The production of a large volume electric discharge

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THE PRODUCTION OF A LARGE VOLUME ELECTRIC DISCHARGE

by

LESLIE HOBSON

A DOCTORAL THESIS

Submitted in partial fulfilment of the requirements for the award of Ph.D. of the Loughborough University of Technology 1980.

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Department of Electronic and Electrical Engineering

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Summary

The purpose of this work was to investigate the production of a large volume electric discharge with particular reference to the superposition of d.c. and high frequency discharges. The principle objective was to enable a reduction in the operating frequency of the high frequency power source to values more amenable to industrial application. This has been achieved.

An extensive literature survey has been made including:

(i) Arc discharge processes relevant to the production of large volume discharges,

(ii) Induction coupled discharges,

(iii) Methods of producing thermal plasmas suitable for chemical and metallurgical synthesis

Preliminary investigations indicated a major problem in obtaining significant coupling between a high frequency power source at 450 kHz and a single d.c. discharge. A detailed study of the processes involved enabled a method of analysis to be developed which explained the low efficiency of coupling between the high frequency source and the d.c. discharge.

Methods of increasing the efficiency of coupling were assessed including the use of multiple arc systems. The need for further fundamental information on the behaviour of coalescing arcs was indicated. In particular the conditions for arc stability and the incorporation of such systems to produce discharges of a diffuse nature were required. These problems were thus investigated both theoretically and experimentally.

(ii)
A horizontal multiple arc configuration was developed which formed a large volume discharge of an apparently diffuse nature.

A vertical multiple arc configuration was also developed which provided a system of d.c. discharges into which high frequency power at 450 kHz was efficiently coupled to form a large volume discharge.

Concurrently with the multiple arc investigations, a discharge vessel using d.c. power and high frequency power at 6.5 MHz to avoid initiation problems, was designed and operated. The characteristics of the combined discharges were investigated and useful design information about the discharge vessel obtained. An assessment was also made of the validity of the analysis developed for use with the combined discharge.

In addition results of a wider application have been obtained including the use of optical filters in an attempt to improve high speed photographic plasma diagnostic techniques.
ACKNOWLEDGEMENTS

I would like to acknowledge Dr. J. E. Harry for his encouragement and guidance throughout this work and I am grateful to all my other colleagues for their understanding and support.

I would also like to thank the Electricity Council Research Centre for the loan of the high frequency generator used in the work described in Chapter 5.
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<tr>
<td>$D_v$</td>
<td>diameter of hollow cylindrical work piece model of vertical multiple arc system</td>
<td>(m)</td>
</tr>
<tr>
<td>$E$</td>
<td>electric field strength</td>
<td>(V/m)</td>
</tr>
<tr>
<td>$E_c$</td>
<td>work coil voltage</td>
<td>(V)</td>
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<tr>
<td>$E_z(0)$</td>
<td>electric field strength on axis of discharge</td>
<td>(V/m)</td>
</tr>
<tr>
<td>$E_z(r)$</td>
<td>electric field strength at radial distance $r$</td>
<td>(V/m)</td>
</tr>
<tr>
<td>$G$</td>
<td>conductance</td>
<td>(S)</td>
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<td>$H_0$</td>
<td>peak magnetic field strength at surface of conductor</td>
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</tr>
<tr>
<td>$I$</td>
<td>arc current</td>
<td>(A)</td>
</tr>
<tr>
<td>$I_1, I_2$</td>
<td>arc current in parallel arc system</td>
<td>(A)</td>
</tr>
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<td>$I_c$</td>
<td>work coil current</td>
<td>(A)</td>
</tr>
<tr>
<td>$J_0$</td>
<td>Bessel function of first kind, zero order</td>
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</tr>
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<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
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<td>tank circuit inductance</td>
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<tr>
<td>N</td>
<td>number of work coil turns per unit length</td>
<td>(m&lt;sup&gt;-1&lt;/sup&gt;)</td>
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<tr>
<td>N&lt;sub&gt;c&lt;/sub&gt;</td>
<td>number of work coil turns</td>
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<tr>
<td>\overline{P}</td>
<td>power density</td>
<td>(W/m&lt;sup&gt;2&lt;/sup&gt;)</td>
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<td>P&lt;sub&gt;1&lt;/sub&gt;, P&lt;sub&gt;2&lt;/sub&gt;</td>
<td>operating points on arc characteristics—Fig. 6</td>
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<td>P&lt;sub&gt;av&lt;/sub&gt;</td>
<td>average power density</td>
<td>(W/m&lt;sup&gt;2&lt;/sup&gt;)</td>
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<td>P&lt;sub&gt;dc&lt;/sub&gt;</td>
<td>d.c. power input</td>
<td>(W)</td>
</tr>
<tr>
<td>P&lt;sub&gt;L&lt;/sub&gt;</td>
<td>power dissipated per metre length of arc column</td>
<td>(W/m)</td>
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<tr>
<td>P&lt;sub&gt;w&lt;/sub&gt;</td>
<td>power input per metre length</td>
<td>(W/m)</td>
</tr>
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<td>P</td>
<td>power input per metre length</td>
<td></td>
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<td>Q, P</td>
<td>dimensionless flux factors—Appendix 1</td>
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<tr>
<td>Q&lt;sub&gt;1&lt;/sub&gt;</td>
<td>heat transfer from conduction zone</td>
<td>(W/m&lt;sup&gt;3&lt;/sup&gt;)</td>
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<tr>
<td>R</td>
<td>electrical resistance</td>
<td>(Ω)</td>
</tr>
<tr>
<td>R&lt;sub&gt;0&lt;/sub&gt;, R&lt;sub&gt;1&lt;/sub&gt;, R&lt;sub&gt;2&lt;/sub&gt;</td>
<td>stabilising resistances in parallel arc system</td>
<td>(Ω)</td>
</tr>
<tr>
<td>R&lt;sub&gt;c&lt;/sub&gt;</td>
<td>reflected work coil resistance</td>
<td>(Ω)</td>
</tr>
<tr>
<td>R&lt;sub&gt;0&lt;/sub&gt;'</td>
<td>total effective work coil resistance</td>
<td>(Ω)</td>
</tr>
<tr>
<td>R&lt;sub&gt;s&lt;/sub&gt;</td>
<td>stabilising resistance</td>
<td>(Ω)</td>
</tr>
<tr>
<td>R&lt;sub&gt;T&lt;/sub&gt;</td>
<td>tank circuit resistance</td>
<td>(Ω)</td>
</tr>
<tr>
<td>R&lt;sub&gt;w&lt;/sub&gt;</td>
<td>reflected work coil resistance</td>
<td>(Ω)</td>
</tr>
<tr>
<td>R&lt;sub&gt;w&lt;/sub&gt;'</td>
<td>reflected load resistance corrected for end effects</td>
<td>(Ω)</td>
</tr>
<tr>
<td>R&lt;sub&gt;x&lt;/sub&gt;</td>
<td>effective resistance of discharge load for one turn work coil</td>
<td>(Ω)</td>
</tr>
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<td>S</td>
<td>heat conduction potential—equation (2.8)</td>
<td>(W/m)</td>
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(\infty)
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<thead>
<tr>
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<th>Description</th>
<th>Unit</th>
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<td>$S_0$</td>
<td>heat conduction potential on axis</td>
<td>(W/m)</td>
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<td>$S_1$</td>
<td>constant coefficient - equation 2.10</td>
<td></td>
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<tr>
<td>$T$</td>
<td>temperature</td>
<td>(K)</td>
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<tr>
<td>$T_0$</td>
<td>temperature on axis</td>
<td>(K)</td>
</tr>
<tr>
<td>$U$</td>
<td>velocity</td>
<td>(m/s)</td>
</tr>
<tr>
<td>$V$</td>
<td>voltage</td>
<td>(V)</td>
</tr>
<tr>
<td>$V_i$</td>
<td>voltage across parallel arc system</td>
<td>(V)</td>
</tr>
<tr>
<td>$W(T)$</td>
<td>radiation source strength</td>
<td>(W/m³)</td>
</tr>
<tr>
<td>$X_1$</td>
<td>see equation A.20</td>
<td></td>
</tr>
<tr>
<td>$X_e$</td>
<td>end effect reactance</td>
<td>(Ω)</td>
</tr>
<tr>
<td>$X_g$</td>
<td>reactance due to air gap flux</td>
<td>(Ω)</td>
</tr>
<tr>
<td>$X_0$</td>
<td>total work coil reactance</td>
<td>(Ω)</td>
</tr>
<tr>
<td>$X_w$</td>
<td>reactance due to flux through work piece</td>
<td>(Ω)</td>
</tr>
<tr>
<td>$Z_c$</td>
<td>work coil impedance</td>
<td>(Ω)</td>
</tr>
<tr>
<td>$Z_G$</td>
<td>oscillator output impedance</td>
<td>(Ω)</td>
</tr>
<tr>
<td>$Z_T$</td>
<td>tank circuit impedance</td>
<td>(Ω)</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>thermal diffusivity</td>
<td>(m²/s)</td>
</tr>
<tr>
<td>$\delta$</td>
<td>skin depth - equation 2.2±</td>
<td>(m)</td>
</tr>
<tr>
<td>$\delta_c$</td>
<td>skin depth in copper</td>
<td>(m)</td>
</tr>
<tr>
<td>$\eta$</td>
<td>efficiency</td>
<td></td>
</tr>
<tr>
<td>$\eta_1$</td>
<td>efficiency of high voltage transformer and rectifier of high frequency generator</td>
<td></td>
</tr>
<tr>
<td>$\eta_2$</td>
<td>efficiency of power conversion from d.c. to a.c. in valve</td>
<td></td>
</tr>
<tr>
<td>$\eta_3$</td>
<td>efficiency of power transfer between valve and tank circuit</td>
<td>(xxi)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
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</tr>
<tr>
<td>( h_{t4} )</td>
<td>efficiency of power transfer from tank circuit to load</td>
<td></td>
</tr>
<tr>
<td>( \lambda_i )</td>
<td>wavelength of radiation - table 2.2</td>
<td>(m)</td>
</tr>
<tr>
<td>( \mu )</td>
<td>relative permeability</td>
<td></td>
</tr>
<tr>
<td>( \mu_0 )</td>
<td>permeability of free space ((4\pi \cdot 10^{-7}))</td>
<td>(H/m)</td>
</tr>
<tr>
<td>( \nu )</td>
<td>frequency of radiation</td>
<td>(Hz)</td>
</tr>
<tr>
<td>( \rho )</td>
<td>density ((\text{kg/m}^3))</td>
<td></td>
</tr>
<tr>
<td>( \sigma )</td>
<td>electrical conductivity</td>
<td>(S/m)</td>
</tr>
<tr>
<td>( \sigma_r )</td>
<td>electrical conductivity at radial distance (r)</td>
<td>(S/m)</td>
</tr>
<tr>
<td>( \gamma )</td>
<td>decay time of plasma</td>
<td>(s)</td>
</tr>
<tr>
<td>( \phi_c )</td>
<td>magnetic flux in copper</td>
<td>(Wb)</td>
</tr>
<tr>
<td>( \phi_g )</td>
<td>magnetic flux in air gap</td>
<td>(Wb)</td>
</tr>
<tr>
<td>( \phi_T )</td>
<td>total magnetic flux</td>
<td>(Wb)</td>
</tr>
<tr>
<td>( \phi_w )</td>
<td>magnetic flux in work piece</td>
<td>(Wb)</td>
</tr>
<tr>
<td>( \omega )</td>
<td>angular frequency</td>
<td>(rad/s)</td>
</tr>
<tr>
<td>( \Lambda )</td>
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<td>constant coefficient - equation 2.10</td>
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CHAPTER 1

Introduction

An introduction to the investigations described in the following chapters and a brief summary of the reasons for the instigation of this work are given.
1. Introduction

Plasma processes may be used in chemical and metallurgical synthesis where either the high temperatures associated with plasmas in thermal equilibrium i.e. ions, electrons and neutral gas atoms having equal temperatures, or where the high electron energies of non equilibrium plasmas are required. The various processes that are possible have been extensively reviewed (Reed 1967, Hamblyn 1977) * but only a few of these processes have been developed to the stage of industrial significance. Non thermal plasma processes tend to suffer from disadvantages limiting the ability to scale up the process to throughputs adequate for industrial applications. Plasmas in thermal equilibrium normally have large temperature variations in the reaction zone reducing the product yields obtainable.

The utilisation of a process which relies entirely on electrical energy, with its relatively low efficiency of conversion from the base fuel, may seem uneconomic. However this must be set against the possible savings of using new production routes which may offer reduced total energy costs, a reduction in overall capital cost, and reduced internal wastage. Added to which the increase in awareness of the eventual exhaustion of alternative energy supplies, has led to a work situation in which the tendency is to increase the use of electricity in industrial processes.

* References are keyed to the alphabetical list on page 298.
Production of high temperature plasmas for chemical and metallurgical synthesis has centred around d.c. and mains frequency a.c. discharges or high frequency induction coupled discharges. The basic construction of an induction coupled discharge is shown in Fig. 1.1.**

In an induction coupled discharge energy is transferred to a stream of pre-ionised gas by an oscillating magnetic field produced by a coil surrounding the discharge region. The magnetic field produces eddy currents within the ionised gas and as the eddy currents meet resistance to their flow energy is transferred to the discharge by Joule heating. The majority of induction coupled discharges used to date have had operating frequencies above one megahertz. In order to generate these frequencies, the a.c. line power must be stepped up in voltage, rectified, and fed into a valve oscillator. A block diagram of a typical valve oscillator power supply is shown in Fig. 1.2. Each section requires expensive equipment and involves losses, the total efficiency of conversion of a.c. input power to r.f. power in the discharge being typically less than 50%. If the operating frequency could be reduced below 10 kHz i.e. within the range of static inverter systems or motor generator sets the capital expenditure required would be substantially reduced and power supply efficiencies of greater than 90% would be available. A comparison of the capital cost of various high frequency power sources is shown in Fig. 1.3. Any attempt, therefore, to create a high temperature plasma using an induction coupled discharge would be more commercially viable if the operating frequency could be reduced below 10 kHz.

** Figures are referred to by the chapter number followed by the order in which they appear in the chapter.
The radial temperature in an induction coupled discharge has a minimum temperature on the axis (Johnston 1968) increasing towards the outer zone of the plasma region, Fig. 1.4a. This non-uniformity of temperature distribution increases as the operating frequency decreases and would be pronounced for operating
Fig. 1.2 Induction torch power supply.
Fig. 1.3 Approximate capital costs of basic induction heating systems (less coils, handling equipment et c.) (Simpson 1979)

frequencies below 10 kHz (Vogel et al 1971). The radial temperature distribution (King 1957) in the positive column of an arc discharge between two electrodes has a maximum along the central axis of the arc, Fig. 1.4b. Consideration of these two temperature
Fig. 1.4 Variation of radial temperature distribution in
a) An induction coupled discharge
b) A d.c. arc.

distributions gave rise to the concept that a combination of a d.c. and a low frequency induction coupled discharge would provide a large volume of high temperature plasma suitable for chemical and metallurgical synthesis.

The overall structure of the thesis is shown in Fig. 1.5. Two
Chapter

1 INTRODUCTION

2 REVIEW OF ARC PROCESSES

3 REVIEW OF METHODS OF PRODUCING THERMAL PLASMAS FOR CHEMICAL AND METALLURGICAL SYNTHESIS

4 PRELIMINARY INVESTIGATIONS AND ANALYSIS

5 MULTIPLE ARC SYSTEMS

6 COUPLING OF R.F. ENERGY INTO MULTIPLE ARC DISCHARGES

7 HIGH FREQUENCY AND D.C. COUPLED DISCHARGE

8 CONCLUSIONS AND RECOMMENDATIONS

Fig. 1.5 Structure of Thesis
review sections are presented in this thesis. The first in Chapter 2 deals with the discharge theory relevant to the production of a large volume of ionised gas. Chapter 3 reviews the methods of producing thermal plasmas including arc heater design and the applications up to the most recently available information.

Chapter 4 describes the preliminary investigations into the factors influencing the coupling of d.c. and high frequency discharges. An analysis of the efficiency of coupling between d.c. arcs and an r.f. power source was developed and the difficulty in initiating coupling when using an operating frequency of 450 kHz was explained. Methods of increasing the efficiency of coupling were assessed and the areas in which more fundamental research was required were established. High frequency discharges with axial electric field and current flow were also investigated experimentally and their suitability for use as a means of producing a large volume of plasma with or without the addition of a d.c. arc was assessed.
CHAPTER 2

Review of Discharge Processes

Discharge characteristics and phenomena likely to be encountered in the production of large volume electric discharges are discussed.
2. Review of Discharge Processes

Several reviews of discharge processes have been written (Papoular 1965, Nasser 1971, Meek et al 1978), extending over a wide range of conditions. This chapter deals with only such phenomena that are likely to be encountered in the production of large volumes of ionised gas suitable for use in industry for chemical synthesis or metallurgical reduction processes. A background of information is provided from which the behaviour of the ionised gas under a variety of complex conditions can be considered.

2.1. Electrical Properties of the Gaseous State

The characteristics of a discharge that results on the electrical breakdown of a gap between two electrodes depends on the gas pressure, the gap length and shape, the nature of the applied voltage and the constants of the external circuit.

