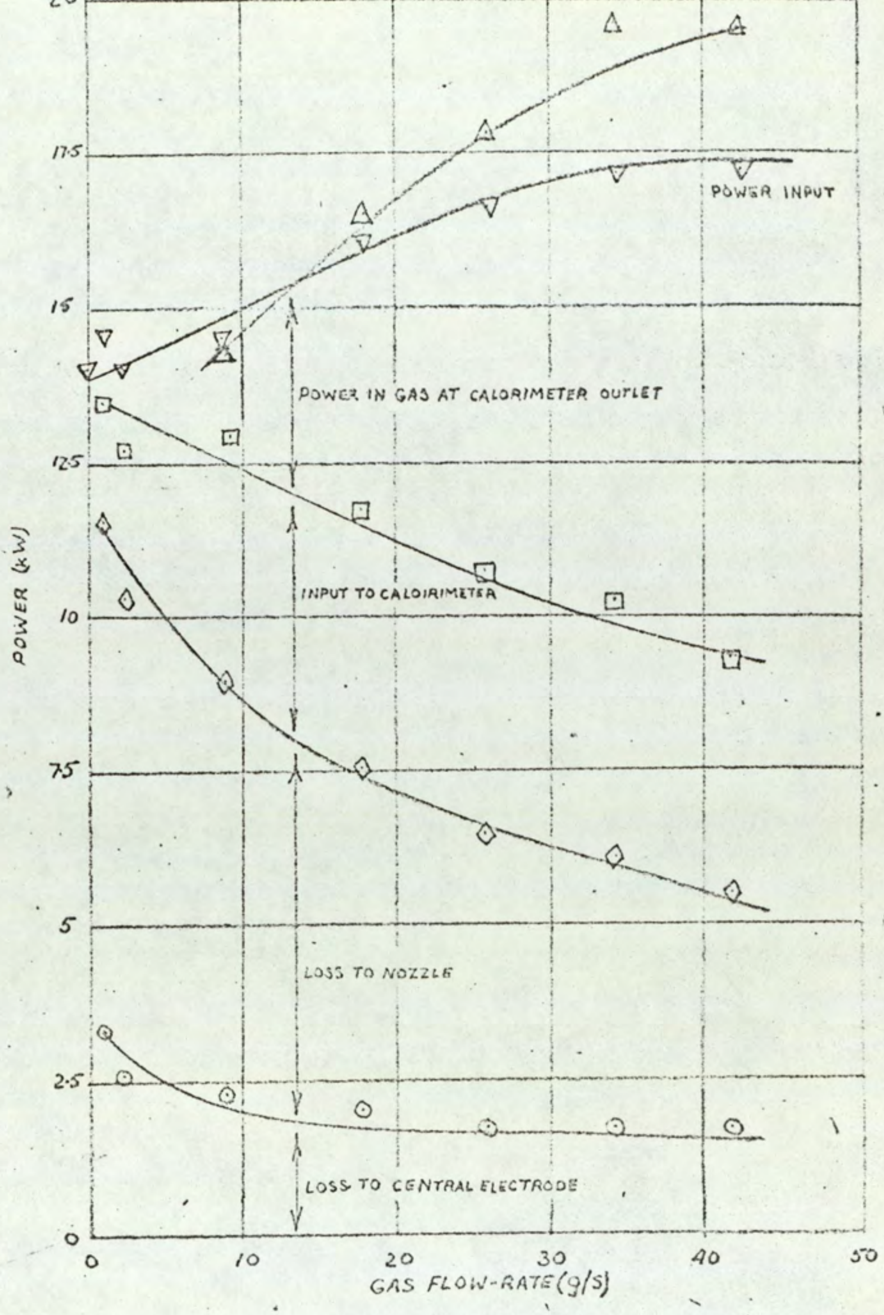
6.2.1. The Energy Balance.

The results of the energy balance measurements are shown in Fig. 6.17.

Unaccounted energy losses to the uncooled parts of the torch body are likely to be small since at 140A at low gas flow-rates the input power approaches the total losses to the electrodes to within less than 5%. At the higher value of arc current the low accuracy of measurement of the arc power due to instability does not enable this comparison to be made. Measurements of the gas temperature at the outlet of the calorimeter could not be made with a repeatability better than 10% at the higher value of arc current due to variation in the temperature over the cross-section of the calorimeter bore. The power in the gas at the outlet of the calorimeter was always less than 50% of the total power input and therefore the overall error in the energy balance is less than half the percentage error in gas temperature measurement (5%).

Errors in the measurement of the total electrical power input are negligible at 140A when the arc was very stable and accurate measurements of the mean power input could be made. At 400A the effect of rapid transient fluctuations and fluctuations of longer duration made it difficult to estimate the readings to an accuracy greater than about $\pm 10\%$.

The energy balance results show that the loss to the electrodes varies from nearly 100% at low gas flow-rates to about 30% of the total power input at high gas flow-rates at both values of current over the same range of gas flow-rates. This indicates that the electrode geometry used is greatly influenced at low gas flow-



ENERGY BALANCE AT 140A 0·25 Wb/m²

FIGURE 6.17

rates by the gas flow-rate or velocity. The minimum gas flow-rate below which the gas temperature no longer increases as the flow-rate decreases due to the greater losses to the electrodes is about 5 g/s. The effect of the small increase in gas pressure is negligible.

The minimum power loss to the electrodes assuming no power is dissipated by evaporation of electrode material, is due to the power dissipated in the anode and cathode fall region. Since both electrodes serve alternatively as anode and cathode half the total power dissipated in the fall regions will be dissipated at each electrode. For copper the combined sum of the anode and cathode fall voltages is about 25V.

The minimum power dissipated at each electrode

$$W_{min'} = 12.5I.$$

This is obtained ~~within~~ less than $\pm 5\%$ W_{min} for the rod electrode at high gas flow rates at 140A and except at very low flow rates at 400A.

The loss to the nozzle was of the order of 2 to 3 times the loss to the rod electrode which indicates that a more efficient nozzle could still be obtained. The greater surface area of the surface of the nozzle exposed to the arc and gas flow will affect the efficiency and the concave surface will tend to allow more contact with the circumfrential components of the arc column than the rod electrode. (See also 5.2.5).

The calorimeter is less efficient at the highest gas flow-rates, less than half the total energy in the heated gas being dissipated in it. More baffles in the calorimeter bore or a different method of construction to increase the surface area exposed to the gas flow would improve this.

Increase in magnetic flux density had little apparent effect except to increase the total power by a small amount.

The thermal time constant of the electrode cooling system during the heating mode was about 20s and about 2 minutes for the calorimeter. Initially very high temperatures at the outlet were obtained largely independent of the gas flow-rate caused by radiation from the arc falling on the thermo-couple. This was overcome by inserting radiation shields inside the bore of the calorimeter to prevent direct radiation from the arc falling on the probe.

There is some difficulty in determining a true mean value of the heated gas at the outlet rather than local temperatures and even with a thermal heat sink in the outlet, temperatures at localised hot spots may still be measured. This could be overcome with a more effective calorimeter design so that the temperature at the gas outlet was at all times near to ambient.

Anything but the simplest calorimeter design of the type used here inevitably becomes highly complex mechanically and the small increase in accuracy obtainable was not thought to be sufficient to justify the construction of a more complex calorimeter.

At the higher value of arc current, even with the calorimeter and radiation shields in place a golden 'flame' showed at the top of the torch during the tests at high currents and gas flows. The highest mean temperature measured at the outlet of the calorimeter is about 600°C and it is unlikely that the golden flame is ionised gas from the arc. A more likely explanation is that it is due to active nitrogen returning to an unexcited state, which is believed to have been previously observed (See also section 4.1.5).

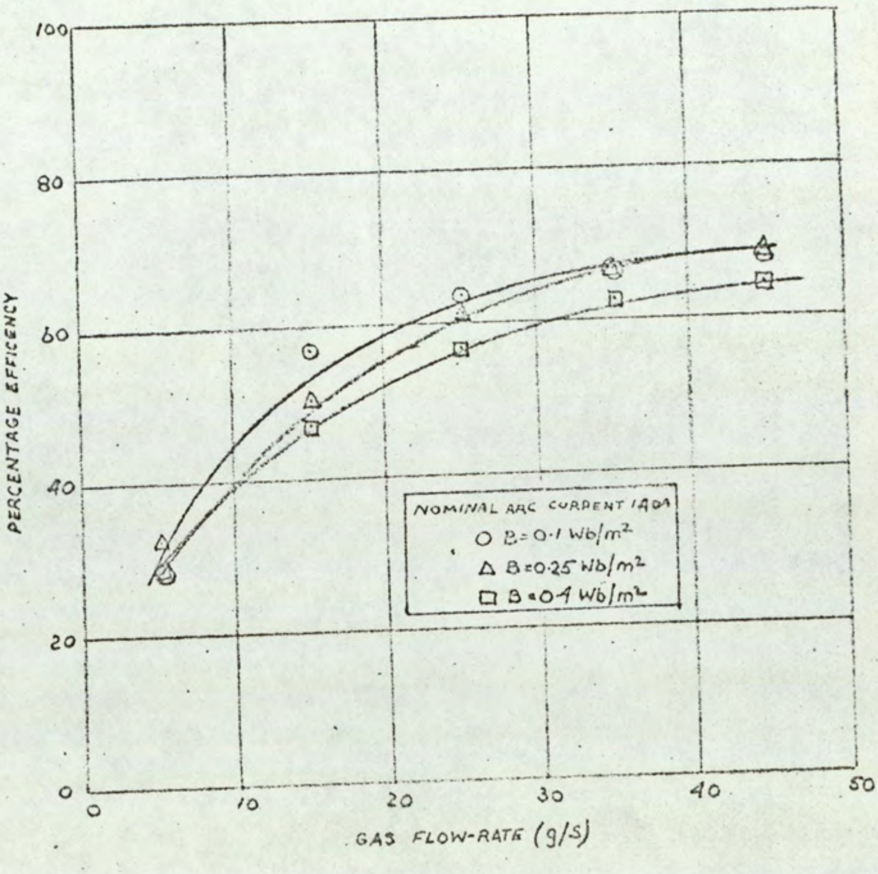
The conversion efficiency as a function of gas flow-rate and the magnetic flux density has been determined at 140A and is shown in Fig. 6.18. The efficiency decreases with increase in the magnetic flux density, the variation being greatest at medium gas flow-rates little difference occurring at low or high gas flow-rates.

The efficiency increases with gas flow-rate tending to a maximum at high gas flow-rates, of about 63%. The efficiency has not been obtained for the higher value of current because of the uncertainty in the measurement of the total power input. It does not however seem unreasonable to predict that the efficiency would be of the same order since the relative magnitude and variation of the electrode losses were similar.

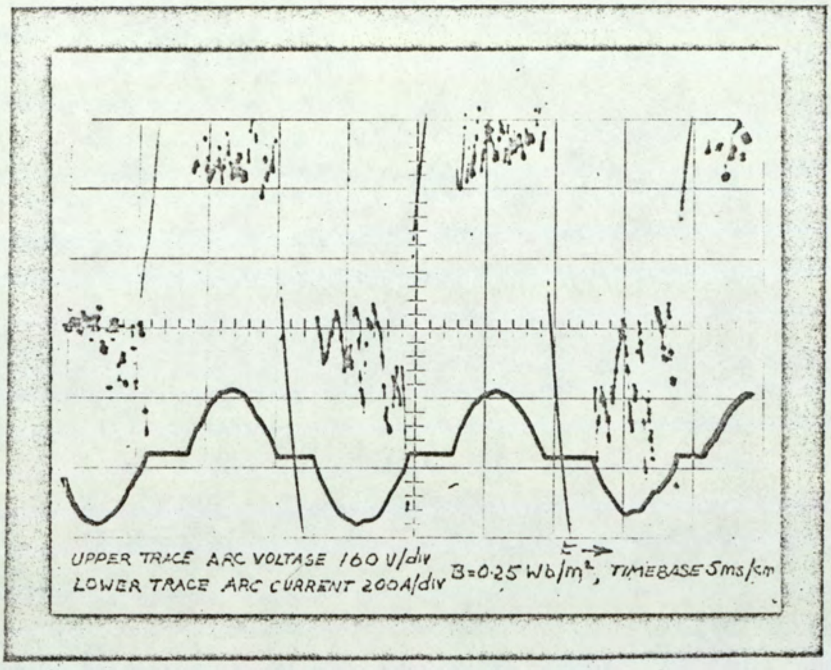
6.2.2. Electrical Measurements.

Typical waveforms of arc voltage and current are shown in Fig 6.19. at low values of arc currents and medium gas flows and magnetic flux densities. More stable waveforms are obtained at lower gas flow-rates and higher magnetic flux densities. The difficulties described in section 6.1.5. in obtaining meaningful values of arc voltage current and power are apparent.

The minimum value of arc voltage obtained from the mean of several cycles with a high speed chart recorder have been plotted in Fig. 6.20. This is normally constant for several milliseconds during each half cycle and can therefore be compared with d.c. values obtained for the same arc gap. Relative measurements of the effect of increase in gas flow-rate, magnetic flux density and arc current on the minimum arc voltage can be seen. The lower value of arc current shows quite an appreciable dependence of arc voltage



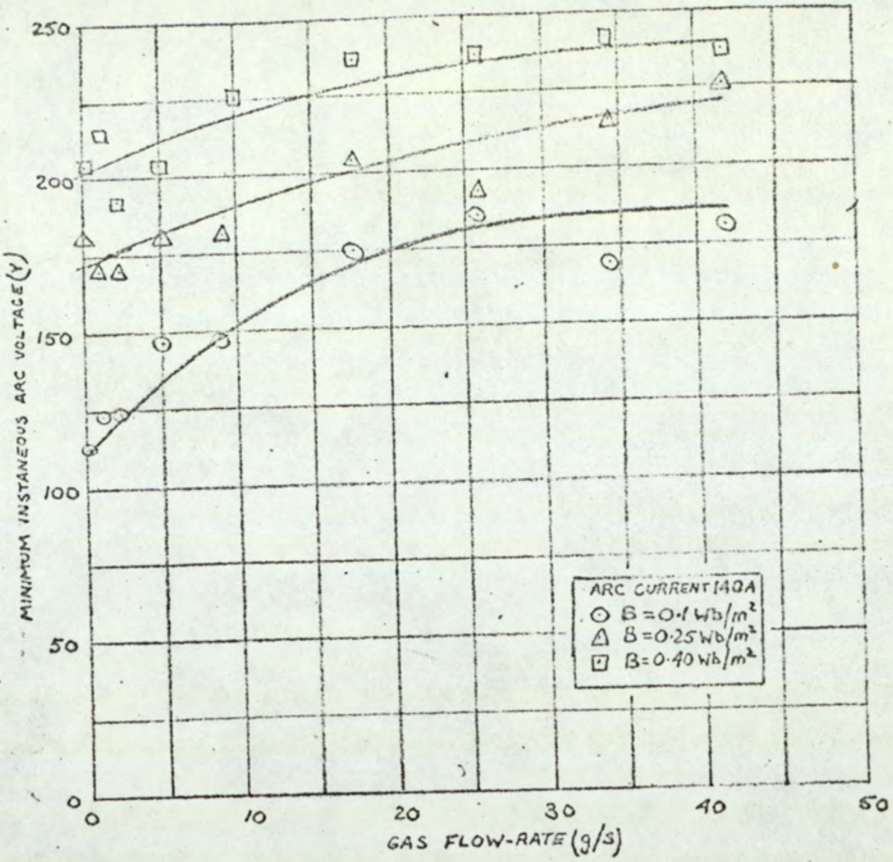
VARIATION OF CONVERSION EFFICENCY WITH GAS FLOW-RATE
(EXCLUDING POWER LOSS IN FIELD COIL)
FIGURE 6.18