If the current in an electrical discharge in a low pressure gas is slowly increased, by reducing a series resistance, the visual characteristics of the discharge formed will vary as will the current density and the voltage across the discharge, Fig. 2.1.

The first part of the characteristic, extending to about $10^{-5}$ A, is known as the Townsend discharge. On increasing the current to about $10^{-4}$ A a glow discharge is formed which is characterised by a voltage that is nearly independent of the discharge current and by the appearance of several diffuse luminous zones.
Increasing the discharge current into the region of 1A, the discharge will suddenly change to an arc which is characterised by the following:

(a) the current density is very high; it may reach several hundreds of \( \text{A mm}^{-2} \) on the electrodes and up to \( 1 \text{A mm}^{-2} \) in the column of the discharge.

(b) the cathode fall potential, of the order of 10V is very much smaller than in a glow discharge which is typically 300V.

(c) the presence of large temperature gradients and high electric field strengths especially near the electrode regions.
2.1.1. Ionisation

A necessary condition for the existence of an electric discharge is the partial ionisation of the gas mixture in the discharge column. The energy for ionisation may be given to an atom by an electron impact, the impact of a positive ion, or the absorption of a quantum of radiant energy or the gas may become so hot as to ionise the atoms thermally. These processes may occur either singly or in combination within the discharge.

2.1.1.1. Thermal Ionisation

Thermal ionisation occurs when a mass of gas is heated sufficiently for the random thermal velocities of the particles to cause ionisation. The degree of ionisation depends on the pressure, the temperature and the ionisation potential of the gas or vapour. The ionisation potential is the work done in removing an electron from an atom or molecule, and is measured in electron volts; more than one electron may be removed per particle in highly ionised plasmas.

The detailed collision processes that cause thermal ionisation vary according to the gas temperature (Engel 1965). At the lower temperatures, where the degree of ionisation is small, photons and molecules impacting with molecules or atoms are responsible for the largest proportion of the ionising collisions but at higher temperatures electron collisions are the dominant ionising process. For these, the energy of the particles has been obtained thermally and not because of any high electric field accelerating the particles.
Fig. 2.2 Degree of ionisation as a function of temperature for a range of ionisation potentials at atmospheric pressure.

The proportion of particles in a gas that are thermally ionised was first derived by Saha (1920) and Fig. 2.2 shows the curves developed of the degree of ionisation as a function of temperature at atmospheric pressure. The assumptions made in deriving these curves limit their use and care must be taken in their application. The gas is assumed to be homogenous, whereas arcs may often burn in mixtures of gases and vapour where ionisation potentials may vary considerably. The presence of constricting walls, turbulence and other factors may also interfere with the ideal thermal equilibrium assumed throughout the gas.
At the high temperatures associated with atmospheric pressure arc columns a considerable fraction of the molecules of the gas may be dissociated. Table 2.1. gives the values of the molecular dissociation potentials of a number of gases and Fig. 2.3. shows the degree of dissociation of various gases against temperature. The degree of dissociation should be calculated when using the Saha equation because the ionisation potential of the products of dissociation must be used.

2.1.1.2. Ionisation by Electron Collision

When a single electron, accelerated by the high electric gradients within a discharge, is in collision with a neutral gas molecule ionisation will take place if the energy of the electron exceeds the ionisation energy of the molecule and, in general, a positive ion and two slow electrons result. The probability of ionisation by this process is zero when the impacting electron has an energy less than the ionisation potential of the molecule. The probability increases with electron energy up to a maximum, occurring with most gases at an electron energy of approximately 100 eV, and decreasing slowly as the energy of the impacting electron is further increased (Rapp et al 1965, Meek et al 1978). The number of ionising collisions per second is directly proportional to the concentration of free electrons, i.e., the rate of ionisation is directly proportional to the discharge current.
Table 2.1 Molecular dissociation potentials (Smythe 1931)

<table>
<thead>
<tr>
<th>Gas</th>
<th>Dissociation Products</th>
<th>Dissociation Potential (V)</th>
</tr>
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<tbody>
<tr>
<td>H₂</td>
<td>H + H</td>
<td>4.4</td>
</tr>
<tr>
<td>N₂</td>
<td>N + N</td>
<td>9.1</td>
</tr>
<tr>
<td>O₂</td>
<td>O + O</td>
<td>5.1</td>
</tr>
<tr>
<td>CO</td>
<td>C + O</td>
<td>10.0</td>
</tr>
<tr>
<td>NO</td>
<td>N + O</td>
<td>6.1</td>
</tr>
<tr>
<td>CO₂</td>
<td>CO + O</td>
<td>5.5</td>
</tr>
<tr>
<td>NO₂</td>
<td>NO + O</td>
<td>15.5</td>
</tr>
<tr>
<td>N₂O</td>
<td>N + O₂</td>
<td>18.4</td>
</tr>
<tr>
<td>H₂O</td>
<td>OH + H</td>
<td>4.4</td>
</tr>
<tr>
<td>C₂N₂</td>
<td>2C + 2N</td>
<td>18.4</td>
</tr>
<tr>
<td>CN</td>
<td>C + N</td>
<td>8.1</td>
</tr>
</tbody>
</table>

Fig 2.3 Degree of dissociation as a function of temperature
2.1.1.3. Ion-Atom Collision Ionisation

If the interaction between an ion and an atom takes place slowly the collision is said to be elastic and no energy interchange occurs. If however, the collision is very rapid there will be insufficient time for internal adjustment of the system to take place and an inelastic collision occurs, resulting in radiation or ionisation.

The probability of this process taking place is small and investigations (Sutton et al 1930) have indicated that positive ion energies greater than 300 eV were necessary for ionisation. Energies of this order are unlikely to occur in discharges at atmospheric pressures and such an ionisation process would consequently be of little significance.

2.1.1.4. Ionisation by Radiation

Since radiation is a form of energy, a photon may excite or ionise an atom. For ionisation, the energy of the photon, defined as the product of Planck's constant $h$ and the frequency of radiation $\nu$, must be greater than the ionisation energy of the atom which is commonly written as the product of the electronic charge and the ionisation potential $V_i$. 
Table 2.2 gives the ionisation potentials $V_i$ and corresponding wavelength of radiation $\lambda_i$, for various gases, alkali and metal vapours.

The probability of a photon ionising an atom or molecule is a maximum when the energy of the photon is approximately equal to the ionisation energy of the atom or molecule. Photo-ionisation can occur in steps, although the probability of this process is small; it becomes important only in regions of high photon density because of the relatively short time the atom will remain in an excited state. Photons of very large energy, i.e., X-rays, eject electrons from the inner shells of atoms and these electrons often produce far more
ionisation than the original photons. In general the amount of photoionisation in gas discharges is very much less than that of ionisation by electron collision.

2.1.1.5. Cumulative Ionisation

The impingement of a photon, electron or positive ion of energy below the ionisation potential of a gas may excite an atom, and then this excited atom may in turn be ionised by interaction with another low energy electron, photon or positive ion. This is known as cumulative ionisation.

An atom excited to a metastable state is more susceptible to cumulative ionisation because of its longer lifetime. An excited atom can return from a normal excitation level to the ground state typically within $10^{-8}$ s. An atom in a metastable state requires the impact of a third body to return it to the ground state and this gives rise to the long life-times of certain metastable states, between $10^{-3}$ s and $10^{-1}$ s.

The presence of metastable atoms can have a considerable effect on the electrical conductivity of a gas, when it contains atoms of a different element with an ionisation potential less than the potential corresponding to the metastable level of the gas atoms. In a collision between these two particles the potential energy transferred from the metastable atom is now great enough to produce ionisation of the other particle. Since the ionisation potential of the common molecular gases such as oxygen, nitrogen and hydrogen is about 15 eV, then collisions of the second kind can be very important in
monatomic gases such as argon because slight traces of impurity can lead to increased ionisation. This process is known as the Penning effect (Penning 1931).

As the excited metastable atom reverts to its ground state the energy released usually takes the form of radiation. Because of the relatively longer life times of the metastable states, emission of radiation from a discharge will continue after electrical conduction has ceased and may lead to errors in the interpretation of certain high speed photographic plasma diagnostic techniques (Harry et al. 1968).

2.1.2. Deionisation

If all sources of ionisation are removed from an ionised gas, it rapidly assumes a neutral state due to a variety of processes the most important of which are:

(a) Recombination on solid surfaces
(b) Negative ion - positive ion recombination
(c) Electron - positive ion recombination

When a concentration gradient of ions exists there will be a flow of ions from the regions of high concentration to regions of lower concentration. In a low pressure discharge the ions and electrons diffuse to the surrounding walls under the influence of concentration gradients and there recombination takes place to form neutral atoms. When there are equal positive and negative ion concentrations, the existence of electrostatic forces tend to equalise the diffusion velocities producing what is known as ambipolar diffusion. This
form of deionisation is dominant in the positive column of a glow discharge.

In an arc discharge the mean free path of the ions is less than $10^{-7}$ m and the probability of any ion encountering a solid surface is very small so that volume recombination processes dominate. Negative ion-positive ion recombination has a higher probability than electron-positive ion recombination because the particles are moving more slowly at any given temperature and thus remain adjacent for a longer time. However noble gases do not form negative ions by attachment of electrons and at the high temperature usually associated with arc discharges the probability of negative ion formation is so low that electron-positive ion recombination becomes the most important recombination process.

2.1.3. Transportation Phenomena

The conduction of an electric current through a gaseous medium involves the transportation of charged particles across the inter-electrode region at a drift speed much less than their individual random velocities. The magnitude of the average drift velocity for a unit electrical field strength is the mobility of the particle. Many different values can be found in the literature for the mobilities of ions and electrons since the mobility depends on the species of ion in a gas and, for electrons, on the nature of the gas. At atmospheric pressure ion mobilities are in the range $10^{-4}$ m s$^{-1}$ V$^{-1}$ to $10^{-3}$ m s$^{-1}$ V$^{-1}$ and electron mobilities between $10^{-3}$ m s$^{-1}$ V$^{-1}$ to $1$ m s$^{-1}$ V$^{-1}$. 
The current density within a discharge column is proportional to the number of charges crossing a plane perpendicular to the axis of the column per second. In an arc column where the voltage gradient is small and therefore the positive and negative ion densities are equal, the relative mobilities of the electrons and positive ions will indicate the order of magnitude contribution to the discharge current. Since the mobilities of ions are typically one-thousandth of the electron mobilities the ion current is only about 0.1% of the total current and can often be neglected. Therefore if the mobility of the electrons is known and the ionisation density found from the Saha equation (chapter 2.1.1.1.) the electrical conductivity of the discharge as a function of temperature can be calculated.

Fig. 2.4 The effect of temperature on the electrical conductivity of argon, nitrogen and hydrogen (Emmons 1967, Yos 1967)

Fig. 2.4 shows the electrical conductivity as a function of temperature for argon, nitrogen and hydrogen (Emmons, 1967, Yos 1967).
2.2 Glow and Arc Discharges

The production of a large volume electric discharge for use in chemical and metallurgical processes is usually associated with the high temperature properties of the arc discharge or with the high energy levels of a low pressure glow discharge.

The characteristics of any discharge are greatly influenced by the processes occurring at the electrodes but the positive column of a discharge is of paramount importance when the production of a large volume discharge is to be considered.

2.2.1. Electrode Processes

Within the positive column of a discharge the number of ions and electrons is approximately equal and so the current is due mainly to the electrons because of their greater mobility (chapter 2.1.3.). Near the electrodes this state of quasi-neutrality no longer holds and either electrons or ions predominate leading to the formation by space charge effects, of the anode and cathode fall regions. The processes encountered at each electrode are largely dependent on the requirements of these zones.

2.2.1.1. The Cathode

A characteristic of a glow discharge is its large cathode fall potential being typically 300V. The magnitude of the cathode fall depends mainly on the gas and the cathode material; Table 2.3., and varies little with the pressure, the distance between the electrodes or the discharge current.
Table 2.3 Glow discharge cathode fall potentials (Engel et al 1934, Thomson et al 1933)

<table>
<thead>
<tr>
<th>Electrode Material</th>
<th>Working Gas</th>
<th>Al</th>
<th>A</th>
<th>H₂</th>
<th>Na</th>
<th>O₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>Air</td>
<td>229</td>
<td>100</td>
<td>170</td>
<td>180</td>
<td>311</td>
</tr>
<tr>
<td></td>
<td>A</td>
<td>280</td>
<td>130</td>
<td>216</td>
<td>233</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>H₂</td>
<td>370</td>
<td>130</td>
<td>214</td>
<td>208</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Na</td>
<td>269</td>
<td>165</td>
<td>250</td>
<td>215</td>
<td>290</td>
</tr>
<tr>
<td></td>
<td>O₂</td>
<td>277</td>
<td>131</td>
<td>276</td>
<td>216</td>
<td>364</td>
</tr>
<tr>
<td>Zn</td>
<td>Air</td>
<td>277</td>
<td>119</td>
<td>184</td>
<td>216</td>
<td>354</td>
</tr>
</tbody>
</table>

The cathode current density of a glow discharge is proportional to the square of the gas pressure being between 1 A mm⁻² and 10 A mm⁻² in air at atmospheric pressure but remains constant at any given pressure as long as any part of the cathode remains uncovered by the discharge. Once the cathode is completely covered, a further increase in current causes the current density to increase, until an arc is formed.
The cathode fall potential of an arc discharge is much smaller than that in the glow discharge, typically 10 V, Table 2.4, and the mechanism of electron emission from the cathode surface depends greatly on the electrode material. If the melting point of the electrode material is high enough, a sufficiently high temperature may be attained to supply the majority of the electrons by thermionic emission. Alternatively if the cathode is made of a low boiling point metal (a cold cathode), then the cathode behaviour of such arcs is characterised by extremely high cathode current densities, greater than $10^8$ Amm$^{-2}$ (Reece 1963), by irregular movement of the cathode spot over the cathode surface, and often by the existence of several cathode spots. The majority of electrons in this case are supplied by field emission processes (Kesaev 1964, 1968).

Table 2.4 Arc cathode and anode voltage drops (Engel et al 1934)

<table>
<thead>
<tr>
<th>Electrodes</th>
<th>Gas</th>
<th>Current Range (A)</th>
<th>Cathode Voltage (V)</th>
<th>Anode Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>Air</td>
<td>1-20</td>
<td>8-9</td>
<td>2-6</td>
</tr>
<tr>
<td>C</td>
<td>Air</td>
<td>2-20</td>
<td>9-11</td>
<td>11-12</td>
</tr>
<tr>
<td>Fe</td>
<td>Air</td>
<td>10-300</td>
<td>8-12</td>
<td>2-10</td>
</tr>
<tr>
<td>Hg</td>
<td>Vacuum</td>
<td>1-1000</td>
<td>7-10</td>
<td>0-10</td>
</tr>
<tr>
<td>Na</td>
<td>Vacuum</td>
<td>5</td>
<td>4-5</td>
<td>-</td>
</tr>
</tbody>
</table>
2.2.1.2. The Anode

The anode does not emit a significant amount of positive ions except in the Beck arc (Beck 1921, Finkelnburg 1949) and the current at the surface is carried solely by electrons. There will therefore be an excess negative space charge near the anode and an anode fall potential will develop dependent in magnitude on the electrode material and the gas, Table 2.4.

<table>
<thead>
<tr>
<th>Electrode Material</th>
<th>Gas</th>
<th>Current Range (A)</th>
<th>Temperature of cathode (K)</th>
<th>Temperature of anode (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>Air</td>
<td>2-12</td>
<td>3500</td>
<td>4200</td>
</tr>
<tr>
<td>C</td>
<td>N₂</td>
<td>4-10</td>
<td>3500</td>
<td>4000</td>
</tr>
<tr>
<td>Cu</td>
<td>Air, N₂</td>
<td>10-20</td>
<td>2200</td>
<td>2400</td>
</tr>
<tr>
<td>Fe</td>
<td>Air, N₂</td>
<td>4-17</td>
<td>2400</td>
<td>2600</td>
</tr>
<tr>
<td>Ni</td>
<td>Air, N₂</td>
<td>4-20</td>
<td>2370</td>
<td>2450</td>
</tr>
<tr>
<td>W</td>
<td>Air</td>
<td>2</td>
<td>3000</td>
<td>4250</td>
</tr>
<tr>
<td>Al</td>
<td>Air</td>
<td>9</td>
<td>3400</td>
<td>3400</td>
</tr>
<tr>
<td>Mg</td>
<td>Air</td>
<td>&lt;10</td>
<td>3000</td>
<td>3000</td>
</tr>
<tr>
<td>Zn</td>
<td>Air</td>
<td>2</td>
<td>2350</td>
<td>2350</td>
</tr>
</tbody>
</table>

Table 2.5 Typical arc cathode and anode temperatures at atmospheric pressure (Engel et al 1934)
The anode is heated by the impingement on its surface of the electrons accelerated in the electric field of the anode fall region and by heat transfer from the discharge. In general it will attain a high temperature, greater than the cathode, Table 2.5., limited only by the boiling point of the material. Consumable anode arc devices have been applied to chemical and metallurgical synthesis (Wilks et al 1972, Sheer et al 1974) but as the high temperature of the anode is not essential to the operation of the arc, it may be water cooled to reduce the electrode erosion or decrease the contamination of the discharge.

In the energy balance at the anode, the energy gained is given by the sum of the kinetic and potential energy of the electrons hitting the anode and the excitation, chemical reaction, and thermal energy of the gas atoms. The losses are due to evaporation of the anode material, radiation, and conduction from the anode spot into the electrode. It is these mechanisms which determine the area of the anode spot and hence the anode current and power densities.

2.2.1.3. The Glow to Arc Transition

The factors controlling the transition from a glow to an arc discharge are primarily those concerned with processes occurring at the cathode. The transition is one from the high cathode fall, low cathode current density of the glow, to the low cathode fall, high cathode current density mechanism of the arc.

In a low current glow discharge the cathode current density at any particular pressure is essentially constant and any increase in discharge current causes an increase in the surface area of the cathode covered by the discharge. When the whole of the surface-
area of the cathode is covered any increase in discharge current necessitates an increase in the cathode current density and the discharge moves into the abnormal glow discharge regime (Wehrli 1928, Engel et al 1931). To increase the cathode current density a larger cathode emission is necessary and the potential gradient in the vicinity of the cathode is increased. The energy given to the positive ions is thus increased which leads to an increase in the temperature of the cathode as the ions release their energy on impact with the cathode surface. Refactory cathodes such as carbon and tungsten can reach temperatures high enough for thermionic emission from the cathode surface to become significant. The increased current produced by thermionic emission increases the number of positive ions impinging on the cathode surface, which in turn increases the heating of the cathode. This runaway effect leads to the formation of an arc discharge. The factors controlling the current at which the transition occurs when using refractory cathodes are thus mainly those affecting the heat transfer at the cathode surface i.e. the gas, the pressure, the electrode size and the electrode material.

When the cathode material is a non-refractory metal the transition is discontinuous and a thermionic cathode mechanism is unlikely. The current at which the glow to arc transition occurs is directly related to the energy required for sublimation of the cathode material (Plesse 1935), and inversely related to the purity of the cathode material (Fan 1939).

Localised increases in vapour density have been suggested as a mechanism causing the transition (Engel et al 1931). The increase in localised vapour density must be accompanied by an increase in current density and localised heating, thereby further increasing the vapour pressure and hence current density which eventually would result in the formation of an arc. More recently Lutz (1974)
suggested that breakdown within insulating inclusions embedded in the electrodes surface could produce a burst of vapour thereby aiding the formation of an arc. This can only happen for a range of particle sizes and this range in turn is dependent on the current density and voltage of the glow discharge.

2.2.2. Discharge Column Process

The discharge 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.

2.2.2.1. The Positive Column of the Glow Discharge

The positive column fills the whole of the part of the discharge tube from the Faraday dark space to the anode and has equal concentrations of positive ions and electrons, each with its own Maxwellian velocity distribution and characteristic temperature. The temperature of the positive ions is usually slightly higher than the gas temperature whilst the electron temperature can be many times greater. At a pressure of $10^2$ Pa the charge density is of the order of $10^7$ mm$^{-3}$ giving a degree of ionisation of approximately $10^{-6}$.

In any limited tube geometry there is a relationship between the tube radius and the electron mean free path within the gas. For tubes of about 10mm radius at pressures less than 0.1 Pa, space charge and diffusion effects are small while at high pressures, approximately $7.10^4$ Pa, the current density can be high enough to introduce ionisation processes, such as cumulative and thermal ionisation and
the column can take the form of a very narrow filament. The most common glow discharge devices, such as fluorescent discharge tubes for example, have gas pressures between $10^2$ Pa and $10^4$ Pa with a tube radii of 10 mm to 50 mm. Increasing the pressure within this range compresses the negative zones of the discharge towards the cathode, while the positive column expands longitudinally. Beyond pressures of approximately $10^4$ Pa the positive column begins to contract radially, the cathode rises in temperature, and the probability of a glow to arc transition is increased.

2.2.2.2. The Column of an Arc Discharge

The characteristics of the arc column depend on the transport properties of the gas used. The gases principally considered are argon, nitrogen, air and hydrogen which are most frequently used in plasma processes.

An essential difference exists in the behaviour of arcs in monatomic and polyatomic gases. A monatomic gas such as argon ionises to give:

$$\text{Ar} \rightarrow \text{Ar}^+ + e \quad (2.1)$$

A polyatomic gas such as nitrogen requires dissociation of the gas molecule before ionisation can occur and consequently a higher enthalpy level is required for nitrogen:

$$\text{N}_2 \rightarrow 2\text{N} \quad \text{at dissociation} \quad (2.2)$$

$$2\text{N} \rightarrow 2\text{N}^+ + 2e \quad \text{at ionisation} \quad (2.3)$$

The variation of the total enthalpy for several gases with temperatures is shown in Fig. 2.5.
Fig. 2.5 The variation of the total enthalpy for several gases as a function of temperature
The electric field in an arc column as a function of the current in various gases has been measured over pressures from $10^5 \text{ Pa}$ to $5 \cdot 10^6 \text{ Pa}$ and at arc currents of 1 A to 10 A (Suits 1939a). The relationships between the voltage gradient $E(\text{V/m})$ and the arc current $i$ (A) and pressure $p$ (Pa) are

$$E \propto i^{-n}$$

$$E \propto p^m$$

The experimental values of the exponents $n$ and $m$ for nitrogen were 0.6 and 0.32 respectively, while the theoretical values were 0.74 and 0.031 (Champion 1953).

![Figure 2.6: Arc column voltage gradient as a function of current (King 1964)](image-url)
The results at atmospheric pressure for the variation of the voltage gradient with arc current (Strom 1946, King 1961), have been used to extend to 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 2.6. The axial pressure gradient along the arc column is highest at the cathode where the constriction is greatest. The flow of charged particles from the cathode into the arc column also entrain cold surrounding gas which will cause an increase in the voltage gradient of the arc column and may even cause the gradient of the arc voltage - current characteristic to become positive (Maecker 1955).

<table>
<thead>
<tr>
<th>Gas</th>
<th>Pressure (atm)</th>
<th>Current Density (A/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na</td>
<td>10</td>
<td>0.06</td>
</tr>
<tr>
<td></td>
<td>50</td>
<td>0.117</td>
</tr>
<tr>
<td></td>
<td>10.0</td>
<td>0.201</td>
</tr>
<tr>
<td></td>
<td>30.0</td>
<td>0.625</td>
</tr>
<tr>
<td>H₂</td>
<td>1</td>
<td>5.63</td>
</tr>
<tr>
<td>He</td>
<td>1</td>
<td>0.447</td>
</tr>
<tr>
<td>A</td>
<td>1</td>
<td>0.323</td>
</tr>
</tbody>
</table>

Table 2.6 Current density in an arc column (Suits 1939b)
Fig 2.7 Variation of thermal conductivity of air with temperature and pressure (Yos 1963)

The current density in the arc column at medium currents is not accurately known due to the difficulty in defining the arc boundary. The results of Suits (1939b) are shown in Table 2.6 and indicate a mean current density of about 0.1A/mm$^2$ over a range of 1A to 10A in nitrogen at atmospheric pressure.

King (1954) calculated the current densities for medium current arcs using a model based on the energy balance of a static arc column at atmospheric pressure in air. The results implied that the arc had
a constant radius from 20 A to 200 A and a mean current density at 200 A of about 2 A mm$^{-2}$. At currents above 200 A the diameter of the arc column increased with the arc current. Nicolai (1970), using photographic measurements to obtain the arc dimensions, found that for arc currents between 190 A and 400 A over a pressure range of $2 \times 10^{3}$ Pa to $10^{5}$ Pa in air, diameter was proportional to the square root of the arc current. Similar results of approximately constant current density have also been reported in very high current free burning arcs up to $3 \times 10^{4}$ A in air, measurements in this case being made by small magnetic probes (Barrault et al 1971). A central core develops within arcs in air or nitrogen in the region of 40 A to 60 A at atmospheric pressure and at lower currents when the arc is subjected to a forced axial flow of gas. This is attributed to the peak in the thermal conductivity due to the effect of molecular dissociation, which occurs between 6000 K and 7000 K for air at atmospheric pressure (King 1957). The appearance of a second core was predicted at about 15 000 K 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. Fig. 2.7. shows the variation of thermal conductivity of air with temperature and pressure.

2.3. The Properties of a Free Burning Arc

In the following sections the processes involved in an energy balance and the definitions of the effective diameter of a free burning arc have been reviewed leading to the theoretical formulation of an equivalent conductor, representative of the arc column. This equivalent
conductor is subsequently used in the development of an analysis of the coupling of r.f. energy into a free burning arc.

2.3.1. The Energy Balance of a Free Burning Arc

The energy balance equation in a unit volume of a free burning arc can be represented

\[- \nabla \cdot k \nabla T + W(T) + \varrho \rho \ C_p \ U \ \nabla T = \sigma \ E^2 \]  

(2.6)

where

\[k = \text{thermal conductivity (W/m K)}\]
\[T = \text{temperature (K)}\]
\[W(T) = \text{power radiated per unit volume, (W/m}^3)\]
\[\varrho = \text{density (kg m}^{-3})\]
\[\rho = \text{specific heat at constant pressure (J/kg K)}\]
\[U = \text{velocity (m/s)}\]
\[\sigma = \text{electrical conductivity (S/m)}\]
\[E = \text{electric field strength (V/m)}\]

The thermal conductivity plays an important part in almost all the regions of the discharge except in the extreme outer portions of the arc where the temperature is close to the ambient and where convective heat transfer predominates.

Plasma radiation at atmospheric pressure constitutes a small percentage of the energy generated in the arc. Calculations for an arc in nitrogen (Pelzer 1958) indicate that even for currents of the order of several hundred amperes the radiation losses do not exceed 20% of the total discharge power. Experiments utilizing a carbon arc between 1 A and 10 A also point to insignificant radiation losses (Suits 1939b, Holm et al. 1934).
Convective heat transfer is practically non-existent in the central regions of the arc (Suits 1939c). This is because of the low density of gases at high temperatures and because the isothermal surfaces in the central regions of the arc are approximately parallel to the axis of the arc column and the direction of the gas flow, (Maecker 1955).

The distribution of the electrical power density in the arc cross-section is determined by the radial distribution of the electrical conductivity, as the electric field strength within the limits of the conducting column is constant.

The whole region occupied by the column of a free burning arc can therefore be divided into the following three zones:

(i) The conduction zone where the electrical energy is dissipated as heat which in turn is conducted away to the periphery of the arc.

(ii) The neutral zone, in which the concentration of electrons and ions is negligible compared with the conduction zone and hence the electrical conductivity is zero, but the heat transfer mechanism is still that of conduction.

(iii) The convection zone, where the electrical conductivity is again zero but the heat transfer mechanism combines both conduction and convection.

In the derivation of an equivalent conductor model of the arc column the conduction zone is of principal importance as this is the region in which electrical energy is dissipated. The convection zone is also discussed because of its effects on the overall appearance and characteristics of the free burning arc.
2.3.1.1. The Conduction Zone

The energy balance equation in the conduction zone, assuming that the arc is axially symmetrical with the heat transfer predominantly in the radial direction, reduces to

\[
Q_1 = -\frac{1}{r} \frac{d}{dr} \left[r \cdot k \cdot \frac{dT}{dr}\right] = \sigma E^2
\]  

(2.7)

where

- \(Q_1\) = heat transfer from the conduction zone \((W/m^2)\)
- \(r\) = radial distance \((m)\)

The electrical conductivity of both monatomic and polyatomic gases is a continuously increasing function of temperature (chapter 2.1.3.). As the electric field strength is constant across the conducting region of an arc then from equation (2.7) the temperature profile across this region is predominantly dependent on the variation of thermal conductivity of the gas with temperature.

The thermal conductivity of any gas includes the following components:

(i) \(k_c\) - the thermal conductivity due to the motions of atoms and ions.

(ii) \(k_e\) - the thermal conductivity due to the motion of electrons.

(iii) \(k_d\) - the thermal conductivity due to the diffusion of molecules and associated atoms.

(iv) \(k_i^+\) - the thermal conductivity due to the motion of electrons and singly ionised atoms.

(v) \(k_i^{++}\) - the thermal conductivity due to the motion of doubly ionised atoms.
Fig. 2.8 The variation of the components of the thermal conductivity of nitrogen against temperature (King 1957)

Fig. 2.8 shows the variation of the components of the thermal conductivity of nitrogen against temperature.

Monatomic gases such as argon have a continuously increasing value of thermal conductivity with temperature while the thermal conductivity of polyatomic gases show a number of distinct peaks at various temperatures. The peaks are due to the effects of molecular dissociation and diffusion of electrons and singly or multiply ionised atoms (King 1957).

The temperature profile in monatomic gases across the conduction zone is parabolic. Polyatomic gases have a similar radial temperature distribution only at temperatures below the molecular
dissociation temperature. The thermal conductivity curve of nitrogen, Fig 2.8, has a discontinuity at about 7000 K and drops sharply above this temperature. Increasing the temperature at the axis of the arc to 11 000 K requires an increase in the temperature gradient to compensate for the reduction in the thermal conductivity and hence a high temperature core is formed within the arc. The existence of a stable arc with an axial temperature of between 7000 K - 10 000 K in nitrogen is not possible.

The thermal conductivity due to the diffusion of ion pairs causes another negative slope in Fig 2.8 in the temperature region of 14 000 K - 20 000 K. This second negative slope causes another sudden increase in the axial arc temperature and hence a second inner core should theoretically be formed.

The heat conduction potential \( S(W/m) \) was first used in the theory of arcs by Schmitz (1950) and it is convenient to use in the solution of equation (2.7) because the thermal conductivity is such a strong function of temperature. The heat conduction potential \( S(W/m) \) is defined as

\[
S = \int_{\text{const}}^{T} k \, dT
\]

and substituting it into equation 2.7 gives

\[
-\frac{1}{r} \frac{d}{dr} \left\{ r \frac{dS}{dr} \right\} = \sigma E^2
\]

The electrical conductivity \( \sigma \) (S/m) is a function of the heat conduction potential (Emmons 1967) and can be approximated by a linear function (Schmitz 1950):
\[ \sigma(S) = 0 \quad \text{for } S_1 \geq S \]
\[ = \Sigma^2 (S-S_1) \quad \text{for } S \geq S_1 \]  
(2.10)

where \( \Sigma^2 (V^{-2}) \) and \( S_1 (W/m) \) are constant coefficients determined from the transport properties of the gas (Krinberg 1964).

Assuming the arc to be axially symmetric the solution to equation (2.9) becomes

\[ S = S_1 + C_1 J_0 (\Sigma E r) \]  
(2.11)

where

\[ C_1 = \text{constant of integration} \]
\[ J_0 = \text{a Bessel function of the first kind, zero order} \]

A normalised radial distribution of the electrical conductivity within the arc column can then be obtained (Krinberg 1964)

\[ \sigma(r) = \sigma(o) J_0 \left[ 1.521 \frac{r}{r_{0.5}} \right] \]  
(2.12)

where

\[ \sigma(r) = \text{the electrical conductivity at radius } r (S/m) \]
\[ \sigma(o) = \text{the electrical conductivity on axis } (S/m) \]

and \( r_{0.5} \) is the radial distance (m) defined by

\[ \sigma(r_{0.5}) = \frac{1}{2} \sigma(o) \]  
(2.13)

The shape of the radial distribution of electrical conductivity in the column of an arc discharge in a mixture of argon and hydrogen was shown experimentally (Kolensnikov et al 1963) to be independent of current value and hydrogen content. It approximated to the function,
Fig. 2.9 Normalised radial distribution of the electrical conductivity in the column of an arc

\[
\sigma(r) = \sigma(0) \exp \left[ -\left( \frac{r}{r_{0.5}} \right) e^{\log_e 2} \right]
\]  

(2.14)

Fig 2.9 shows the normalised radial distribution of the electrical conductivity in the column of an arc.

Further comparisons have been made between the theory and experimental data in air, nitrogen, oxygen, hydrogen and argon for arc currents of 1A - 300A at atmospheric pressure. A discussion into possible refinements of the theory is also given (Krinberg 1969).
2.3.1.2. The Convection Zone

The interaction of the column of an arc discharge with its surroundings is largely dependent on the heat transfer within the outer or convection zone of the arc. The solution of the energy balance equation within this region requires not only the knowledge of the variation of the thermal conductivity of the gas with temperature, but also the velocity of the gas within this zone.

The theory of thermal similarity has been applied to the arc by comparing the heat losses from a high pressure arc with those from a hot cylindrical object in a flowing gas (Suits et al 1939, Champion 1952). This method was used to obtain the relationships between the electric field strength with arc current and pressure, and between the arc diameter, measured photographically, and the pressure (Suits et al 1939). Certain refinements to this work and further progress with both horizontal and vertical arcs, and the effect of a magnetic field, were carried out by Champion (1952).