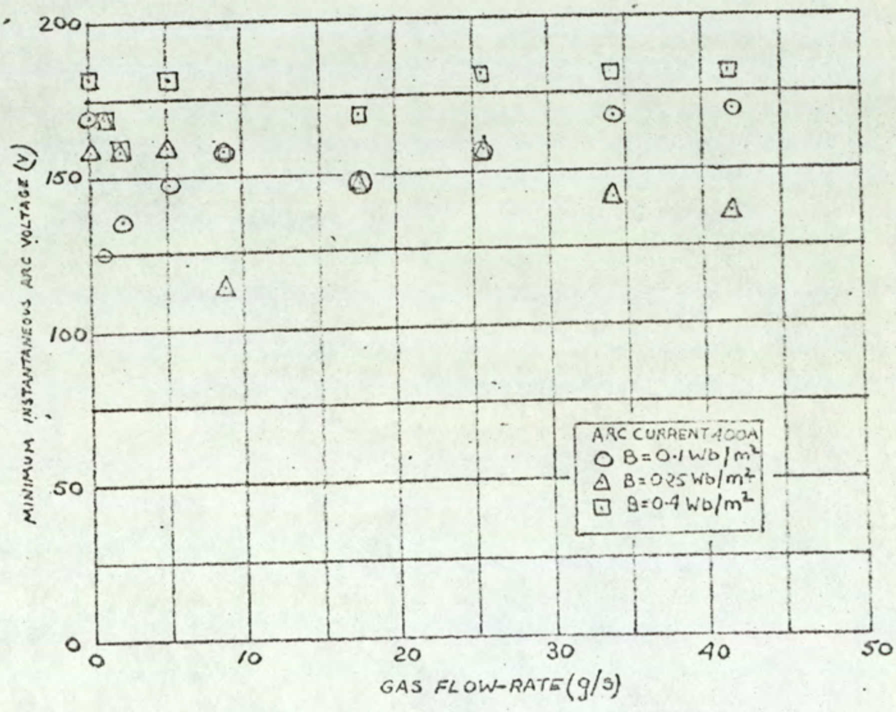


Waveforms of Arc Voltage and Current.

Figure 6.19.

on the axial magnetic flux density and gas flow-rate. The relative effects of increasing the gas flow-rate rate from 0 to 50 g/s and the magnetic flux density from 0.15 Wb/m^2 to 0.4 Wb/m^2 are approximately the same. At 400A arc current the variation is less obvious probably due to the greater instability which tends to conceal any definite trend. The arc voltage is significantly less at the higher current indicating that the increase in velocity with arc current shown in Fig. 6.21. is insufficient to offset the negative variation of the voltage gradient in the arc column with increase in arc current.



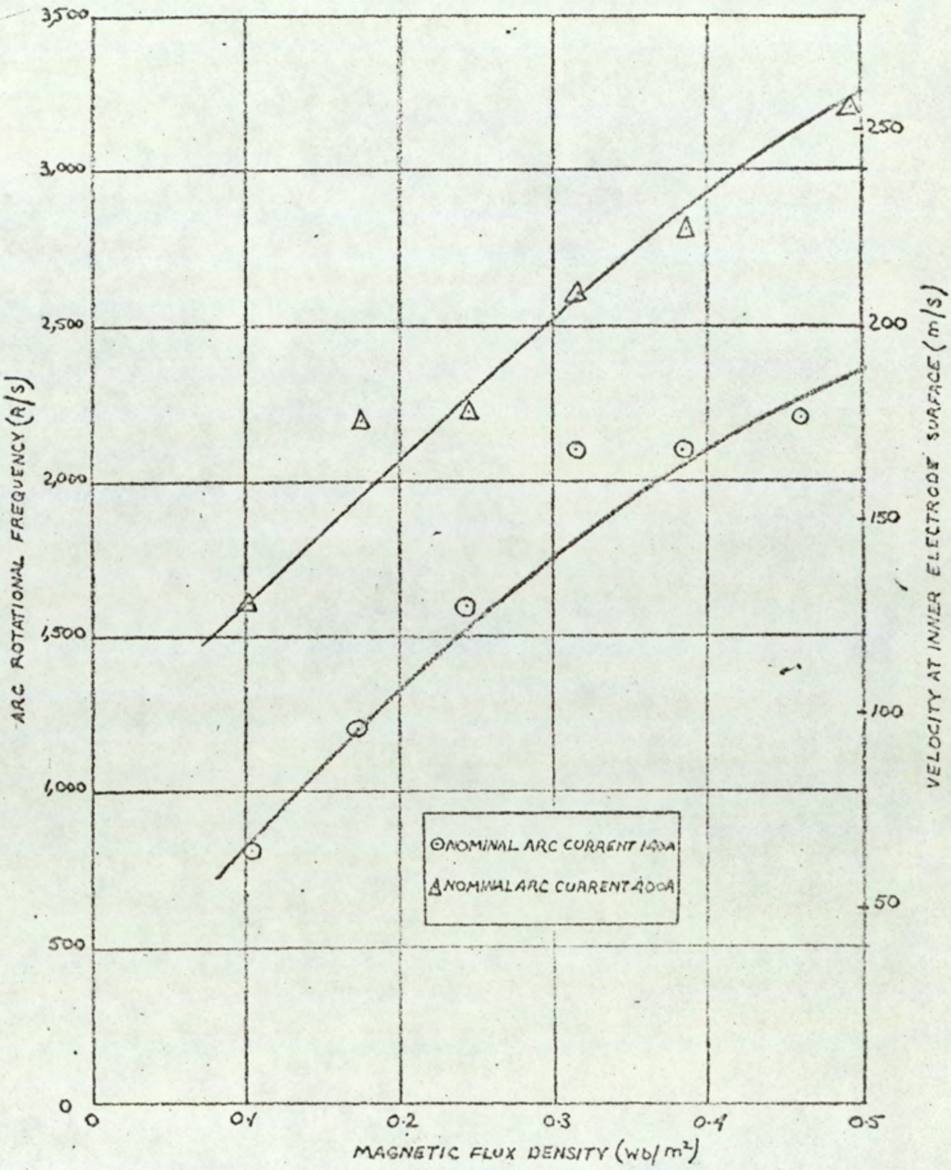


VARIATION OF MINIMUM INSTANTANEOUS ARC VOLTAGE
WITH GAS FLOW-RATE
FIGURE 6.20

Comparison of the measured plateau with the mean d.c. arc voltage obtained in the erosion test (Fig. 5.19.) is difficult due to the apparent dependence of the arc voltage in the erosion test on electrode polarity. No significant variation in arc voltage with electrode polarity was observed in the a.c. tests.

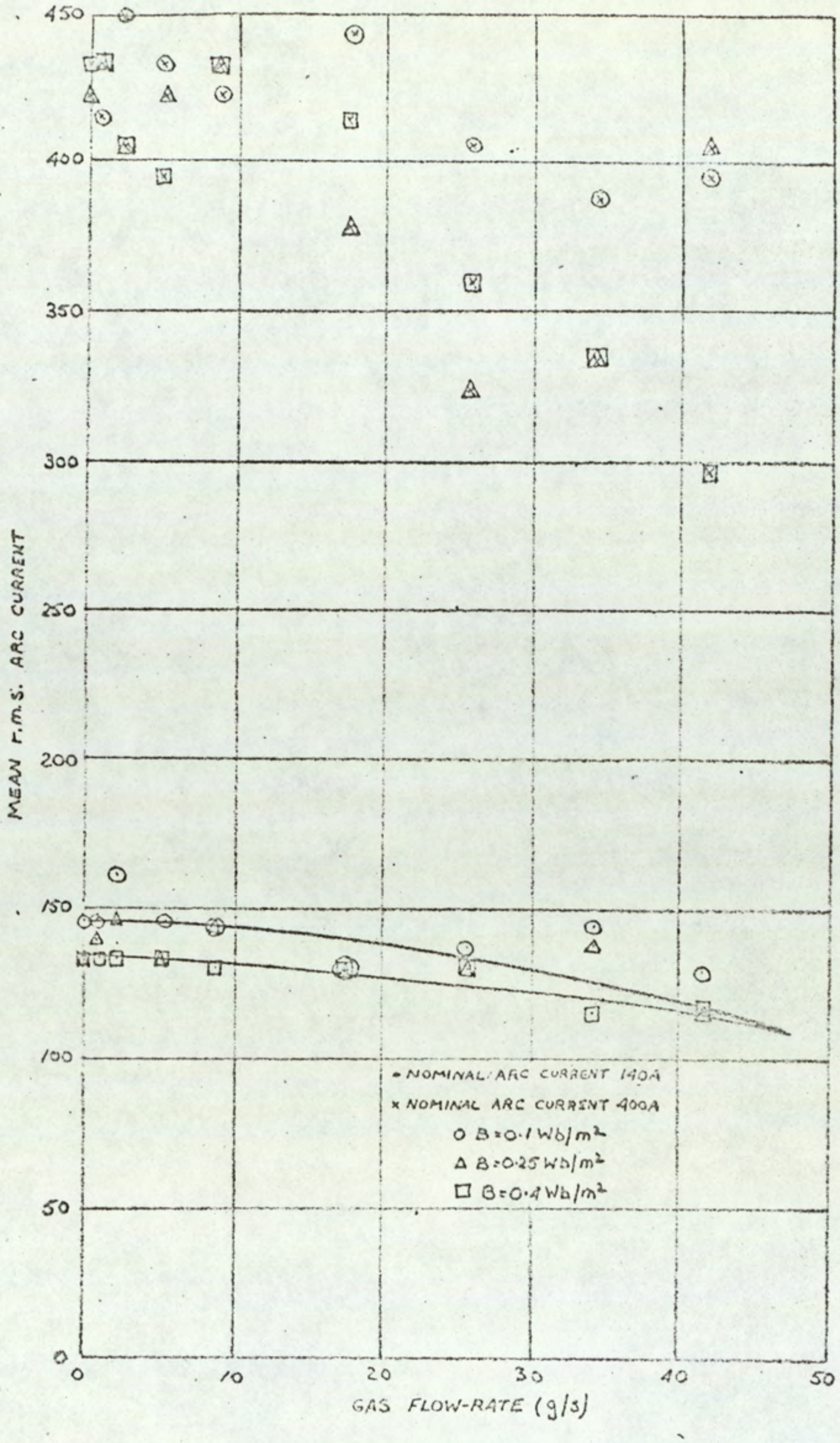
The variation of the mean rotational frequency and velocity in Fig. 6.21. show good agreement with the values obtained in the erosion test. A subsidary test showed no variation in the arc velocity with gas flow rate contrary to the results of Adams (1967). ~~The increase in gas flow rate was not accompanied by any significant increase in gas pressure that occurred at the increased gas flow-rates used by Adams.~~ The results show the relative independence of arc velocity on the arc current and justify the use of a mean value of arc velocity averaged over a half cycle.

The arc current (Fig. 6.22.) is generally more significant than the arc voltage and can be treated in a similar way to the r.m.s. value of a sinusoidal waveform of the same amplitude since the duration of arc extinction after voltage zero is small. This error is negligible compared with that due to random fluctuations at the higher value of arc current.



VARIATION OF MEAN ROTATIONAL FREQUENCY AND VELOCITY WITH MAGNETIC FLUX DENSITY

FIGURE 6.21

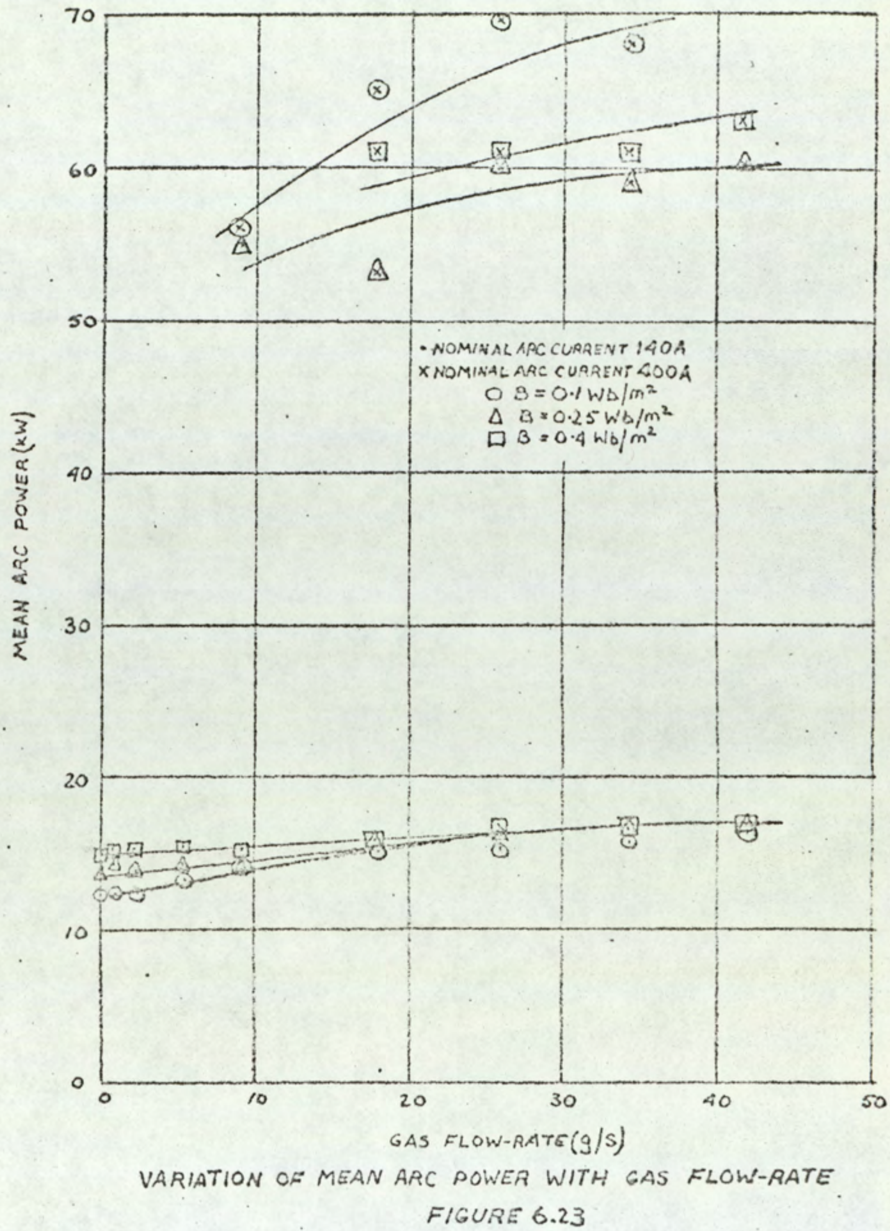


VARIATION OF MEAN r.m.s. ARC CURRENT WITH GAS FLOW-RATE

FIGURE 6.22

The r.m.s. arc current shown in Fig. 6.22. was determined by measurements over several cycles of the peak current from the chart recorder is largely independent of the magnetic flux density decreasing slightly with the gas flow-rate as the arc voltage increases. At the higher value of arc current the random distribution of the measured values is much greater due to the decreased stability. The current generally decreases with increase in the magnetic flux density.

The variation of power input with gas flow-rate is shown in Fig. 6.23. The stability of the readings has already been discussed and the results are subject to the same errors due to random fluctuations and extinction of the arc at current zero as the current readings. The magnitude of the errors will be affected by the greater inertia of the meter movement. By connecting the voltage coil at the input to the series impedance the effect of voltage fluctuations were reduced. The power input was shown to increase with magnetic flux density and gas flow-rate although at high gas flow-rates there is some indication of a decrease probably due to the greater instability at high gas flow-rates.



VARIATION OF MEAN ARC POWER WITH GAS FLOW-RATE

FIGURE 6.23

6.3. Summary of Results.

Previously obtained results for the efficiency of a plasma torch have indicated that conversion efficiencies of up to 82% were measured but in no case was a thermal balance obtained and it is doubtful if the real efficiency was as high as this. (See also 3.2.3.)

The results obtained here have shown that the type of electrode configuration used can give relatively high values of efficiency of more than 60% and have been verified with an energy balance.