2.3.2. The Arc Diameter

The luminosity and electrical conductivity of a gas are functions of temperature and because of the large temperature gradients within the outer regions of the arc, they both decrease rapidly with radial distance from the axis of the arc. The luminous and electrically conducting regions of an arc correspond approximately (Bramhall 1931) and photographic measurements of the arc diameter have been used to correlate theoretical work on the thermal similarity applied to arc columns (Suits et al 1939, Champion 1952). The diameter of low current arcs, up to 10A in nitrogen was found to be
directly proportional to the square root of the arc current and more recently the same relationship was found for high current arcs 190A - 400A in air, the diameter of the arcs again being measured photographically (Nicolai 1970).

The diameter of an arc can be defined by a peripheral temperature but the choice of this temperature is arbitrary dependent on the gas, its pressure and the application (Lord 1973). This leads to differences in the temperature chosen and an inability to correlate the results (Lord et al 1965, Wells 1967).

The most useful definition of an arc diameter is to relate it directly to the distribution of electrical conductivity, and hence the current density and the source of heat generation within the arc.

The radial distribution of the electrical conductivity in the column of an arc discharge is independent of the arc current or gas mixture (Kolesnikov et al 1963) and can be approximated by the function given in equation (2.14), (chapter 2.3.1.1.).

The total arc current $I$ (A) can be expressed as

$$ I = 2\pi E \int_0^\infty r \sigma (r) \, dr $$  \hspace{1cm} (2.15)

Assuming that the radius of the arc is $r_{0.5}$, the radius at which the electrical conductivity has decreased to half the value on the axis, equation (2.15) can be written,

$$ I = 2\pi E r_{0.5}^2 \sigma (0) \int_0^1 \frac{\sigma (r)}{\sigma (0)} \frac{r}{r_{0.5}} \, d\left(\frac{r}{r_{0.5}}\right) $$  \hspace{1cm} (2.16)

Since the shape of all the curves is the same, then the integral has a constant value. This has been estimated as 0.595 (Kolesnikov et al 1963) and equation (2.16) further reduces to
\[ I = \pi (1.1 r_{0.5})^2 \sigma (0) E \]  (2.17)

Thus equations (2.17) leads to the formulation of an equivalent conductor, representative of the arc column, which has a radius equal to 1.1 \( r_{0.5} \) and a constant electrical conductivity equal to that on the axis of the arc.

Using the relationship between the temperature on the axis of a d.c. arc in argon and its current (Krinberg 1964)

\[ T (0) = 3000 + 1800 \log_e I \]  (2.18)

and the variation of the electrical conductivity of argon with temperature (Emmons 1967), an equivalent conductor model can therefore be obtained for any value of arc current. Table 2.7 shows the values of \( T (0), \sigma (0), r_{0.5}, \) the equivalent diameter of free-burning arc, and skin depth \( \delta \) for an operating frequency of 450 kHz for various arc currents.

2.4. The Stability of an Arc

The stability of an arc determines the operating conditions and the interaction of an arc with its supply circuit. The arc normally has a negative dynamic impedance and hence the supply circuit has a large influence on the arc behaviour. Stable operation of an arc is an important consideration for applications including a continuous flow process, for example in the chemical industry. The factors which influence arc stability are considered here.

The criterion for the stability of an electric arc requires the sum of the resistance characteristic of the arc and the gradient of the load line to be positive (Kaufmann, 1900).
Table 2.7. Values of axial temperature, electrical conductivity, radius and effective skin depth $\delta$ at an operating frequency of 450 kHz, for an equivalent conductor model defined in Chapter 2.3.2.

<table>
<thead>
<tr>
<th>Arc current $I$ (A)</th>
<th>Temperature on axis $T(0)$ (K)</th>
<th>Electrical conductivity on axis $\sigma(0)$ (S/m)</th>
<th>$r_{0.5}$ (see equation 2.13) (mm)</th>
<th>Equivalent diameter of single free burning arc $2.2r_{0.5}$ (mm)</th>
<th>Skin depth $\delta$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>9800</td>
<td>2940</td>
<td>1.6</td>
<td>3.5</td>
<td>13.8</td>
</tr>
<tr>
<td>20</td>
<td>10,340</td>
<td>3350</td>
<td>2.1</td>
<td>4.6</td>
<td>13</td>
</tr>
<tr>
<td>40</td>
<td>10,880</td>
<td>3700</td>
<td>2.5</td>
<td>5.5</td>
<td>12.25</td>
</tr>
<tr>
<td>60</td>
<td>11,200</td>
<td>4100</td>
<td>2.9</td>
<td>6.4</td>
<td>11.8</td>
</tr>
<tr>
<td>80</td>
<td>11,430</td>
<td>4370</td>
<td>3.3</td>
<td>7.2</td>
<td>11.4</td>
</tr>
<tr>
<td>100</td>
<td>11,600</td>
<td>4500</td>
<td>3.6</td>
<td>8.0</td>
<td>11.1</td>
</tr>
</tbody>
</table>

\[ \frac{dv}{di} + R_S > 0 \]  

(2.19)

where \( \frac{dv}{di} \) = dynamic resistance of an arc (\( \Omega \))

\( R_S \) = stabilising resistance (\( \Omega \))

The load line and arc characteristic is illustrated in Fig. 2.10. 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.
Even though the Kaufmann criterion may be satisfied the life-time of an arc is not certain and the concept of an average arc life-time is often useful (Attia 1973). The average arc life-time increases with arc current and gas pressure and varies with the electrode material and the value of the external circuit constants (Farrall et al 1965, Klapas et al 1976).

Methods of improving the stability of high current electric arcs include the introduction of compounds of low ionisation potential into the arc stream with cored, coated or impregnated electrodes (Cobine et al 1951). Hollow electrodes through which a gas of ionisation potential lower than air has been passed have also been used (Charles et al 1960, Dunski et al 1968).

The overall effect of these methods is to lower the arc impedance, decreasing the arc voltage, the voltage gradient, and the temperature in the arc column. The reduction in the arc impedance increases the
ratio of the series impedance to arc impedance which tends to improve stability following Kaufmann's reasoning. A similar effect might be obtained by using a higher voltage supply and an increased stabilising impedance without decreasing the arc power.

There is no quantitative data available on the optimum values of stabilising impedance required for a given application. D.C. welding arcs are normally operated with a ratio of open circuit voltage to arc voltage of up to 4 : 1 and large arc furnaces operate at a power factor, before correction, of about 0.7 indicating a ratio of open circuit voltage to arc voltage of 2 : 1.

Theoretical attempts have been made to derive quantitative criteria relating to arc stability. A criterion based on the integrated deviation of the arc voltage waveform from some defined optimum waveform was proposed by Harry (1966). An analytical technique for the selection of the relevant parameters of an arc circuit using basically the same criterion has also been devised (Luxat et al 1970).

There are no details within the literature of any experimental or theoretical investigation into the stability of two or more arcs supplied from the same power source. Two separate arcs connected from the same power source cannot normally exist without individual stabilising impedances because of the negative dynamic impedance of each of the arcs. The stability is further complicated by the interaction between the individual arcs through any common impedance, especially when the ratio of common impedance to individual stabilising impedance is large and the arc current small. Very high current arcs, however, can be operated in parallel, if each is connected to its own stabilising impedance even though the common impedance may be much larger.
This occurs especially in arcs with rising voltage-current characteristics for example in parallel connected mercury arc rectifiers which have been used for rectification on railway networks.

2.4.1. Dynamic Stability

The static arc characteristics, Fig 2.10, only apply when the changes of arc current occur slowly because of the stored energy within the arc. If the current changes suddenly in a step function form the arc acts as a linear resistor, the voltage change being proportional to the change in current. If the current remains constant at its new value the voltage exponentially approaches the level predicted by the static characteristic of Fig 2.10.

The dynamic behaviour of an electric arc 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. Theoretical analysis of the dynamic behaviour has been carried out (Bowmans et al 1969, Fang et al 1973) for wall stabilised arcs. The equilibrium times may be taken as not more than $10^{-3}$ s in the arc column (Witte, 1934), $50.10^{-6}$ s to establish the cathode fall (Froome, 1948) and $10^{-9}$ s to disrupt the cathode fall (Mierdel, 1936).

Low frequency fluctuations of the order of a few Hz within a d.c. arc enable the arc to closely follow the static characteristic, shown in Fig 2.10. As the frequency increases the arc current tends to lag the arc voltage defined by the static characteristic. This is due to the finite time required for thermal equilibrium to be established.
at the new value of arc voltage. As result the dynamic characteristic lies above the curve when the current is increasing and below the curve when it decreases.

The behaviour of an a.c. arc can be considered as a special case of the dynamic behaviour.

2.5. Alternating Current Arcs

The characteristics of an a.c. arc are affected by the nature of the electrodes, the surrounding environment, the length of the arc and by the frequency of the power source. At low frequencies, approximately 50Hz as the arc current goes through zero, deionisation of the gas and cooling of the electrodes takes place and a considerable voltage may be required to restrike the arc. Increasing the frequency reduces the time available for the plasma within the interelectrode region to decay. A continuity criteria has been derived for low pressure discharges (Edels et al 1965) and more recently adapted for use with large volume thermal plasmas (Eckert 1971b). Fig 2.11 shows the variations of the electric field strength $E$ (V m$^{-1}$) and the conductance of the discharge $G$ (S) over one period for various values of the parameter $\omega \tau$, where $\omega$ is the angular frequency (rad/s) and $\tau$ the decay time of the plasma (Edels et al 1965).

For values of

$$\omega \tau > 10$$

the electric field strength is sinusoidal and the conductance shows only small fluctuations about the steady state value. For a thermal
Fig 2.11 Arc voltage and conduction wave forms of arcs for various values of parameter $\omega \tau$ (Edels et al 1965). Curve A, $\omega \tau = 0.1$; Curve B, $\omega \tau = 1.0$; Curve C, $\omega \tau = 10$.

Plasma column, controlled by the heat conduction losses to the discharge tube, the decay time of the plasma can be approximated by

$$\tau = \frac{\Lambda^2}{\alpha}$$  \hspace{1cm} (2.21)

Where $\Lambda$ is the diffusion length (m) and $\alpha$ is the thermal diffusivity ($m^2 s^{-1}$). The diffusion length within a discharge tube of circular cross-section is equal to the discharge radius $r$, divided by the first zero of the Bessel function which has a value of 2.405 if the temperature of the surrounding environment is assumed to be zero. The equation (2.21) then becomes,
Table 2.8. Diameter of discharge tube in which an alternating current arc would behave in a steady state manner for a particular operating frequency

<table>
<thead>
<tr>
<th>Operating Frequency</th>
<th>Minimum Diameter of Tube from Equation (2.23)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 kHz</td>
<td>25mm</td>
</tr>
<tr>
<td>10 kHz</td>
<td>8mm</td>
</tr>
<tr>
<td>100 kHz</td>
<td>2.5mm</td>
</tr>
<tr>
<td>1 MHz</td>
<td>0.8mm</td>
</tr>
</tbody>
</table>

A discharge in air or argon at atmospheric pressure and a temperature of $10^4 \text{K}$ has a value of thermal diffusivity of approximately $0.02 \text{m}^2/\text{sec}$ (Emmons 1967). For the high frequency discharge to behave in a steady manner then equation (2.20) becomes

$$\omega \frac{r^2}{5.78 \alpha} \geq 1$$ \hspace{1cm} (2.23)

Using equation (2.23) the minimum diameter of discharge tube in which an alternating current arc would behave in a steady manner for a particular operating frequency is given in Table 2.8.
Fig 2.12 A. C. arc volt-amp characteristics

(1) Low frequency  (2) High frequency  (3) Static characteristic

Fig 2.12 shows the a.c. volt-ampere characteristic of an arc. At low frequencies, the characteristic follows the static characteristic of Fig 2.10, but as the frequency is increased the finite time required to establish thermal equilibrium within the arc causes the a.c. characteristic to lie above the static characteristic when the current is increasing and below it when the current is decreasing.

Arc discharges in air or argon at atmospheric pressure attain an approximately constant conductivity at frequencies in the region of 1kHz. It is only at frequencies above this level that a steady state analysis can strictly be applied as in the case of the equivalent conductor formulated in chapter 2.3 and the a.c. characteristic of the discharge can be approximated by a straight line through the origin, Fig 2.12. The arc then behaves as a purely resistive circuit element.
For frequencies in the range of 1MHz, a discharge can be maintained independently of any electrode processes i.e. an electrodeless discharge, as the electron amplitude is less than the discharge length unless the pressure is extremely low.

2.5.1. Electrodeless Discharges

There are two forms of high frequency electrodeless discharge within the megahertz range depending on the coupling arrangement between the oscillatory circuit and the discharge. A capacitatively coupled discharge is maintained by the power input created within the discharge region by an axial high frequency electric field.

A study of the characteristics of capacitatively coupled discharges as a function of gas pressure and frequency was carried out by Babat (1947). The capacitatively coupled discharges formed up to 1MHz have current values of less than 1mA and discharge powers of fractions of a watt. It is only at frequencies between 10MHz - 100MHz that large current, high power discharges are formed but these have generally very small diameters of the order of 2 mm (Egorova 1967).

An induction coupled discharge is maintained by the power input to it due to the currents induced in the discharge by a high frequency magnetic field and is characterised by its relatively large volume. A great deal of research has been carried out on this type of discharge with a view to the industrial application of this device for chemical and metallurgical synthesis.
Fig 2.13 Measured temperature distributions in air and argon induction coupled discharges
D: Johnston (1966).

The radial distribution of temperature within an induction coupled discharge has a maximum value in the outer regions of the discharge, Fig 2.13, attributable to the skin depth phenomena inherent in all high frequency heating applications. The application of the electromagnetic theory, more commonly associated with the induction heating of metals (Baker 1957), shows that the optimum dissipation of energy within the load is obtained when the ratio of the radius of the cylindrical load to the skin depth \( \delta \), is approximately 1.75.
The term skin depth being defined as

\[ \delta = \sqrt{\frac{2}{\sigma \omega \mu \mu_o}} \]  
\[ (2.24) \]

where

\[ \mu_o = \text{the permeability of free space} = 4\pi \times 10^{-7} \text{(H/m)} \]

\[ \mu = \text{the relative permeability} \]

Dymshits et al (1965) reported that with variations of frequency between 290kHz - 3.3MHz, of pressure between \(2 \times 10^4\) Pa - \(2 \times 10^5\) Pa and tube radius of 15mm - 45mm, the ratio of the discharge radius to the estimated skin depth varied between 1.65 and 1.75 only. Operation with ratios below 1.75 means that current cancellation effects are encountered reducing the efficiency of power input to the discharge. No experimental results have been published with values of the ratio of discharge radius to skin depth substantially below 1.75 and this can be used as a criterion for the minimum diameter of the discharge tube. Operation is possible with ratios in excess of 1.75, this is accomplished by simply increasing the power output from the generator and ratios up to 10 have been reported (Eckert 1971).

The discharge can be characterized by the operating frequency, the magnitude of the power input, the axis temperature and the radius of the discharge. The interaction between these four variables can best be understood by considering the energy balance of each zone of the discharge. Approximately 90% of the electrical input power is dissipated within the skin depth of the discharge (Baker 1957) and this must be balanced by the heat transfer to the surrounding walls and conduction to inner parts of the discharge. The non-uniformity
of the radial temperature distribution within the discharge increases with larger power input and higher axial temperature (Ebihara 1973). Increasing the power input means a larger heat loss to the surroundings can be sustained and the discharge increases in diameter. If the same axial temperature is to be maintained the heat transfer to the inner zones must remain the same and as the radial distance increases, so must the temperature difference. Similarly increasing the axial temperature increases the radiation losses from the axial regions to the outer zones and this again means an increase in the heat transfer by conduction from the outer regions and an increase in temperature gradient. Similar reasoning shows that when the power input and axial temperature are constant, the plasma radius decreases, the plasma surface electric field increases and the magnetic field decreases with an increase in operating frequency.

A radial inflow exists in an induction coupled discharge because of a phenomenon known as 'magnetic pumping' (Chase 1969, Mensing et al 1969). The interaction between the induced current in the discharge and the high frequency magnetic field produces a pressure gradient due to the Lorentz forces which create an inflow in the radial direction. The magnitude of the pressure difference due to this phenomenon is of the order of only 4 Pa (Chase 1969), but the effect it has on the gas flow pattern within the discharge is significant. A double vortex flow system is produced which is superimposed on the axial flow. Typical flow patterns associated with induction coupled discharges are shown in Fig 2.14. Axial velocities of the order of 10 ms$^{-1}$ have been calculated (Boulos 1976) and measured (Waldie 1975).
Fig. 2. Typical flow patterns associated with an induction coupled discharge

A complete analysis of an induction coupled discharge in the steady state requires the simultaneous solution of the energy balance equation, Maxwell's field equations, the radiation transport equation and the momentum balance equation. Many attempts have been made to use computer simulation techniques to analyse the induction coupled discharge and these have been reviewed extensively elsewhere (Jordan 1971, Eckert 1974a). Mathematical models have now been developed which calculate the two-dimensional flow and temperature fields as well as the electrical and magnetic fields in an induction coupled plasma (Boulos 1976). These numerical approaches, however, provide no insight into the ignition mechanism within the discharge and very little work has been published on this subject (Kustov et al 1968, Nomoto et al 1973). The power input to an induction coupled plasma torch can be accounted for by three separate loss mechanisms: radiation from the plasma, heat transfer
by conduction to the torch walls, and by any increase in the enthalpy of the gas leaving the torch. Estimates have been made of the relative values of each of the mechanisms for particular torches (Borgianni et al 1969, Charles et al 1970) and examples of total calorimetry include placing the entire torch in a liquid bath (Scholz et al 1967), passing an opaque coolant through the water jacket surrounding the discharge tube (Miller et al 1969), or blackening the discharge tube (Dresvin et al 1966). The results differed tremendously with power lost by radiation varying from zero (Dresvin et al 1971) to as high as 33% (Reed 1961a) of the power input to the discharge whilst the power into the gas stream varied between 20% and 50%. The energy balance of any discharge depends on the power level, the length and diameter of the discharge tube, the type of gas and its flow rate. Generalisations about the heat loss mechanisms can be seriously in error as has been discussed in detail by Boulos (1976).