The efficiency of this type of geometry is appreciably influenced by the gas flow-rate and is unsuitable for operation at low values of gas flow-rate below about 5 g/s at which the effect of reducing the gas flow-rate in increasing the specific enthalpy of the gas is off-set by the reduced efficiency. The measurements of the power loss at the arc electrodes indicate that the losses at the central electrode are close to the minimum theoretical value but the losses to the nozzle are considerably greater. Modification to the nozzle design, in particular different methods of sealing the water channels enabling a shorter nozzle to be used without damaging the O rings, may substantially decrease the losses at the nozzle.

The main difficulties encountered have been in the measurement of arc current and power at high arc currents due to instability of the arc. This in itself is an important result and shows the need for a better understanding of the stabilising effects of the series impedance and in particular the time constant of the arc circuit. A simplified analysis of the arc circuit indicates that where the arc current is not dominated by the series impedance an optimum value of the time constant of the circuit exists when the time constant associated with the arc and the circuit time constant are approximately equal. Increase beyond this value may decrease the arc stability.

The main sources of error and difficulties in instrumentation encountered are associated with the measurement of arc voltage, current and power.

The tests carried out on the d.c. and a.c. plasma torch described in Chapter 4 indicated some of the difficulties encountered in measuring values of arc voltage, current and power. It was found difficult to ascribe a value of any significance to the a.c. arc voltage. In the present series of tests errors in the measurement of the arc voltage, current and power are more obvious as the results were used for an energy balance and the accuracy of measurement of the input power affected the overall accuracy.

It has been shown that conventional electro-mechanical instruments are subject to several errors when used for the measurement of arc voltage current and power. These may be reduced by using a high frequency vibrating galvanometer chart recorder but the deflection is subject to amplitude and phase shift and errors due to the inertia of the movement. Best results of all will be obtained with an oscilloscope indicating instantaneous values. The difficulty in assessing mean values from instantaneous values has been shown particularly the measurement of arc voltage. Two possible values of significance are the minimum or 'plateau' value of voltage that can be compared with that of a d.c. arc and the r.m.s. value derived from stable readings of current and power.

Whilst relatively stable measurements of arc power may be made with the method of connection of the wattmeter used in these tests, a preferable method would be to use an electronic multiplier. If the frequency response is sufficiently high the output can be integrated to give

$$J = \int_0^T v.i\,.dt \qquad (6.9)$$

where v = instantaneous arc voltage

i = instantaneous arc current

t = period of integration

J = total dissipated energy

This, unlike integrated values of arc voltage or current, has a real significance in the determination of the total power input.

CHAPTER 7.

The Design of a Plasma Torch.

The method of design of a plasma torch over a range of power input of from 3 kW to 60 kW with a rotating arc between co-axial electrodes is considered using the results from the preceding Chapters. The a. c. torch is considered as a special case of d. c. torch design and the results are first derived for d. c. The additional factors affecting operation from a. c. are considered separately.

7.1. A Generalised Procedure for the Design of a Plasma Torch.

The interacting factors affecting the design of a plasma torch are indicated in Fig. 7.1.

The main independent factors affecting design are :

(1) Application (gas, gas flow-rate, etc.)

(2) Power rating.

Factors common to most applications are

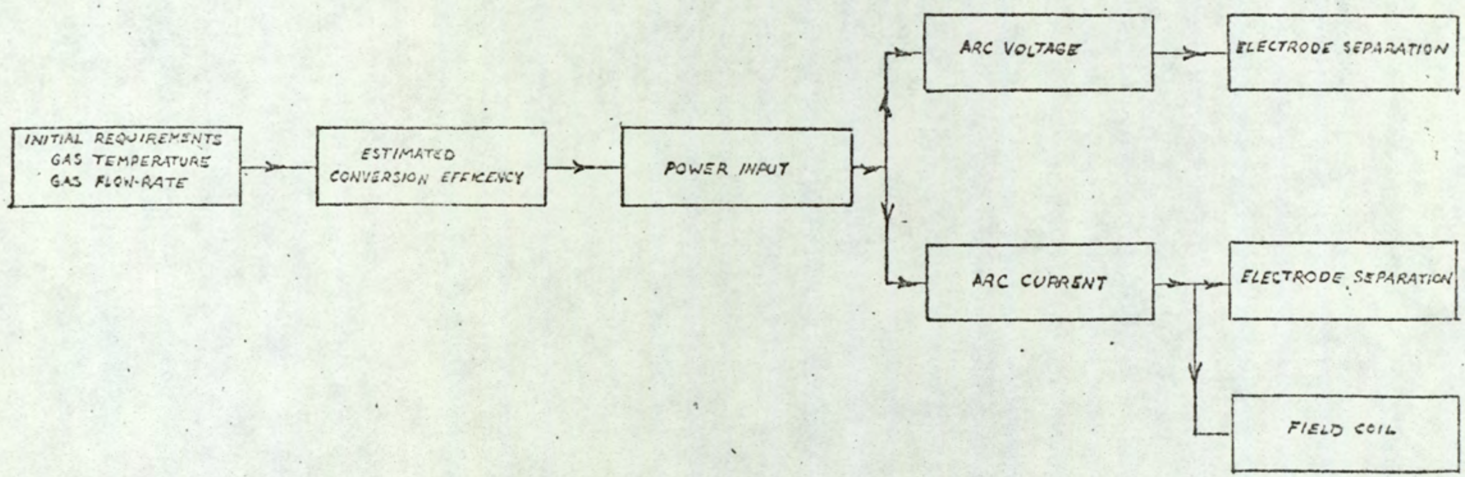
(1) Efficiency

(2) Reliability.

The application affects the choice of electrode material but for most applications copper is suitable. Marginally improved results may be obtained by using silver but only copper will be considered here.

7.1.1. Initial Requirements Affecting the Design.

The steps in the design procedure are illustrated in the flow diagram shown in Fig. 7.1. The initial output requirements for the given application enable the mean temperature and specific enthalpy of the heated gas to be obtained. The total energy required in the heated gas can then be estimated. An allowance for efficiency of conversion of the input power to useful heat output must be made, which will depend on the particular application. The results obtained for the final version of the a.c. plasma torch in Chapter 6 show that conversion efficiencies of more than 60% are obtainable over a useful range of gas flow-rate, at high power inputs up to 60 kW with a co-axial electrode configuration.



STEPS IN THE DESIGN OF A PLASMA TORCH

FIGURE 7.1.

The efficiency depends on power losses at the arc root and containment losses. It is difficult to predict the containment loss but the losses at the arc roots may be estimated. The percentage of the total power input dissipated at the arc electrodes can be calculated approximately from the ratio of the sum of the cathode and anode fall voltages to the total arc voltage.

i.e. $$\frac{(V_c + V_a)}{V_A} \times 100\% \qquad (7.1.)$$

where V_c = cathode fall voltage (about 15V for copper)

V_a = anode fall voltage (about 10V for copper)

V_A = arc voltage.

If the percentage loss due to containment is of the order of 30% little advantage is obtained by making the electrode loss very much less than 10%. The minimum arc voltage required is therefore about 250V. The arc current required may now be determined from the total input power and arc voltage making an approximate estimate of the expected efficiency.

7.1.2. Determination of the Electrode Dimensions.

The diameter of the inner electrode may be obtained when the arc current and power losses have been estimated. The minimum diameter is governed by

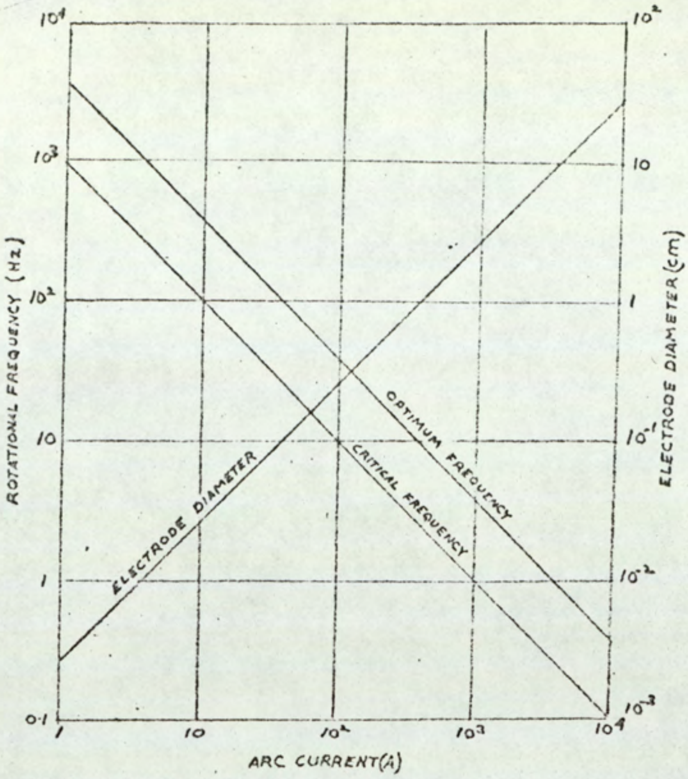
(1) The minimum conditions required for the electrode surface at the arc root to be maintained below the melting point of the electrode material.

(2) The electrode cooling water flow-rate required.

The minimum electrode diameter for a given arc current can be determined from the results derived in 5. 2.7. and reproduced in Fig. 7. 2 & 7. 3 At currents below about 1, 000A the diameter is normally governed by mechanical considerations and the water flow-rate required. The water flow-rate necessary can be deduced from the power loss allowing a maximum rise in water temperature of about 20^{o}c or an outlet temperature of 40^{o}c whichever is lowest. This is to ensure that local boiling in the electrodes, which can cause rapid erosion, does not occur.

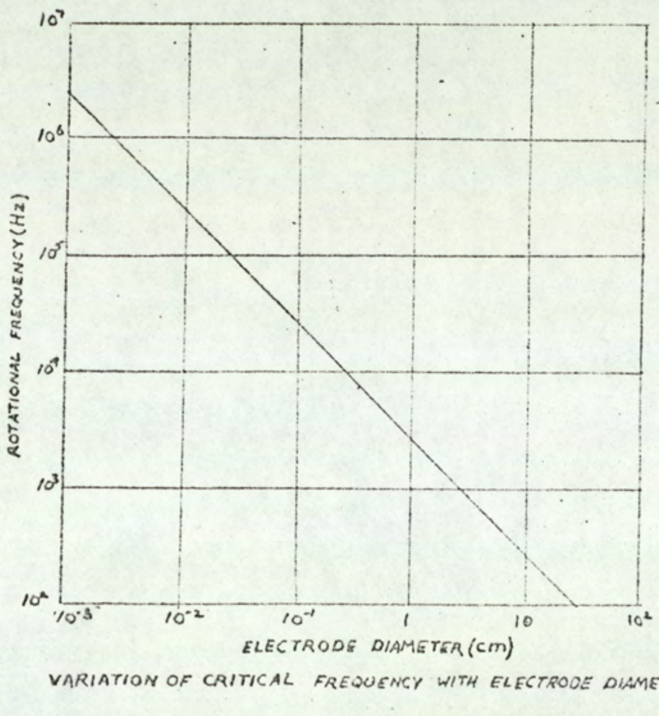
A high pressure water supply is not normally essential except at high power ratings where the total containment loss may be high. At the same time the diameter of the inner electrode should be as small as possible in order that the size and power input of the field coil used to rotate the arc should be a minimum. Reduction in size of the central electrode is not however justified if the proportional decrease in the overall diameter of the torch is small.

The internal diameter of the central electrode having been determined the electrode wall thickness can be decided. The results obtained in the erosion test in Chapter 5 indicate that this is not critical contrary to previous reports (see also 5. 2. 6) and typically electrode wall thicknesses of between 0. 25 cm and 0. 5 cm can be used satisfactorily. No advantage at all was shown to be obtained by using thin walled intensively cooled electrodes when containment losses were small.



VARIATION OF CRITICAL FREQUENCY, OPTIMUM FREQUENCY AND ELECTRODE DIAMETER WITH ARC CURRENT

FIGURE 7.2



VARIATION OF CRITICAL FREQUENCY WITH ELECTRODE DIAMETER

FIGURE 7.3

7.1.3. Calculation of Electrode Separation Required.

If the outer diameter of the central electrode is greater than the minimum value, the critical rotational frequency below which electrode melting cannot be prevented will be reduced. This is shown as a function of the electrode diameter in Fig. 7.3. If a.c. is used the peak current should be used to determine the minimum electrode diameter and critical frequency. The corresponding critical velocity is independent of arc current or electrode diameter and for copper is of the order of 80 m/s. The voltage gradient in the arc column may be approximately deduced at this velocity from the generalised electric characteristic equation (Adams et al, 1967). (See also 2.4.3.).

$$\frac{Ed^2}{I} = 10^3 \left(\frac{J^2}{Ud^3}\right)^{-\frac{2}{3}} \qquad (7.3)$$

where E = voltage gradient (V/m)

d = electrode separation (m)

I = arc current (A)

U = arc velocity (m/s)

The electrode separation required is dependent on the voltage gradient of the arc column. An arc rotating between co-axial electrodes takes up an approximately involute shape (Adams 1964). The arc length is therefore given by

$$S = \frac{r}{2}\left(\frac{R^2}{r^2} - 1\right) \qquad (7.4)$$

where s = arc length (m)

r = radius of centre electrode (m)

R = internal radius of outer electrode (m)

and $r + d = R$.

The total arc voltage required has already been determined. If the sum of the anode and cathode fall voltages is assumed to be 25V, the gradient in the arc column E may be determined from

$$V = 25 + E s \qquad (7.5.)$$

and by substituting for E in equation (7.5.) d may now be calculated. The electrode separation should be sufficient to allow the required gas flow to be obtained at gas flow below sonic velocities. This is normally satisfied but if it is not, either the diameter of the outer electrode or the electrode separation should be increased, and the conditions re-calculated.

7.1.4. Estimation of Value of Magnetic Flux Density Required at the Critical Arc Velocity.

When the electrode separation is known the magnetic flux density required to rotate the arc at the required velocity can be determined from the equation for the magnetic characteristic, (2.4.2.).

$$\frac{Ud}{I} = 4.6 \left(\frac{I}{Bd}\right)^{-0.6} \qquad (7.6.)$$

where U = arc velocity (m)

I = arc current (A)

B = magnetic flux density (Wb/m^2)

d = electrode separation (m).

A factor should be allowed to compensate for the drop in arc velocity that occurs if the increase in gas flow is accompanied by an increase in gas pressure of more than 1 Atmosphere (Adams, 1967).

The external diameter of the outer electrode can be obtained as the internal diameter is known from the cooling requirements. These will be rather larger than for the inner electrode due to the higher containment loss caused by the larger surface area and shunting of the arc on the concave electrode surface. (See also 5 . 2. 5.).

When the size of the outer electrode is known the dimensions of the field coil used to rotate the arc and the power input required can also be determined. This can be done using the design procedure and computer program in Appendices 1 and 2. For continuous use the optimum coil dimensions should be used and it may be necessary to water cool the coil. For discontinuous applications water cooling may be unnecessary and a coil smaller than the optimum size may be used. The effective operating time starting from room temperature can be estimated from the power input to the coil, the thermal capacity and the maximum operating temperature of the coil.

7.1.5. Design of Torch Body, Insulator and Gas Inlet .

The torch body and base can be either an inorganic insulator (organic materials deteriorate in the ultra-voilet light from the arc) or metal. If the body is metal the body and base should be isolated from the electrodes to prevent arcing to them at low gas flow-rates. The insulation between the electrodes should also be an inorganic material.

The gas inlets are most conveniently positioned in the end of the torch on the outside of the torch with a gas inlet co-axial with the central electrode.

7.16. Power Supplies Required.

Insufficient information is available to enable the optimum ratio of opencircuit voltage to arc voltage to be predicted. Normally where a high efficiency, good utilisation of the power supply(and a high power factor when operation is from a. c.) are required a ratio of open circuit voltage to arc voltage of 2:1 may be used. For high stability and for continuous uninterrupted operation ratios of up to 10:1 have been used. Under these conditions the power input to the arc will be approximately independent of the gas flow-rate.