Energy balances have been reported for torches operating in argon, nitrogen, hydrogen, oxygen and helium, at frequencies ranging from 450 kHz to 4 MHz input power up to 1 MW and discharge tube diameters between 25 mm and 250 mm (Thorpe et al 1968). In argon with total input powers up to 600 kW, approximately 70% of the input power is coupled to the plasma of which 20% is lost to the cooling water of the torch and 46% emerges in the exit stream. The efficiency of heating hydrogen and helium was found to be much lower than in argon, due to the high thermal conductivities of hydrogen and helium. Only about 7-15% of the total input power of approximately 100 kW was contained in the emergent stream and more than 50% of the power input was lost to the walls of the surrounding tube.
2.6. Diagnostic Techniques

The diversity of the various diagnostic techniques that have been applied to discharges is enormous, and extensive reviews of the practical and theoretical techniques have been made. (Lochte-Holtgreven et al 1968, Huddlestone et al 1965). The use of probes together with spectroscopic and photographic techniques account for a large part of the work to date, especially that which can be considered directly relevant to thermal plasmas.

2.6.1. Probe Techniques

Langmuir probes, used for many years to diagnose the properties of stationary and flowing low temperature plasmas, have advantages in that they are simple to construct and operate, and can give time resolved measurements of local plasma properties (Langmuir 1924). The probes are metallic electrodes, usually a wire for cylindrical probes, which are inserted into the plasma and from the current collected by the probe as a function of the probe voltage, information can be obtained about the plasma density and temperature. Interpretation of the probe signals is usually complicated because the current-voltage characteristic depends on the plasma-probe interaction (Swift et al 1970). The introduction of the probe should produce a negligible disturbance to the plasma being studied, in particular, the conduction of carriers to the probe. This usually puts constraints on the maximum probe radius and design of the probe support.

In atmospheric pressure plasmas the excessive heat flux to the probe limits the time which the probe may be immersed within the
plasma. Rotating probes are therefore used (Clements et al 1972, Gick et al 1973). The probe passes through the plasma with a velocity limited by the heat flux to the probe and the need to minimise any physical disturbance to the plasma. Whilst the velocity of the probe is not usually excessive, a rigid support is needed for the probe and the thickness of the probe must be such that overheating does not occur when carrying the larger probe currents associated with atmospheric plasmas. The probe is within the plasma for a very short length of time, but some thermal disturbance of the plasma by the probe must occur as a result of the temperature gradient set up between the probe and the plasma. The concentration and temperature of the charge carriers and neutral particles may decrease in the vicinity of the probe. If excessive heating of the probe takes place thermionic emission from the probe surface may cause a perturbation of the electric field near the probe.

The choice of measuring circuit is determined by the nature of the plasma being studied. In transient high frequency plasmas and high pressure plasmas where a rotating probe is used, instantaneous methods of recording the probe characteristic must be employed, while stable plasma readings can be taken over a period of time (Chen 1965).

Finally in order to decide on the particular probe theory to be applied, for example see Johnson et al (1950), Su et al (1963), Waymouth (1964) and Wasserstrom et al (1965), an estimate of the electron and ion mean free paths should be made, the range of values of Debye length likely to be encountered should be calculated and the effects of gas flow should be assessed. Even so the choice of the correct probe theory is uncertain, especially in high temperature, atmospheric pressure plasmas (Clements et al 1973).
2.6.2. Spectroscopic Techniques

Spectroscopic methods are the most extensively used for determining the temperature within a plasma (Drawin 1970, Lapworth 1974) and include emission - absorption and line reversal techniques, relative and absolute intensity measurements, and measurements of intensity maxima.

Using spectroscopic techniques the velocity distribution functions, number densities, and population densities of discrete energy levels should ideally be known, for each particle, at each point within the discharge, and at each instant of time. Details of the radiation process taking place are also necessary. If complete thermodynamic equilibrium prevails then the velocity distribution functions for each type of particle, the population densities of discrete energy levels and the number densities are characterised by one temperature. The radiation is also given simply by Planck's law over the whole of the spectral range.

Complete thermodynamic equilibrium is an ideal state and in most high temperature discharges the simplifying approximation of local thermodynamic equilibrium is made. A discharge is said to be in local thermodynamic equilibrium if the velocity and energy distribution functions can be characterised by one temperature.

Drawin (1970) has given a comprehensive review of the conditions necessary for the attainment of local thermodynamic equilibrium in plasmas and experimental evidence and theoretical considerations indicate that the conditions for this state are closely approached in
atmospheric pressure discharges between electrodes (Griem 1964). Local thermodynamic equilibrium has also been shown to exist within the central regions of an induction coupled discharge (Scholz et al 1968). However, calculated temperature distributions in the outer regions of an induction coupled discharge show much steeper gradients than the experimental values and this discrepancy has been attributed to non-equilibrium effects (Eckert et al 1971).

Gradients in electron density caused by the strong temperature gradients near the wall, give rise to ambipolar diffusion of electrons and ions and bring the electron concentration above those predicted by the Saha equation. Spectroscopic techniques will therefore give temperature that are higher than they should be within the outer regions (Stokes 1971).

The line reversal method of temperature measurement represents a special case of the emission-absorption techniques. These methods rely on the plasma having a high emissivity in one or more spectral regions. If the emissivity is low then the radiation from the background source alone and from the plasma and background source will be very much greater than the radiation from the plasma leading to large errors in the expression for the Planck radiation function (Lapworth 1974). Thus this method works well on the fundamental vibration - rotation bands in the infra-red, but if used in the visible region of the spectrum it is usual to introduce atoms such as sodium into the gas giving strong resonance lines (Johnston et al 1971).

Although the emission - absorption method can be used to measure temperatures greater than the background temperature, the maximum temperature that can be measured with accuracy is limited.
The intensity of radiation changes exponentially with temperature and if the gas temperature is greatly in excess of the background temperature large errors can be incurred.

Estimating the temperature of a plasma by measurements of the absolute or relative intensities of radiation at various wavelengths (Housby-Smith et al 1978) requires that the plasma is optically thin for the relevant wavelengths. From the absolute intensity of a spectral line, or the continuum, the temperature can be derived if the transition probabilities and the number of emitting particles per unit volume are known. The transition probabilities, however, are not always known to any great accuracy and the number of emitting particles has to be derived from subsidiary conditions.

In relative intensity methods the intensities of several spectral lines are measured and the temperature estimated providing the values of the transition probabilities and the statistical weights of each energy level are known. This method is possibly the simplest of the spectroscopic techniques but is subject to errors. If the spectral line is not optically thin the intensity will be smaller than expected and it is advisable to use a large number of lines to eliminate this error. The assumption of homogeneity is not always valid and the temperature obtained by this method would then be higher than the actual temperature.

Temperature evaluation from measurements of intensity maxima is only relevant to high pressure arc columns in which there is a significant amount of self-absorption. The temperature must be a monotonically decreasing function of the radius and this method must not be used with induction coupled discharges or where the
radial temperature distribution is uncertain (Reed 1967). The method is also restricted to where the line is self-reversed and therefore cannot be used right to the edge of even a d.c. plasma column.

Discharges at atmospheric pressure have very steep temperature gradients, often greater than $10^3 \text{K mm}^{-1}$, at their boundaries. Spectroscopic observations made side on, record therefore, the integrated radiation from regions of greatly differing temperatures along the line of sight and can only be analysed if further simplifying assumptions are made regarding the symmetry of the discharge.

A radial temperature distribution for a symmetrical optically thin source can be obtained by making observations at different points scanning across the source and various methods have been proposed to carry out the inversion to give a radial distribution (Lochte-Holtgreven 1968).

The method has been extended to the case with self-absorption (Tourin 1966) but this involves the measurement of the gas transmittance as well as its intensity in the spectral region of interest.

2.6.3. High Speed Photographic Techniques

Photographic methods have been used extensively to investigate the behaviour of electric arcs and applications include the measurement of arc length and cross-section and the observation of arc behaviour in switchgear (Airey 1978) and arc furnaces (Strachan 1976).

Very little quantitative information can be obtained about an arc by simple single shot photography and this method is usually confined
to a generalised description of the state of the discharge or perhaps
the observation of dark sheaths surrounding probes or similar
objects immersed in the plasma (Gick et al 1973).

Shadowgraph (Airey et al 1976) and schlieren techniques (Bothwell
et al 1974), have been applied to the study of the flow patterns
within discharges using lasers as the high intensity light source.

For a transient or rapidly moving discharges streak photography may
be used (Walmsley et al 1978). The velocity of particles emerging
from a plasma flame has also been measured using this technique
(Lewis et al 1971). If the arc has an everchanging pattern, however
without any definite periodicity, the more straight forward high speed
photographic techniques are preferred.

High speed photographs have been used to investigate cathode spot
motion (Sherman et al 1973), the axial velocities within free burning
arcs (Strachan et al 1975), and the stability of an arc (Klapas et al
1976). The most common uses are, however, to investigate arc
movement especially within arc furnaces (Jordan et al 1970), and to
assess the arc diameter (Strachan 1976). Photography is experimentally
the simplest method of comparing the diameters of different arcs but
absolute measurements of arc dimensions are liable to error (Siddons
1971). Interposing an increasing number of neutral density filters
between the arc and the camera until no further reduction in apparent
arc diameter is observed, only a general reduction in image brilliance,
can reduce the error (Airey 1972).

The use of high speed photography in the investigation of magnetically
rotated arc discharges (Mayo et al 1962) initially gave rise to the
impression that the discharge became diffuse at high rotational speeds but this was later attributed to the persistence of luminosity in high pressure arcs, especially in air or nitrogen (Harry 1968a).

In conclusion it must be appreciated that the choice of any diagnostic technique is invariably a compromise between the level of accuracy that is required and the time, equipment and expertise needed to achieve it. The use of probe techniques to investigate atmospheric pressure discharges is subject to severe limitations. Even if the geometry of the discharge system is suitable for rotating probes or the diameter of the discharge large enough so that water cooled probes may be used without excessive disturbance the choice of theoretical analysis to apply to the results obtained is far from certain.

Spectroscopic techniques require the use of relatively sophisticated equipment and a high standard of optical alignment. Because of the steep temperature gradients associated with high pressure discharges, the radiation detected in any spectroscopic diagnostic technique would be the sum of that emitted by various elements of the discharge at greatly differing temperatures. If the geometry of the discharge is uncertain then the analysis of the spectroscopic data is subject to severe errors and the use of high speed photography may be advantageous especially if the effects of the persistence of imminiosity can be accounted for.

When the discharge geometry can be defined and it does approach the symmetrical conditions suitable for spectropic techniques, the accuracy required may not justify the more sophisticated experimentation and more complicated theoretical analysis. For example when an estimate of the overall diameter of an induction coupled discharge is required to within ±2mm it is unlikely that spectroscopic techniques offer any advantage over the use of single short photographic techniques.
CHAPTER 3

The Production of Thermal Plasmas for Chemical and Metallurgical Synthesis

A review of the methods of producing thermal plasmas with particular emphasis on the arc heater design and the application to chemical and metallurgical synthesis is presented.
3. The Production of Thermal Plasmas for Chemical and Metallurgical Synthesis

Work on arc discharge devices began in the nineteenth century (Davy 1809, Moissan 1896 and Hare 1841) but it was not until the early twentieth century and the availability of relatively cheap hydroelectric power that an industrial process was forthcoming. Birkeland and Eyde developed a process for the synthesis of nitric oxide from air using an a.c. electric arc with a maximum voltage of 5000V at a power level of several hundred kilowatts. A number of these units operated profitably in Norway (Edstrom 1904) until the process was superseded.

During the second world war Germany began to make large quantities of acetylene for the manufacture of synthetic rubber by the pyrolysis of methane in an arc. The plant was opened in 1940 by Chemische Werke Hüls A G (Gladische 1962) and the reactor is shown schematically in Fig 3.1. The gases are fed tangentially into the heater creating a stabilising vortex within the hollow water-cooled electrodes. A d.c. arc approximately one metre long is struck between the iron electrodes (Schmidt et al 1965) and the motion of the gas ensures that the arc roots rotate rapidly spreading the thermal load. Typically operating conditions are 7000V at 1150 A, giving 8 MW of energy input to the heater. This arc process continued to be operated after the war, with certain adaptations of the reactant inputs (Gehrmann et al 1971), and, together with an ozone producing process (Siemens 1857) using a corona discharge, constituted the principal industrially used plasma processes for some years.
The advent of space travel in the mid-1950's meant that facilities for environmental simulation of outer space and re-entry conditions were required. The United States government initiated a number of research contracts to design arc heated wind tunnels for this purpose and the various designs that resulted have been reviewed extensively elsewhere (John et al 1961). The subsequent availability of high power arc heaters, however, renewed the enthusiasm for plasma chemistry research. Those arc heaters that have since been adapted for use in chemical metallurgical synthesis, together with the more recent developments will now be discussed in more detail.
3.1. High Voltage Arc Heaters

Many of the earliest arc devices operated with relatively long arcs, approximately 7 m long in one case (Schönherr 1909), high arc voltages, low arc currents and d.c. power. A very similar series of high voltage arc heaters have been developed by the Linde Division of Union Carbide Corp (1967) and the basic design shown in Fig 3.2. Magnetic rotation of the anode arc root and vortex stabilisation are employed and a silver-copper alloy anode and copper cathode combination gave very low electrode material loss (Bryson et al 1965). The torch has been used for the vapour-phase oxidation of titanium tetrachloride to manufacture pigment titania (Reed 1967) and as part of the Linde Plasmarc Furnace (Magnolo 1964) for melting metal in which the absence of consumable electrodes and the use of an inert atmosphere mean less contamination of the melt.

The production of acetylene for the manufacture of neoprene was carried out by Du Pont for several years (Schulze 1968). Vapourized liquid hydrocarbon fuel and recycled hydrogen was pyrolysed in a d.c. arc which was stabilised by magnetic rotation. A consumable carbon cathode was used with a water-cooled copper anode and typical operating conditions were 7100 V at 1200 A giving approximately 8.5 MW energy input. The operating pressure was reduced to approximately 5.10^4 Pa to decrease the carbon formation so troublesome in the earlier operations of Huls (Gehrmann et al 1971). The process was commercially viable for about five years but reduced demand for acetylene and access to inexpensive supplies of calcium carbide rendered the process uneconomic and it was closed down (Anon 1968).
High voltage arc heaters are subject to scaling laws (Ibberson 1969), which it is claimed allow extrapolation from laboratory models to large scale units. They suffer from major disadvantages, however, when continuous use for chemical processing is needed. The greater the length of the arc column the more difficult it is to stabilise and as the arc length and power level varies with gas flow in this type of heater it is difficult to optimise the electrode configuration and the large interior surface area exposed to the arc results in high heat losses to the walls of the torch. The high arc temperatures achieved and the low rate of rotation of the arc column mean that steep temperature gradients exist between the arc core and the outer gas stream with little mixing taking place in the arc region. Although the Union Carbide torch has been
operated with a.c. power (Sarlitto 1964) the problems of re-
ignition of such a long arc each cycle mean that the torch is
essentially a d.c. device requiring facilities for rectification with
the subsequent increase in cost and reduction in efficiency.

Recently a torch of similar high voltage, long arc design has
become available (Camacho 1977) which it is claimed can work with
both a.c. and d.c. powers in excess of 3 MW in the transferred mode.
The successful a.c. operation is said to be due to the novel method
of arc initiation and stabilisation (both subject to patent applications)
used but as yet no reference of an industrial process using this torch
in the a.c. mode has been found.

3.2. Plasma Torches

A variety of plasma torches have been developed (Gross et al 1968,
Reed 1967) and used industrially for many years in welding, cutting
and spraying refractory metals. Largely because of the availability
of these devices many early attempts at plasma chemical processes
involved this type of arc heater (Leutner 1963). A cross-section of
a typical torch is shown in Fig 3.3. In this device an arc is struck
between an axial water-cooled cathode, typically thoriated tungsten,
and an annular water-cooled copper anode. A gas stream, fed axially
or tangentially into the arc chamber, sweeps the anode arc root
into the constricted section of the anode nozzle enabling high axial
temperatures typically between 8000 K - 30 000 K to be attained but
with steep radial temperature gradients (Jahn 1963). Powers of
up to 100 kW and thermal efficiencies of between 60-85% are typical
of this type of torch. The common operating gases are argon (also
used when starting because of its relative ease of ionisation), helium,
nitrogen, hydrogen, ammonia or their mixtures.
Fig 3.3 Typical d.c. plasma torch for use in plasma chemical process research (Sayce 1971)

The high velocity, viscosity and thermal gradients of the conventional d.c. plasma torch combine to ensure that the injection of particles or reactants into the hottest region of the arc is difficult and their retention time is short. If the processing of hydrocarbons and corrosive gases or materials is attempted within the arc region excessive electrode erosion or deposition of carbon can take place. For many processes, therefore, the reactants have to be introduced into the plasma downstream of the arc zone which gives rise to inefficiencies. It is also necessary to achieve good mixing of the reactants with this hot carrier gas and to maintain an adequate residence time in order to attain the required thermal and chemical equilibrium.
In the above designs the anode serves as the arc constrictor, but it is possible to constrict the arc by a separate means as in the case of the Gerdien arc (Gerdien et al 1922, Burhown et al 1951). In this case the d.c. arc between two electrodes is constricted by a vortex of water and an adaptation of this principle was used in the tandem gerdien plasma jet (McGinn et al 1958) proposed for hypersonic wind tunnel use. More recently the method has been used in a range of torches for cutting (Grosse et al 1968) and by using liquid compounds of metals or hydrocarbons as the stabilising medium, the compounds are heated to a high temperature with high efficiency without the need for a carrier gas as the heat transfer agent (Kugler et al 1970 a, b). This process is only on a laboratory scale and with the complexity of the devices and the excessively high temperatures attained it shows little promise of large scale industrial use in the near future.

Constriction by a layer of fluid has also been used in certain laboratory scale transpiration cooled d.c. torches. The plasma forming gas was passed radially inward through the walls of the constrictor (Pfender et al 1969) giving higher efficiencies and higher plasma temperatures.

Relatively small scale plasma torches using a.c. power have been investigated. By use of coaxial water-cooled copper electrodes and magnetic rotation of the arc a variety of gases were heated including air in a 100 kW torch operated at 50 Hz (Harry 1968b). In order to re-establish the arc after each current zero a one MHz ignition unit was used and efficiencies of more than 60% attained (Roots et al 1969).
Conventional d.c. plasma torches used in the non-transferred mode have found little industrial application in chemical processing. Small scale experiments with d.c. plasma torches have been carried out including the reduction of iron ore on which patents have been issued proposing large scale processes (Gillies et al. 1970).

In the transferred arc plasma torch the current to the anode nozzle is limited to about 20 A and the main current being transferred to the workpiece located downstream from the nozzle (Thorpe 1960). This type of torch is used extensively in cutting and welding applications but can be adapted to metal melting operations. The Linde Plasmarc Furnace Fig 3.4 (Magnolo 1964) uses a high voltage arc heater mounted on the roof of conventional melting furnace. With argon as feed gas the pilot arc between cathode and
anode of the torch is struck and once electrical contact is established between the plasma and metal the full plasma power is transferred to the metal. The torch is placed in the furnace roof, avoiding the possibility of short circuits resulting from charge collapse and the low voltage gradient in the gas plasma means that changes in arc length cause smaller fluctuations in current, thus eliminating two of the major problems associated with arc melting furnaces. The absence of consumable carbon electrodes also means lower contamination levels. This type of furnace has been proposed for the reduction of iron ore in the presence of a hydrocarbon gas (Death 1967), titanium formation from titanium tetrachloride (Rio Algom Mines Ltd 1967), and chromium oxide reduction in a similar furnace to form an iron-chromium alloy (Tischendorf 1964). A large scale three phase apparatus has also been patented (IRSID 1966). After comprehensive investigations using three phase unconstricted arc devices and a non-transferred d. c. plasma torch, recent work on the formation of ferromolybdenum or pure molybdenum from its ore is being carried out using a d. c. plasma torch working in the transferred mode (Kubanek et al 1977) and commercialization of this process is under consideration at the present time (Gauvin 1978).

Precessing a plasma torch working in the transferred mode relative to its external anode, which may be a water cooled copper ring if powders are to be processed or the molten bath during metal melting, increases, it is claimed, the stability of the plasma volume (Tylko 1974). The plasma torch is inclined at an angle of about ten degrees to the vertical and precesses at a rate of 25 Hz. Small scale experiments have been carried out on various extractive metallurgical applications and at present a pilot plant with arc currents of 1500 A, arc voltages of 900 V and arc lengths of 300 mm is being developed for the reduction of iron ore (Heanley 1979).
Applying the transferred arc mode of operation of a d.c. plasma torch to certain non-conducting materials has been described for the surface treating of refractory materials (Tetronics 1966). This mode can also be used in plasma electrolysis by transferring the arc to the surface of a molten electrolyte, when the plasma can act as a gaseous electrode for the electrolytic process (Shelley et al 1970).

An adaptation of the technique has been proposed in the evaporation of silica (M.H.D Research Inc 1970). A d.c plasma torch using tungsten electrodes was operated while pointing vertically downward, Fig 3.5, and feeding a stream of silica in a gas vortex onto the inner wall of the lower electrode (usually cathode), or onto the wall of a tungsten tube which served to contain the tail-flame. The oxide melted on the reactor walls and flowed slowly downwards, surrounding the
tail-flame. The cathode arc root then moved freely over the surface of the molten silica, which received additional heat from the plasma column streaming through the reactor. More recently a basically similar process for the reduction of iron ore in a mixture of methane and hydrogen has been patented by the Bethlehem Steel Corporation (MacRae et al 1977). High purity iron has been formed at a rate of 257 kilograms per hour and the torch has a power of approximately 850 kW. The arc current was of the order of 500 A and the arc voltage varied between 1525 V and 1850 V, the relatively high value being due to the elongation of the arc by the movement of the anode root down the reaction chamber. Relative to the conventional d.c. torch these last two processes represent a useful means of simultaneously increasing the retention time of the reactants within the heating zone and decreasing the electrode heat losses.

Another device which has been used to extend the particle retention times and to improve the thermal contact between the plasma and solid reactants is the centrifugal plasma furnace. The simplest furnace, heated by a non-transferred plasma jet, Fig 3.6, has been used to melt and vaporise such oxides as alumina, magnesia and silica (Grosse et al 1965, Selton et al 1969, Sayce et al 1972, Everest et al 1973). Transferred arc operation has also been achieved in which the arc is struck between a consumable carbon electrode and the melt itself, which acts as the anode (Sayce 1976). When this is not possible the centrifugal furnace can be heated by arcs transferred between two plasma torches and both horizontal and vertical configurations have been reported with transfer between d.c. plasma torches (Foex et al 1970a, Howie et al 1974) and also between a d.c. and an induction torch (Bush et al 1973). A
Fig 3.6 A centrifugal furnace using a non-transferred d.c. plasma torch (Selton et al 1969)

centrifugal furnace using two d.c. plasma torches with either a high power d.c. or a.c. arc between them is commercially available (Schoumaker 1976). The length of the plasma column is about 500 mm and with a transferred power of about 100 kW the power to each of the pilot plasma torches is about 10 kW Fig 3.7. Various refractory materials have been melted including zirconia.

The use of a transferred arc in a centrifugal furnace has certain advantages. Because of the length of the transferred arc a high voltage is used and hence a relatively high power input is attained
Fig 3. A centrifugal furnace using a transferred arc between two d. c. plasma torches (Foex et al 1970a)

without excessively high arc currents. The plasma jet is completely surrounded by the material to be treated and the furnace losses from the entrance and exit apertures are low. This type of furnace, however, does not lend itself to easy scaling up to the megawatt region or to the use of continuous material throughput. The power required to rotate the furnace is wasted and the intrinsic efficiency of the device is also reduced because of the poor utilization of the power input to the pilot plasma torches at each end which may account for between 10% - 30% of the total power input (Schoumaker 1976).
Centrifugal furnaces are unsuitable for use with particulate feedstock and the difficulties of using a conventional d.c. plasma torch when particle entrainment into the arc is required have already been mentioned. A recent adaptation of a phenomenon first noticed by Maecker (1955) has been found to facilitate particle entrainment into an arc (Bryant et al 1969). Where any current carrying plasma column is constricted, there exists a radial component of current flow and the resulting magnetohydrodynamic forces give rise to a pressure drop in the region of the constriction. Thus there is a low pressure zone in the vicinity of the cathode arc root and this gives rise to an inflow of gas resulting in the cathode jet in a conventional carbon arc. While efficient particle injection into a simple plasma column is difficult, the exploitation of these magnetohydrodynamic forces can ensure efficient particle entrainment into the current carrying region of the arc (Sheer et al 1974a, 1974b, Bayliss et al 1977). A similar device is currently incorporated in commercially available equipment for treatment of particles including zircon sand and silicate ores (Humphreys Corporation 1973a, 1973b, 1974).

3.3 Non constricted arc devices

The earliest unconstricted arc heating device is commonly known as the high intensity arc (Beck 1921, Finkelnburg 1949). As the current density in an unconstricted arc is increased, the proportion of input energy released at the anode is increased until the heat input is too great to be dissipated by heat transfer and the anode either sublimes or, if molten (and suitably contained), boils. The transition from normal arc to high intensity arc is accompanied by a change in the
usual falling voltage current characteristic to a rising curve and the appearance of a brilliant plume of vapour streaming away from the anode. Various materials have been fabricated with carbon into an anode shape and either melted (Gibson et al 1963) or volatilised (Sheer et al 1956), and this type of process has been used commercially to produce a variety of sub-micron powders (Holmgren et al 1964).

The major disadvantage of this technique is the need to fabricate mechanically strong and thermally shock resistant electrodes. All the products must be raised to a temperature of several thousand degrees in order to maintain the electrical conductivity of the arc. Silica, for example, may be vaporised at high rates in the presence of carbon at temperatures in the region of 2000°C and to heat the gases to a higher temperature represents a waste of thermal energy. Despite these reservations, this process has been used in a number of applications including extraction of manganese from rhodonite (Harris 1959), vaporisation of ilmenite, alumina, silica, euxenite and zircon (Sheer et al 1963 a), the production of high purity uranium carbide spheres (Sheer et al 1963 b) and the extraction of molybdenum (Freeman 1969).

Three phase carbon arc heaters have been produced, the first in large scale production was the arc acetylene reactor built at Knapsack - Griesheim A.G. (Sennewald et al 1963) Fig 3.8. This device, with power inputs up to 4 MW, heats a hydrogen gas stream by means of an arc between three continuously fed carbon electrodes with petroleum vapour added as the reactant downstream of the discharge. Development of a three-phase carbon electrode heater has also been described (Iwasyk 1969) as part of investigations into
the type of reactor used in the Du Pont acetylene process. A d.c. reactor chapter 3.1., was eventually chosen for the Du Pont process but the efficiency and reliability of the three-phase device has since led to the commercial availability of similar units employed in the Ionarc process for the plasma treatment of ores (Wilks et al 1972). In the Ionarc process Fig 3.9., the arc operates with consumable carbon anodes in a high intensity mode at powers up to one megawatt. This produces a large plasma flame up to 250 mm diameter and 1.3 m long which streams downward through a vertical reactor. A small d.c. or induction plasma torch provides ionised gas to enable the re-ignition of the arc when a.c. power is used. The process is very similar to that used by Sheer et al (1974a) with a fluid convection cathode and transpiration cooled anodes (Chapter 3.2.). Powders are directed into the cathode jet.
region of the Ionarc heater by a series of ports set around the cathode orifice and the pinch effect (Maeker 1955) will again be important in ensuring successful entrainment of particles into the current-carrying region of the arc.

Heat losses via the electrodes are used when using consumable electrodes but there are applications when a carbon free atmosphere is required. A three phase 100 kW arc heater has been described (Bonet et al 1970) in which three water cooled copper electrodes were arranged about a central axis. Each electrode was surrounded by a sheath gas and a d.c. torch was used to initiate the discharge. Efficiencies of more than 90% for power input to the discharge have been claimed. An adaptation of this device has been used with thoriated molybdenum electrodes in attempt to produce molybdenum
of high purity (Kubanek et al 1977, Bonet et al 1976). Whilst conversion efficiencies between 72% and 30% were achieved at specific power consumptions of 90 kWh/kg and 11 kWh/kg respectively, this did not compare favourably with the 99.8% conversion efficiency at 10 kWh/kg thought necessary to make the project commercially viable.

The replacement of electrodes in a three phase arc metallurgical furnace with plasma jets has long been advocated (Lunau et al 1964). The use of d.c. torches to supply pilot arcs permits ready re-ignition of the arc at each current zero, enables the transfer of a long arc to the metal surface and minimizes contamination and electrical fluctuations. It is not surprising therefore that a three phase arc gas heater using plasma jets has been patented (Foex et al 1970b).
and is now commercially available at powers up to 600 kW (Schoumaker 1978) Fig 3.10. Three d.c. plasma jets provide a pilot plasma and three phase power is transferred between them, with the bulk of the gas to be heated being fed axially into the plasma formed (Arcos 1978). Pilot plants have been built using this type of device and proposed applications include the production of pigment titania from titanium tetrachloride in an oxygen plasma, formation of tantalum carbide by reduction of tantalum pentachloride in a hydrogen plasma, and the refining under a controlled atmosphere of stainless steels, niobium, tantalum, molybdenum, titanium and certain permanent magnet alloys (Schoumaker 1976, Arcos 1978). More recent applications include the manufacture of reducing gas mixtures from natural gas and air for blast furnace research and the incorporation with an induction furnace for metal melting (Schoumaker 1978). Further details of the last process were not available but it is thought that the design is similar to that used by Daido Steel of Japan and others (Asada et al 1970, Yoshimoto 1971).

A comparison of the above device with the consumable electrode units of Ionarc and similar processes must balance the advantages of reduced contamination, electrical supply fluctuation and arc reignition problems, with the decreased particle entrainment achieved and the lower efficiency due to electrode losses. A criticism of both three phase arc heaters was put forward by Kubanek et al (1977) who showed by high speed photography that spatial instability occurred with the discharge being off-centre for approximately 15% of the time.

A device using a d.c. transferred arc between 3 similarly spaced d.c. plasma torches has been developed at the National Physical Laboratory (Bayliss et al 1977). It consists of a central cathode operating within a protective gas sheath, with a transferred arc from this cathode
streaming downwards to meet plasma jets issuing from the (anode) plasma torches. The particulate feed-stock is fed into the low pressure zone around the cathode through an outer annulus surrounding the gas sheath. This concept is similar to that used in the Ionarc process and in the fluid convection cathode developed by Sheer et al (1974a), and has since been studied analytically (Bhattacharyya et al 1976).

Direct comparison between this device and the non-consumable electrode, three phase arc heater designed by Bonet and his co-workers, made in the production of molybdenum from its ore (Kubanek et al 1977) showed that the lowest specific power consumption and the lowest electrode erosion rates were achieved by the d.c. transferred arc system, although both devices gave disappointingly low percentage conversions to molybdenum and specific power consumptions too high for commercial viability.

3.4 The Rotating-Wall Arc Furnace

The diameter of an arc, at any particular arc current, depends largely on the heat transfer from its surface. Constriction of an arc by external means such as a water cooled nozzle or tangential air or water flow systems, causes a decrease in the arc diameter and an increase in the non-uniformity of temperature radially across the arc. Even free-burning arcs used in the arc heating devices are constricted but in this case by the natural convection heat losses within the outer regions of the discharge. A reduction of these convection effects would increase the diameter of an arc thereby producing a larger volume of plasma for any particular arc current. This would be advantageous in chemical and metallurgical synthesis applications because of the subsequent increase in the reactant
Fig 3.11 Rotating-wall plasma arc heater (Whyman 1967)

residence times and the temperature uniformity across the plasma envisaged (King 1964).

Arc heating devices have been reported in which suppression of the convection losses within an arc were obtained by the rotation of the surrounding enclosure about the axis of the discharge, creating a vortex thereby stabilising and expanding the discharge (Pullen 1966).
The early rotating-wall devices were operated at arc currents less than 20A, with discharge powers less than 2 kW. The only attempt made to scale up this process was carried out by Whyman (1967) and this device is shown schematically in Fig 3.11. The device consisted of a d. c. arc column surrounded by a water-cooled copper tube co-axial with the arc, which was rotated about its axis. The cathode was made of a thoriated tungsten rod placed around a central inlet tube and the whole assembly was moveable to control the arc length and hence the volume of plasma produced. The arc was initially struck between the cathode and a water-cooled funnel shaped anode using a 20 kV high frequency unit and then transferred to the principal anode assembly which was mounted externally. The function of the funnel shaped anode was not only to aid in the plasma initiation, but also to stabilise the discharge near the anode root which had been a problem with earlier devices (Audsley et al 1967). The centrifugal and viscous drag forces acting on the outer regions of the arc caused it to expand to a degree dependent on the rate of rotation, which was typically between 5 Hz and 19 Hz. Arc currents up to 500 A and arc lengths of approximately 400 mm were obtained in argon and with an estimated 87% of the energy input transferred to the plasma. The arc voltage varied between 80 V and 160 V and the maximum power input achieved was 40 kW.