7.17. Features of Design Peculiar to the A. C. Torch.

The essential difference between a d. c. and an a. c. torch is that the a. c. arc current varies during each half cycle and the arc normally requires re-ignition with a separate ignition source after current zero. The effect of the cyclic variation in arc current is to vary the instantaneous power output and to a lesser extent the arc velocity. The arc velocity is not greatly influenced by the arc current and a mean value equivalent to that corresponding approximately to the peak arc current can be used,since the maximum arc velocity is normally required at the highest arc current.

If the open circuit voltage is insufficient to breakdown the arc gap a separate ignition supply is required. An auxillary ignition electrode may be used to reduce the ignition voltage necessary to breakdown large arc gaps. Generally a parallel connected high voltage supply is to be preferred of the type described in 6.1.3. This allows higher ignition voltages and greater flexibility in design to be obtained. If very large arc gaps are used and the ignition voltage becomes excessive the auxillary electrode described in 4.2.4. may be used to enable operation at reduced ignition voltages.

CHAPTER 8.

Conclusion.

The results and their implications are summarised and possible areas of further research are suggested.

8.1. Summary of Results.

A mains frequency plasma torch capable of operating reliably at up to 60 kW at conversion efficiencies of 60% at a high power factor has been developed.

A basis for the design of an a.c. or d.c. plasma torch for industrial process heating has been formulated for the first time.

A review of arc processes relevant to the understanding of the operation of a plasma torch has been presented that is unique in its coverage.

A critical review of the design of arc heaters over a very wide range of applications has been made enabling the relative merits of the individual aspects of design to be considered.

The influence of nozzle design on the efficiency of a plasma torch has been investigated.

The behaviour of the arc in the constricted region of a plasma torch has been investigated with a laminated nozzle.

A new explanation has been advanced to account for the long laminar luminous jets of gas obtained at low gas flow-rates in the presence of nitrogen.

The behaviour of arc discharges rotating at high magnetic fields and at high arc currents have been studied where there has been no previous detailed investigation.

A concentrated arc has been obtained over the entire range of arc current and magnetic flux density used, where previously a diffuse discharge had been thought to be obtained.

A high current synchronous switch has been developed which has a wide application where high current pulses are required for a short time.

The first reported measurements of the erosion at the electrodes of an arc rotating in a tranverse magnetic field have been obtained. The variation of erosion with magnetic flux density has been obtained which is applicable to the design of circuit breakers. The minimum value of erosion measured is an order of magnitude lower than the minimum values previously postulated.

The measurements of erosion and arc velocity have been used to formulate the minimum diameter and critical arc velocity for satisfactory operation of a plasma torch.

A new definition of arc stability enabling the quantitative assessment of stability has been proposed.

A minimum condition for a stable a.c. arc has been suggested.

A new method of arc ignition enabling large separations between the main electrodes has been developed.

An improved method of connection of high frequency arc ignition units has been developed enabling the output transformer to be independent of the arc current.

A thermal model of the conditions at an arc root on an electrode has been studied using a resistance analog.

The results obtained where containment losses are small indicate that the effect of electrode wall thickness and intensive cooling of the electrode is not significant contrary to previous beliefs.

A study made of the investigations of the electrical parameters of an arc indicate that sources of error exist which had previously not been realised.

A computer programme has been written enabling the design of an air cored cylindrical field coil to be optimised in terms of power, volume, or operating time.

8.2. Possible Areas of Future Research.

Due to the large field covered by the present investigation it has not been possible to investigage in the detail required some of the aspects of the work. Rather, it has been necessary to curtail many of the investigations such as the measurement of electrode erosion and arc stability in order to fulfill the initial aims outlined in the introduction.

Possible modifications to the plasma torch include a method of reducing axial movement of the arc column in a transverse gas flow which would result in a more stable and controllable discharge. Provision of water cooling of the field coil would enable the torch to be run for indefinite periods. Real values of process efficiency could then be obtained with the torch incorporated into a prototype furnace.

Any potential process should take advantage of the unique characteristics of the plasma torch which are

(1) Low contamination of heated gas output.

(2) Rapid response to control fluctuations.

(3) High specific enthalpy output.

It is recognised that conventional furnace conceptions may be completely unsuited to these characteristics. Typically continuous flow processes making use of the high enthalpy obtainable and low heat losses through rapid heating are envisaged.

Only by investigating the overall process efficiency rather than the efficiency of the plasma torch alone can a realistic assessment of the application of the plasma torch to industrial process heating be made. New processes may enable overall economies to be achieved off-setting the higher energy costs. Examples are the manufacture of tool steel where by eliminating oxygen in the initial stages of production costly vacuum degassing and induction heating might be eliminated. The production of high purity copper from electrolytic copper which is at present carried out using natural gasmight might enable improved end product to be obtained. For high cost products d.c. could be used but the results from this projectarestill applicable.

A feature of the plasma torch is its suitability for control, almost instantaneous variation in the heat output being obtainable over a very wide range of heat outputs. The control variables with fixed geometry and supply voltage are

1. Arc current.
2. Magnetic flux density.
3. Gas flow-rate.

The possibility of using the magnetic flux density to control the arc current enabling a simple method of the control of arc power to be obtained should be investigated.

In addition to the plasma torch itself several other areas of fruitful investigation have been indicated which due to the limited time available it has not been possible to follow up. These include the assessment of arc stability and influence of circuit parameters, and directly related to this the measurement of electrical parameters of a. c. arcs. This has particular application to the operation of large arc furnaces but may also be applied to other arc operated devices. Experimental and analytical investigation of the quantitative effects of external factors affecting arc stability would enable the operating conditions of large arc furnaces to be improved. Further investigation of the errors in the measurement of arc voltage current and power with electro-mechanical instruments is required.

As well as the applications already mentioned the advent of cheap natural gas may justify augmentation of the combustion energy and temperature of the heated gas with an arc heater by small amounts.

The application of an a. c. plasma torch of the type described in Chapter 4 in either the transferred or non transferred mode to cutting and welding processes should be considered. Capital savings could be obtained by eliminating the redification equipment required for d. c. operation. There is also a possibility of improved weld quality being obtained with aluminum by reducing the self rectification effect obtained with conventional a. c. argon shielded welding processes.

Appendices.

APPENDIX 1.

The Design of Air Cored Field Coils.

The power required for a given field strength is obtained from the relation developed by Fabry (1898)

$$B = \frac{G}{100}\left(\frac{W\lambda}{\rho a_0}\right)^{\frac{1}{2}}$$

where B = magnetic flux density (Wb/m^2).

G = Fabry factor.

W = power input (W).

λ = winding space factor

ρ = resistivity of winding (ohm. cm).

a_0 = inner radius of coil (m).

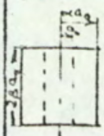
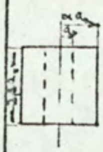
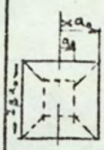
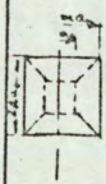
The geometry factor G is obtained from Biot-Savarts' law applied to a multi-layer solenoid. The value of G depends on the coil dimensions and the current distribution in the coil. Maximum values of G for various coil geometries and current distributions and the variation of G with the normalised dimensions of the coil for the more common geometries and current distribution have been obtained (Montgomery & Terrell, 1961). Except in cases where the highest possible magnetic flux density is required or homogeneity of the field is of great importance the choice of coil shape can be reduced to cylindrical or trapezoidal with either uniform current distribution or the current distribution varying inversely with the coil radius. The geometry factor of these coils is shown in the table below in terms of the coil geometry

where α = outer radius normalised with respect to bore radius

β = axial half length of coil normalised with respect to bore radius.

Table 1.1.

Design Constants for Air Cored Solenoids.

Coil Shape	Current Distribution	Geometry Factor	G_{max}
 Cylindrical bore, square ends	Uniform	$\frac{1}{5}\left(\frac{2\pi\beta}{\alpha^2-1}\right)^{\frac{1}{2}} \log \frac{\alpha+(\beta^2+\alpha^2)^{\frac{1}{2}}}{1+(\beta^2+1)^{\frac{1}{2}}}$	0.179 $\alpha = 3, \beta = 2$
 Cylindrical bore, square ends	Inversely proportional to radius	$\frac{1}{5}\left(\frac{\pi}{\beta \log\alpha}\right)^{\frac{1}{2}} \log\alpha . \frac{\beta+(1+\beta^2)^{\frac{1}{2}}}{\beta+(\alpha^2+\beta^2)^{\frac{1}{2}}}$	0.209 $\alpha = 6, \beta = 2$
 Cylindrical bore, tapered ends	Uniform	$\frac{1}{5}\left(\frac{3\pi k}{k^2+1}\right)^{\frac{1}{2}} \frac{\alpha-1}{(\alpha^2-1)^{\frac{1}{2}}}$ $\left(k = \frac{\alpha}{\beta}\right)$	0.172 $\alpha = 2.7, k=1$
 Cylindrical bore, tapered ends	Inversely proportional to radius	$\frac{1}{5}\left(\frac{\pi k}{k^2+1}\right)^{\frac{1}{2}} \frac{\log\alpha}{(\alpha^2-1)^{\frac{1}{2}}}$ $\left(k = \frac{\alpha}{\beta}\right)$	0.201 $\alpha = 4.5, k=1$

A trapezoidal coil section has the advantage that an efficient design may be obtained with a short bore length and losses from the hot gas to the coil may be reduced in this way. This was not important in the present investigation as the heated gas is passed directly into a calorimeter which could be mounted within the coil bore. A cylindrical coil which is easier to construct was therefore chosen. The nozzle could be positioned at the end of the coil with some reduction in field if necessary.

An appreciable reduction in the coil dimension and therefore weight and cost may be made without a significant decrease in the geometry factor, but an increase in the power density. Optimisation of the coil dimensions in terms of the geometry factor and volume at values of G less than the maximum value is not possible from the published curves.

A digital computer was used to determine the variation of the geometry factor, and volume with normalised dimensions for a coil with uniform current density and also with the current density varying inversely with the radius of the coil winding.

The magnetic field strength on the axis of a uniformly wound coil with a constant current distribution at the centre is

$$B = \frac{\pi i \lambda a_0}{500}\left[\mathrm{Log}\left(\frac{(k-\beta)+(\alpha^2+(k-\beta)^2)^{\frac{1}{2}}}{(k+\beta)+(\alpha^2+(k+\beta)^2)^{\frac{1}{2}}}\right) - \mathrm{Log}\left(\frac{(k-\beta)+(1+(k-\beta)^2)^{\frac{1}{2}}}{(k+\beta)+(1+(k+\beta)^2)^{\frac{1}{2}}}\right)\right]$$

and for a coil winding with the current density varying inversely with the radius

$$B = \frac{\pi i_1 \lambda a_0}{500}\left[(k+\beta)\,\mathrm{Log}\left(\frac{\alpha+(\alpha^2+(k+\beta)^2)^{\frac{1}{2}}}{1+(1+(k+\beta)^2)^{\frac{1}{2}}}\right) - (k-\beta)\,\mathrm{Log}\left(\frac{\alpha+(\alpha^2+(k-\beta)^2)^{\frac{1}{2}}}{1+(1+(k-\beta)^2)^{\frac{1}{2}}}\right)\right]$$

where $\quad i = \frac{i_1 a_0}{r}$.

These have been solved

$$\text{for } 1.5 \leqslant \alpha \leqslant 22.1$$
$$0.6 \leqslant \beta \leqslant 17.1$$

using an Elliot 803 digital computer. The computer program in ALGOL is shown on the following page.

APPENDIX 2.

Computer Program Used to Evaluate Field Coil Design.

Table 2.1.

Output Data and Program Symbols.

Column	Program Symbol	Variable	Description
1	A	-	Normalised external radius
2	B	-	Normalised half bore length
3	J	G_1	Geometry factor (constant current density)
4	O	G_2	Geometry factor (current density varying inversely with coil radius).
5	P	-	Normalised volume

Program.

```
LD COIL DESIGN 5.3.67'
IN REAL A,B,C,D,E,F,G,H,I,J,K,L,M,N,O,P'
 A:=1.5 STEP 0.1 UNTIL 2.01,3.0 STEP 1.0 UNTIL 22.1 DO
 B:=0.6 STEP 0.1 UNTIL 1.01,2.0 STEP 1.0 UNTIL 17.1 DO
IN C:=A**2'
   D:=B**2'
   E:=B/A'

   F:=A+SQRT(C+D)'
   G:=1+SQRT(1+D)'
   H:=1+LN(F/G)'
   I:=SQRT(2*3.1416*B/(C-1))'
   J:=H*I/5'

   K:=B+SQRT(1+D)'
   L:=B+SQRT(C+D)'
   M:=LN(A*K/L)'
   N:=SQRT(3.1416/(B*LN(A)))'
   O:=M*N/5'

   P:=2*(C-1)*B'

   PRINT ££L1S??,SAMELINE,FREEPOINT(5),A,PREFIX(££S3??),
   B,J,O,P'
   END'
```

APPENDIX 3.

Some Existing and Potential Applications of Plasma Torches.

Metallurgical Processes.

Application	Comments	Ref.[x]
Metal cutting : Stainless steel, carbon steel, aluminium etc.	High cutting speeds.	1, 2
	Reduced degradation of material at cut.	3
	Improved edge of cut.	
Metal welding : Seam welding of tubing. Low power precision applications.	High speed. Uniform	4
	penetration. Less sensitive to arc length in transferred mode than other arc processes.	5
Material deposition : Weld surfacing. Metal and cermet deposition.	Homogeneous deposits fusion bonded to sub-strate.	6
	Almost any material	7
	including high melting point materials.	8, 9, 10.
	Low contamination compared with flame spraying.	11

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[x] Numbers of references are keyed to references at end of this appendix.

Application	Comments	Ref.
Heat treatment : Wire, strip etc.	Continuous high speed annealing.	12
Spheroidising : Dispersions, and materials science research.	In some cases only possible method.	7
Melting : Refractory metals and alloys for investment casting.	Comparable with those obtained by vacuum melting and casting with good control of alloy composition.	12,
High quality steel.	Could eliminate necessity for vacuum melting and de-gassing.	13
Electrolytic copper melted in shaft furnaces.	May result in economic production of high quality phosphorous free copper.	14
Pre-heating oxygen in F.O.S. process.	Greater output obtainable from same furnace size.	
Augmentation of combustion flames.	High temperatures obtainable from low grade source.	15 16 17.

Chemical Engineering Processes.

Application	Comment	Ref.
Gaseous Reactions $N + O \rightarrow NO$ $2CH_4 \rightarrow C_2H_2 + 3H_2$ $2C + H_2 \rightarrow C_2H_2$ $2C + N \rightarrow (CN)_2$ $2C + H_2 + N_2 \rightarrow 2HCN$	Requires abundant cheap electrical power. Improved output over conventional process on laboratory scale. Capital plant cost is main deciding factor on industrial scale. Improved product purity is major advantage.	18 19 20 23 23
Unstable compounds obtained by rapid quenching.	Metastable chemical products. Super-conducting materials.	24
High Temperature Processes.	Deposition. Production of pyrolytic graphite. Anisotropic graphite formed. Manufacture of graphite whiskers.	25, 26
Spraying polymeric materials.	Plastic fabrication Cavity free layers produced.	27

Space Research.

Application	Comments.	Ref.
Re-entry simulation	Very rapid heating with low contamination obtainable.	28
Space propulsion	No combustion process required.	29
Laboratory Applications.		
Sample production for analysis.	Metallurgical and chemical applications	30
Spectroscopic source.	Very high temperatures obtainable	31
Miscellaneous Applications.		
Light source.	Very high intensity	
Improved adhesion on rail tracks.		
Compact source of very large quantities of low enthalpy gas.	Large volume obtained from small heater.	

References for Appendix 3.

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