This type of furnace was proposed for chemical synthesis especially the vaporisation of powdered materials (Bryant et al 1970) because of the relatively small temperature gradients (Grycz 1967), and the long residence times available (Brown et al 1968). The device has been commercially available on a small scale (Plasma Physics Corp 1968) and its electrical and other characteristics have been studied analytically (Yeh et al 1969). Large scale development of
this type of discharge, however, has never taken place because of certain inherent disadvantages. The likelihood that this type of discharge would remain expanded if large amounts of particulate material were introduced or large gas flow rates used is small and the use of this process at the high powers required for commercial chemical synthesis would create severe mechanical and electrical problems.

3.5 Magnetically Rotated Arcs

The application of an axial magnetic field to a d.c. arc struck between a central cathode and a surrounding anode causes the arc to rotate about the cathode. This principle has been known for some time and has been used in switchgear devices for many years (Slepian 1929). It was incorporated in some of the first high velocity arc heaters for use in space vehicle re-entry simulation (John et al 1961) and in the field of plasma chemistry it found early application in the stabilisation of the long arc column of the Du Pont acetylene reactor (Schulze 1968). Stable arc operation is obtained and low electrode erosion rates because of the uniformity of the anode arc root energy dissipation due to the rapid rotation of the arc over the large part of the surface area of the anode.

Mayo et al (1962) concluded that a diffuse discharge, i.e. a discharge spread uniformly across the cross-section of the torch, was formed when rapid rotation of the arc took place. This has since been refuted in a comprehensive work on magnetically rotated arcs and other high current arc discharge phenomena associated with plasma torches (Harry 1968a).

Patents exist with novel designs to aid magnetic rotation including the incorporation of ferrite cores (A.R.S.R. 1968). Very high power single and three phase units for hypersonic wind tunnel use have also been developed incorporating magnetic rotation (Winkler et al 1962,
Fig 3.12 A magnetically rotated arc heater (Bunting 1972)

Westinghouse 1960).

After attempts by the Avco Corporation to produce acetylene by the pyrolysis of coal using a non-constricted arc consumable anode device had failed (Krukonis et al 1968), a magnetically rotated arc heater was designed (Krukonis et al 1974). Powdered coal was passed through a hydrogen plasma formed by a d.c. rotated arc and quenched immediately downstream of the arc zone.

Research and development work on magnetically rotated arc heaters for use in chemical and metallurgical synthesis including the reduction of titanium tetrachloride to titanium metal has been
carried out by the Electricity Council Research Centre (Bunting 1972). The various components of their arc heater using a magnetically rotated arc are shown schematically in Fig 3.12.

In the presence of a high axial gas flow, the stability of the arc was reduced due to the continuous lengthening and shortening of the arc, caused by the axial movement of the arc root (Humphrey et al. 1972a). The application of an axial magnetic field increased the arc stability by reducing the axial movement of the anode root. The rotation of the arc was then approximately within a plane perpendicular to the axis of the torch (Lawton 1971).

Assuming that the arc motion is controlled entirely by the interaction of the arc column with the applied magnetic field and the surrounding gas, calculations (Lawton 1971) and measurements (Chen et al. 1968, Harry 1968a) have shown that the involute shape adopted by the arc ensures an approximately uniform liberation of power at any radial distance from the axis. This does not mean, however, that the gas is necessarily uniformly heated throughout its volume. The fraction of the gas volume directly heated by the arc is dependent on the rotational speed of the arc and the maximum velocity of the gas for uniform heating must be less than the product of the arc diameter and the time for one rotation of the arc. High rotational speeds, up to 100 kHz can be achieved with moderate magnetic fields and hence reasonably large gas throughputs can be obtained. Flow rates of between 5m/s and 20m/s have been obtained with uniform outlet temperatures of approximately 9000 K and 3000 K respectively (Johnston et al. 1976).

The Westinghouse arc heater originally designed for re-entry simulation has been progressively modified (Hirayma et al. 1966,
Fig 3.13 The Westinghouse single phase a.c. arc heater (Hirayama et al 1966)

Fey et al 1970, Fey et al 1977). The single phase unit Marc 31 is shown in Fig 3.13 and consists of two annular water-cooled copper electrodes, each of 125 mm internal diameter and 250 mm long, separated by a narrow gap of approximately 1 mm. When a voltage (up to 4500 V) is applied across this gap, electrical breakdown occurs and the arc is immediately blown into the arc chamber by the flow of feedstock, part of which enters at high velocity through the inter-electrode gap. Magnetic rotation of the arc is used to reduce the electrode erosion. Typically arc working voltages up to 700 V are used with arc currents, either d.c. or a.c. up to 10 kA and total power inputs claimed up to 3.5 MW for a single device, and 10 MW for a three phase unit (Fey et al 1977). Pilot plants have been built for applications including the production of acetylene by the pyrolysis of liquid hydrocarbons, (Fey 1978a) and the production of ferrochrome from high grade chromite ore (Fey et al 1976). The spheroidization of magnetite grit has also been carried out (Fey et al 1977) which produced commercially acceptable levels of production.
and magnetic properties but unfortunately excessive particle agglomeration and product sintering took place. At present a process is being developed to produce low cost silicon for solar-photovoltaic power applications (Fey 1978b). This process is based upon the reduction of silicon tetrachloride by molten sodium and utilises the arc heater to produce the high temperature gas stream necessary for the collection of the silicon as a liquid.

This type of arc heater has a relatively high capital cost but it is usually more efficient both electrically, in that an a.c. supply can be used, because of the small electrode gap, and thermally, as the lack of arc constriction when compared with a plasma jet heater using a constricting orifice or the reduction in the length of heating zone when compared with the high voltage heaters, decrease the losses due to heat transfer to the walls of the reactor.

Arc rotation generates high levels of free stream turbulence and rapid rotation in the emerging gas. Turbulence can cause the wake of an arc to be many times its diameter thereby encouraging the homogenisation of the regions directly heated by the arc and those that are not (Humphreys et al 1972b). The effect of turbulence is usually negligible a few millimetres from the discharge but the induced rotation on the gas flow persists well downstream (Humphreys et al 1972, Cox et al 1971). This enables the increased heat transfer rates obtained to be maintained to relatively low gas temperatures and can be very useful when mixing reactants or quenching agents downstream of the discharge. High quench rates up to $3 \times 10^7$ K/s (Johnston et al 1976) can be obtained by adding liquid or gaseous quenching agents downstream of the discharge and in simple and relatively large diameter vessels. This is within
the range of quench rates required for most chemical processes proposed as applications for plasma devices (Vurzel et al 1970, Polak et al 1965).

The fixed electrode separations mean that the quenching agent input ports can be positioned very close to the heated zone without fear of interference with the arc but a major disadvantage of this type of heater is the very short residence times that have to be tolerated when large gas throughputs are required. The problems of particulate feedstock entrainment into the arc zone are similar to those mentioned previously for the high voltage and plasma jet reactors as the filamentary nature of the arc still remains. It is not possible to form a large volume of ionised gas by this method, only to increase the heat transfer rates above those of conventional d.c. plasma torches by the production of free stream turbulence and rapid rotational flow in the gas flow.

3.6 Electrically Augmented Flames

Combustion flames are limited in their heat transfer rate by their reaction kinetics and in their ultimate temperature by the partial dissociation of the products of combustion (Altmann 1956, Gutoff 1964). Because of these thermodynamic restrictions few fuels when burnt with air are capable of producing temperatures in excess of 2500 K, Table 3.1 (Brown et al 1968). Higher temperatures can be obtained if the reactants are preheated or if the heat of combustion is increased by the use of oxygen in place of air. Even so, the highest temperatures of combustion flames available for chemical and metallurgical synthesis is approximately 3500 K.
Table 3.1 Temperatures of combustion flames (Brown et al 1968)

Many industrial processes could make advantageous use of an economical source of heat at temperatures intermediate between those of combustion flames and those of electric arcs i.e. between 3000 K and 6000 K. The main difficulty in producing a combined device, an augmented flame, lies in the tendency of discharges to contract into narrow arc channels of very high energy concentration. This is a consequence of the rapid increase in the electrical conductivity of gases with temperature. The combination of an electric arc and a combustion flame results in a small volume of gas at an enthalpy much higher than that occurring in the rest of the flame. Although
mixing processes can distribute the energy from the arc channel throughout the product gases downstream of the discharge region, the advantage of very large throughputs associated with augmented flames, because of the increased resistance to flame blow-off, is lost if the rate of mixing controls the rate of throughput.

A three phase arc using rod electrodes to augment the output of an oil fired burner was first described by Southgate (1924). Line voltages of between 600 V and 6600 V were apparently used with power inputs to each arc of approximately 150 kW. The relatively high values of arc voltage obtained are attributable to the effect of elongation of the arc along the gas stream (Lawton et al 1969). With arc currents typically in excess of 50 A problems of electrode erosion severely limited this device.

The use of high voltage, low current electrical discharges in combination with combustion flames was proposed by Karlovitz (1962a, b). It was claimed that turbulence within a flame, seeded with particles of easily ionisable material, prevented a constricted low voltage arc from developing. The electrical power input was 4.6 kW at 4.7 A 1800 V with a combustion power input of 9.3 kW. Overall electrical efficiencies in terms of the power input and the output energy, measured calorimetrically, of up to 94% were obtained.

The device suffered from two major disadvantages. The maintenance of the discharge was conditional upon the stabilisation of the flame upstream of it and the heat from the discharge was not uniformly distributed until some distance downstream of the flame (Chen et al 1965).
Later examination of augmented flames similar to those produced by Karlovitz (1962 a, b) showed that some of the apparently diffuse arcs were in fact filamentary (Marynowski et al 1967). The diffuse nature of some of the arcs seen by Karlovitz was due to the rapid fluctuation of the discharge and the persistence of luminosity of arcs (Harry et al 1968). A truly diffuse discharge could not be formed above a ratio of electrical power input to combustion power input of 0.1.

Much of the earlier work on augmented flames suffered from misinterpretation brought about by the persistence of luminosity of the arcs and also by the use of loose terminology when describing the dispersion of the discharges within the flame. A d.c. arc used to augment a propane-air flame was claimed to be diffuse (Fells et al 1967). Voltages of 40 V and 400 V sustained arc currents from 2 A to 10 A across electrode gaps of 30 mm to 150 mm with gas flow rates varying between $10^{-5}$ m$^3$/s and $2.5 \times 10^{-3}$ m$^3$/s. The discharge could be maintained without a supply of seed material (Allen et al 1970, 1971) unlike much of the previous work (Karlovitz 1962 a, b, Marynowski et al 1967, Kilham et al 1970), and under certain conditions the discharge was stable even when the fuel supply to the burner was reduced to zero.

More recently other work on d.c. discharges in seeded propane-air flames demonstrated the existence of two stable arc modes dependent on the seed concentration and the arc current (Uhlerr et al 1971). With high seed concentrations and low arc currents the discharge was only slightly brighter than the flame and occupied up to half the cross-sectional area of the reactor. The anode exhibited many arc spots moving continuously about the anode surface and this form of discharge, it was postulated, was similar to that described by Karlovitz (1962a, b).
Increasing the arc current or reducing the seed concentration caused the formation of a single and much brighter anode spot and an intense but smaller diameter arc which was thought similar to that described by Fells and his co-workers. Whilst neither arc could be considered entirely filamentary, only the low current arc filled an appreciable portion of the cross-section of the flame.

Comprehensive surveys of the possible means of adding electrical energy uniformly to flames have been carried out (Chen et al 1965, Lawton et al 1969, Fletcher et al 1972) and experimental studies of the use of electrically augmented flames for chemical synthesis have been published (Marynowski et al 1969, Kilham et al 1970). The use of plasma jets, turbulence, seeding and high frequency discharges has been attempted but the most promising results were obtained with a magnetically rotated arc.

3.6.1 The Use of Plasma Torches to Augment Flames

The use of plasma torches to augment combustion flames is subject to limitations in the maximum flow rate caused by arc instabilities due to the inclusion of atoms requiring large energies of dissociation or having a strong electron affinity.

Two devices based on plasma torches are illustrated in Fig. 3.14 (Lawton et al 1962). When the reactants flow within the burner, Fig 3.14a it may be necessary to shield the cathode by an inert gas flow to prevent electrode erosion due to chemical attack and ignition of the combustion products within the burner. The large temperature difference between the arc and the combustion gases mean that a large proportion of the gas will by-pass the arc and it is only when
passing through the nozzle region that a significant amount of the reactants are heated (Chen et al 1965).

The addition of the combustion products downstream of the torch nozzle, Fig 3.14 b, increases the stability of the arc but the combustion intensity is controlled by the rate of mixing between the output of the plasma torch and the combustion flame.

3.6.2 Turbulence

Obtaining a diffuse discharge by means of turbulence, as proposed by Karlovitz (1962a, b) depends on the ability of such mixing to level.
out any local non-uniformities in temperature and electrical conductivity before they can develop and cause the arc to constrict.

Moving the arc by injecting gas tangentially at a high velocity can cause the arc to spin (John et al 1961) but the arc channel is stationary with respect to the gas. Large turbulent eddy currents also simply displace the arc and although the discharge may appear diffuse, in fact the same pockets of gas are being heated. Chen et al (1965) concluded that only when the scale of turbulence was comparable with the width of the arc channel would the discharge experience an increase in diffusivity that might disperse its boundaries. Turbulence, therefore, is most useful when used in conjunction with methods that widen the discharge channel, such as seeding.

3.6.3 Seeding

The electrical conductivity of a gas, in the temperature range usually associated with arc discharges (in excess of 5000 K), increases rapidly with an increase in temperature. Any slight increase in the temperature of one part of a low current diffuse discharge will cause a runaway effect tending to increase the conductivity and temperature in that region, thus causing the discharge to constrict and to take up a filamentary form.

Alkali metals and their compounds are more easily ionised than the constituents of common gases, (chapter 2.). When added in low concentrations to a flame the fraction of the atoms ionised can approach unity at temperatures several thousands of degrees below those at which any significant ionisation of the gas occurs. The conductivity of such a seeded flame is provided almost entirely by the seed material. Once all the seed material has been ionised the
temperature coefficient of conductivity of the flame has a relatively low value and the tendency of a discharge to adopt a constricted form is reduced.

The choice of seed material is largely dependent on economic factors and a great deal of work has been carried out to assess the most practical material (Ellington et al 1966). The properties of potassium relevant to its use as a seeding material are only slightly inferior to those of caesium. Potassium is much cheaper and more easily available than caesium and is therefore the most commonly used seed material.

Discharges in seeded combustion products have been investigated by high speed photographic techniques (Chen et al 1965). Small concentrations of caesium chloride acted as the seed material, $1.4 \times 10^{-6}$ kg/s per kW of input power being required. The discharge always occupied less than 25% of the cross-sectional area of the flame. In these experiments, as with previous ones (Marynowski et al 1967), seeding was only successfully accomplished if the arc was struck well down-stream of the combustion zone thereby enabling the seed material to be vaporised and uniformly dispersed prior to entering the discharge region.

The conductivity of a seeded flame is determined not only by the electron concentration and the collision cross-section for electrons with neutral atoms in the gas, but also by the collision cross-section for electrons with the neutral and ionised atoms of the seed material. In the temperature range applicable to augmented flames, 2000 K - 5000 K, the collision cross-section for electrons with neutral atoms of the seed material is orders of magnitude greater than the collision
cross-sections for electrons with neutral atoms of common gases (Rosa 1961, Zimin et al 1963 a, b, Ellington et al 1966, Marlin-Smith et al 1966). Consequently although the electron concentration is increased with the introduction of the seed material, more electron-scattering occurs due to the larger collision cross-section between electrons and seeding atoms. These opposing effects mean that an optimum composition for the mixture exists, dependent on the gas temperature and pressure. More recently, this phenomenon has been demonstrated in seeded flames augmented by radio frequency power (Johnston et al 1973). Measurements of power input and temperature along an r.f. augmented flame reactor have shown that at low seed concentrations, less than 0.015 %, the electrical conductivity of the reactants passes through a maximum. At a seed concentration of 0.0015 % the maximum occurs at approximately 3500 K which is within the temperature range required by many industrially important processes. It is possible, theoretically, that this phenomenon could be applied to the production of augmented flames with electrical power input uniformly distributed within the flame. Once a uniform temperature is attained corresponding to the maximum electrical conductivity then any local instabilities within the discharge would not tend to contract the arc. Large volume moderate temperature plasmas produced using this phenomenon are anticipated (Johnston et al 1976, 1977), but as yet, have not been achieved experimentally.

3.6.4 The Use of Magnetically Rotated Arcs to Augment Flames

Magnetically rotated arc heaters have been reviewed previously, chapter 3.5. A system adapted to produce an augmented flame has been studied (Chen et al 1965) by placing a coil co-axially around
the exit nozzle of a plasma jet device similar to that shown in Fig 3.14 a. Relatively small magnetic fields can cause a d.c. arc to spin at high velocities (approximately 1500 Hz) increasing the heat transfer to the combustion products. High speed photographic techniques show that the discharge formed is not diffuse although flame stability and combustion intensity are improved (Chen et al 1965).

3.6.5 Augmentation of Flames by R.F. Power

Induction coupled discharges are typically of far larger volume than that associated with d.c. or low frequency a.c. discharges and consequently the application of this type of discharge to augment a combustion flame could enhance the distribution of electrical energy within the flame.

The first attempt to use an induction coupled discharge to augment a combustion flame proved unsuccessful because of the instability of the discharge in the presence of the combustion reactants (Chen et al 1965). The presence of 0.14% of ethylene by volume was sufficient to extinguish an otherwise stable plasma.

More recently, interest in the possibility of augmenting flames with an induction coupled discharge has been renewed (Johnston et al 1971). The system shown schematically in Fig 3.15. has produced temperatures in the range of 3500 K and typical temperature profiles obtained are shown in Fig 3.16. (Johnston et al 1973). The air-propane flames were seeded with small concentrations, approximately 0.1%, of potassium sulphate with 10% sodium carbonate and augmented with various amounts, up to 3.3 kW, of r.f. power at a frequency of 3 MHz.
The temperature of the r.f. augmented flame is substantially below that normally associated with an r.f. discharge and as the products of combustion will already be at a relatively high temperature, about 2000 K, the problem of the reactants by-passing the hottest regions (Lawton 1967, Johnston et al 1976) will be significantly less than in the case of cold reactants feeding into a conventional induction coupled discharge. Assuming that the r.f. augmented flame
occupied 60 % of the flow area and raised the temperature of the reactants from 2210 K to 3000 K then following the analysis put forward by Lawton (1967) approximately 50 % of the gas would enter the discharge region, whereas only 15 % of cold reactants would enter an r.f. discharge, occupying the same flow area but at a temperature of 16 000 K (Johnston et al 1976).

Fig. 3.13 Temperature profiles within an r.f. augmented flame (Johnston et al 1973)
The use of r.f. augmented flames suffers, however, from many inherent disadvantages. The electrical equipment needed to supply power at frequencies at present associated with r.f. augmented flames (1 MHz and above) is much more expensive and far less efficient than d.c. or low frequency a.c. supplies. The discharge formed is far less stable than a d.c. discharge both in respect of the flow rate and flow pattern available and in the presence of combustion products. Finally, the production of a large volume of uncontaminated plasma is one of the advantages associated with induction coupled plasmas, but this would be completely negated because of the presence of the combustion products and the seeding material some of which are of an extremely corrosive nature.

3.6.6 Concluding Remarks on Electrically Augmented Flames

A commercially viable heat source using a combination of combustion flames and electric discharges to produce a temperature of approximately 4000 K has not been achieved, and no industrial process using such devices that do exist are known.

The major problem associated with augmented flames, that of uniformly distributing the electrical power input throughout the flame has not been solved satisfactorily. Even so, the heat transfer from the systems developed at present is greater than combustion systems alone (Davis 1965, Fells et al 1968a, b). The magnetically rotated arc augmented flame device is the most promising of the d.c. or a.c. systems investigated because of its increased combustion intensity, improved arc stability and elimination of the need for seeding with its product contamination effects.
The use of induction coupled discharges to augment flames suffers many of the disadvantages associated with d.c. augmented flame systems including reactant by-passing, the need for seeding and poor arc stability. If, however, large volume plasmas can be generated at much lower operating frequencies in the range of the static inverter system (<10 kHz), then substantial savings can be made in the capital and running costs envisaged for such a system.

Finally it should be noted that much of the work on augmented flames was instigated prior to 1973. Since this time the industrialised nations have been forced to recognise the forthcoming shortages in liquid and gaseous fuels and the insecurity of their supply and price even in the short term. The economic arguments put forward to initiate research into augmented flames is now not nearly so clear cut.

3.7 The Induction Coupled Plasma Torch

The characteristics of induction coupled discharges at atmospheric pressure were investigated as early as 1947 (Babat) but little progress was made until 1959 when Scholtz developed a high temperature induction coupled plasma torch. The device was operated at 27 MHz and included an earthed electrode on the axis of the discharge. Reed (1961a) using a similar device, found that the electrode could be removed once the discharge was ignited thus creating a high temperature electrodeless induction coupled plasma torch.
3. 7. 1 Construction of an Induction Coupled Plasma Torch

The essential components of an induction coupled plasma torch include a refractory tube through which the gas flows, a high frequency power source, which supplies energy to the discharge by means of a work coil surrounding the tube, and a discharge initiating device.

The use of a single refractory tube to surround the discharge is confined to very low power levels, up to 5 kW, and higher power levels necessitate the use of forced cooling to prevent destruction of the tube. Sheath gas operation has been used at powers up to 10 kW (Gray et al 1966), and simple water cooled torches at powers up to 50 kW (Marynowski et al 1963). Attempts have been made to increase the efficiency of water cooled torches by immersing the work coil in the water which cools the discharge tube and by the addition of sheath gas cooling with operating powers in excess of 100 kW achieved (Thorpe 1966a, 1968). For very high power operation, up to one megawatt, the use of segmented wall water cooled metal tubes is preferred to refractory tubes. (De Bolt 1963).

All induction coupled discharges are inherently unstable and some form of aerodynamic stabilisation is always required. The use of sheath gas (Reed 1961 a) and magnetic stabilisation (Marynowski et al 1963,) has been attempted but by far the most common form is vortex stabilisation (Mironer et al 1963). Introducing the gas tangentially forms a vortex flow which produces a low pressure region on the axis thereby locating the discharge. This method has disadvantages if the induction coupled plasma torch is to be used in the spheroidization of refractory materials, the growth of single crystals or other applications requiring the processing of powders.
within the discharge region. Obtaining predictable particle residence times and high feed rates are the major problems (Charles et al 1970).

The majority of power supplies used in the production of induction coupled plasmas have worked at frequencies above one megahertz and therefore require the use of an r.f. valve oscillator. The characteristics of this type of oscillator vary with the output power level as does the effective tank circuit impedance. This means that the theory of load matching is highly complex and to date no rigorous solution for a plasma load is known (Freeman et al 1968, Mensing et al 1969, Sprouse 1970). Load matching transformers have been used in attempts to improve the efficiency of power transfer but have not been successful, making discharge initiation more difficult and in certain cases impossible (Reed 1967, Thorpe et al 1968).

The discharge can be initiated, usually in an argon atmosphere, by various methods including the application of a Tesla coil (Gray et al 1966); inductively heating a conductor of refractory material to a temperature at which the thermal emission of electrons becomes sufficient to cause breakdown (Reed 1961a); low pressure breakdown of the gas and subsequent increase in pressure to the operating value (Eckert et al 1968, Vogel et al 1971); and pilot arc techniques. Pilot arcs using a d.c. plasma jet and the output from an auxiliary induction coupled plasma torch exhausting into the discharge have been used (Floyd et al 1966, Vermeulen et al 1966, Thorpe 1966b), as have arcs between two axially mounted electrodes (Reed 1961a). This last technique was amongst the first to be used and the one adopted for use in the torch described in chapter 5 because the presence of a d.c. arc is fundamental to this work.
3.7.2 Application of the Induction Coupled Plasma Torch to Industrial Processes

The induction coupled plasma torch has advantages over other plasma devices in that it produces a relatively large volume of uncontaminated, high temperature gas in either inert or reactive atmospheres. Its large scale industrial application has been hindered, however, by the complex and inefficient processes used in plasma generation and the high capital costs involved.

The industrial uses proposed for this type of plasma torch include spectroscopic sources (West et al 1964, Wendt et al 1965), the growth of crystals (Reed 1961b), the spheroidization of refractory materials (Hedger et al 1961), and use in chemical and metallurgical synthesis (Reed 1967, Sayce 1971).

As a spectroscopic source the induction coupled discharge possesses a wide range of exciting energies, a low background level, high sensitivity and good stability due to the low gas throughputs and small amount of particle entrainment required. It is used in many laboratories especially where the detection of very low concentrations or isotropic analysis is required (Dickinson et al 1969, Boumans et al 1973).

Reed (1961b) described the growth of crystals of various refractory materials in an induction coupled plasma torch by a method based on that developed by Verneuil (1904). Since that time the variety of materials processed has increased (Alford et al 1967, Poole et al 1971) but it should be stressed that the torches used were only of a laboratory scale and that no scale up of the process has been attempted.
Spheroidized particles of refractory material can be formed by passing through an induction coupled plasma torch and are of interest in such varied applications as nuclear reactors (Amato et al. 1967), reflecting silica beads (Dundas et al. 1970a) and ink transfer in photocopiers (Anon 1970, Dundas 1976). No industrial scale use of induction coupled discharges for spheroidizing particles can be found in the literature, however, mainly due to the relatively low feed rates attainable without extinguishing the discharge (Charles et al. 1970) and the difficulties in particle entrainment into the hottest regions of the plasma (Waldie 1972a, b). The magneto-hydrodynamic forces within the discharge (Chase 1969, 1971), chapter 2.5, cause the high temperature viscous plasma to stream away from the central zones. Unless the powder is projected into the plasma with sufficient momentum or alternatively fed through a cooled probe into the centre of the discharge, the particles tend to by-pass the discharge and travel in the colder layers of the gas.

The greatest interest in the induction coupled plasma torch has been in its possible use in chemical and metallurgical synthesis. The potential of plasma chemistry lies in the use of the high energy content and high temperature of a plasma, or where it is used as a source of positive and negative ions which take part in the reaction. The induction coupled discharge has advantages over other plasma devices. The absence of internal electrodes facilitates operation in corrosive or oxidising media and avoids the risk of contamination from electrode materials. The residence time of feed materials is greater in an induction coupled plasma torch than in a d.c. plasma torch, because of a lower overall gas velocity and a larger plasma volume. Various chemical and metallurgical process that could, perhaps, be carried out in an induction coupled plasma torch have been extensively reviewed (Parsons et al. 1970, Hamblyn 1977).
Little success has been achieved, however, in attempts to vaporise solid feed materials within the discharge region itself (Warren et al 1965, Huska et al 1967, Charles et al 1970). Not only did the double vortex flow pattern within the discharge, chapter 2.5., hinder particle entrainment but throughput rates were also limited to very low levels if the discharge was to be maintained. For example, the enthalpy of argon at $10^4$ K is approximately 8 MJ kg$^{-1}$, Fig 2.5, whilst the enthalpy of the majority of solid reactants may be an order of magnitude larger (Audsley et al 1969). The introduction of large amounts of solid reactants into the discharge region could not be tolerated, therefore, as this would require an immediate and significant increase in power output from the high frequency generator.

Certain reactions may be effected in the tailflame of the induction coupled discharge (British Titan Products Ltd 1969, 1970) in which case the problems of particle entrainment and low feed rates are significantly reduced. Feed rates of up to twenty times more through the tail flame than through the discharge itself have been reported (Audsley et al 1969). The heat transfer rates and residence times are, however, significantly reduced and in industrial processes it is unlikely that the higher capital costs and lower efficiency associated with induction coupled plasma torches can be offset by the operational advantages that remain.

Attempts have been made to carry out various gas phase reactions including the production of acetylene and hydrogen cyanide (Stokes et al 1965), and nitric oxide (Margrave et al 1965). Although disappointing yields have been attained in the majority of cases largely due to the products by-passing the hot zone, the reduction of boron chloride is carried out on an industrial scale to produce small quantities of boron metal of high purity and fine particle size (Hamblyn et al 1970).
High power induction plasma torches have been made and are commercially available at powers up to one megawatt (Dundas et al 1970a). The torch is operated at 450 kHz, and produced a discharge of between 75 mm and 150 mm and uses a segmented metal wall water cooled surrounding tube to withstand the high heat fluxes involved. The device was proposed for titanium dioxide pigment production (Dundas et al 1970b), as have various other torches, for example (British Titan Products Ltd 1969, 1970), but no details of any large scale industrial application of this type can be found in the literature.

3.7.3 Low Frequency Induction Coupled Plasma Torches

The majority of induction coupled plasma torches have operated in the frequency range of 4 MHz and above. The r.f. valve oscillators used to generate these frequencies involve expensive equipment with low efficiency of power transfer. The total efficiency of conversion of a.c. input power to r.f. power is typically less than 50%. A static inverter or motor generator system, operating in the 1 kHz to 10 kHz range, requires a capital expenditure per kW of output power substantially below that of an r.f. oscillator and the efficiency is increased to approximately 95%. The commercial viability of any large scale industrial application would be enhanced, therefore, if the operating frequency could be reduced to within the range of the static inverter or motor generator set, whilst still retaining the advantageous characteristics of the higher frequency discharge.

At high frequencies the magnitude of the radial temperature differences is relatively small, there being only a 7% difference in the maximum and minimum temperatures in an induction coupled discharge in
argon at 4 MHz with an axial temperature of $10^4$ K (Ebihara 1973). Low frequency and high power operation produces an increase in the diameter of the discharge, chapter 2.5., and an increasing proportion of the radiation from the axial regions is absorbed within the discharge and the non-uniformity in the radial temperature distribution is increased (Vogel et al 1971).

There have been a small number of successful attempts to work at lower frequencies. The operation of a stable torch at 280 kHz has been reported (Floyd et al 1966) using a 20 kW power generator and a relatively large work coil isolated from the plasma by a tube 65 mm in diameter. An axial stream of argon was used and the discharge initiated from a secondary r.f. plasma operating at 4 MHz upstream of the low frequency coil. Dymshits et al (1965) produced a stable plasma working at 290 kHz to 3.3 MHz over a range of tube diameters, 15 mm to 45 mm, and gas pressures $2 \times 10^3$ Pa to $2 \times 10^5$ Pa. Although full details are not given it is believed that a low pressure system was used in the initiation of the discharge. The use of high power output generators increases the possibility of a reduction in the operating frequency of the discharge. A generator with an output power capability of 200 kW was used by Cannon (1962) in conjunction with a low pressure system to aid initiation. Calorimetric energy balance measurements estimated that stable discharges were maintained at 400 kHz with a power input of only 50 kW. Thorpe et al (1968) operated torches in argon, nitrogen, hydrogen and oxygen at frequencies down to 450 kHz using power supplies up to 1 MW and tube diameters up to 250 mm.

Reducing the operating frequency to between 200 kHz and 450 kHz does not reduce the cost of generating the power or increasing the efficiency as the process of power generation over this range of
frequencies is essentially the same as in the megahertz range. Preliminary attempts to operate a torch in argon at frequencies of 10 kHz and 1 kHz have been reported in efforts to simulate a gas-core nuclear reactor (Vogel et al. 1971). At 10 kHz a power source of 450 kW was used with a tube diameter of 175 mm. Unsuccessful attempts were initially made to couple the 10-kHz power into a pilot arc between two electrodes. The pilot arc was inserted in the torch and supplied by a 40 kW d.c. power supply with an open circuit voltage of 160 V. A low pressure glow discharge technique was later adopted to initiate the discharge. It was found to be impossible to sustain the glow discharge with the 10 kHz power source alone, even at power as high as 350 kW, without the addition of steel laminations on the outside of the coil to reduce its leakage reactance. The ignition of the 10 kHz plasma torch with laminations was performed at pressures of 100 Pa to 200 Pa in argon and once the thermal arc was obtained it was possible to raise the pressure in the torch to $10^5$ Pa. The minimum sustaining power found in these experiments was 145 kW.

Further work was carried out at an even lower frequency of 1 kHz (Vogel et al. 1971). A low pressure glow discharge technique was again successfully used to initiate the discharge at powers as low as 475 kW. However, it was not possible to raise the operating pressure of the torch above $4 \times 10^4$ Pa, even though power supplies up to 1.25 MW were used.

Application of devices of this frequency range to large scale chemical and metallurgical processes has been proposed (Dundas et al. 1969, Wilks et al. 1970, Rykalin 1976). No industrial use of such devices is known, however, largely due to the high capital costs relative to carbon arc or d.c. plasma systems (Dundas et al. 1969) and also
the difficulties encountered at these low frequencies of discharge initiation and temperature non-uniformity (Harry et al 1975).

A cylindrical geometry is normally associated with induction coupled plasma torches but discharges requiring only a few kilowatts of power at frequencies well into the audio range have been formed using a toroidal discharge geometry (Smith 1941). In this case a magnetic core was used to improve the coupling between the discharge and the power supply. An induction coupled discharge in the glow discharge regime was maintained in mercury vapour using power obtained directly from motor generator sets at a frequency of 900 Hz.

Laboratory experiments are being carried out to produce an induction coupled discharge at an operating frequency of 1 kHz using toroidal geometry (Shepherd et al 1974). The apparatus consists essentially of a conventional transformer with a laminated iron core and primary winding, but the secondary winding has been replaced by a discharge contained within a torus shaped glass vessel. Energy dissipation has been increased within the furnace region by discharge constriction, using annular discs within the glass tube, and by the addition of nitrogen. Only low pressure, less than 10 Pa, and low power operation has as yet been achieved with this device.

A similar configuration has been used elsewhere (Eckert 1971, 1974) and high pressure, high power operation has been achieved at frequencies as low as 60 Hz. The pressure of the argon within the glass vessel was initially reduced to approximately 10 Pa and breakdown of the gas was provided by a 1200 V d.c. source which produced a glow discharge. An induced field of 300 V/m created by the high frequency power source was sufficient to couple into the glow discharge and cause a significant change in the light output.
Glow and arc discharges at pressures up to $8 \times 10^4$ Pa have been generated in argon at 9600 Hz when using laminated iron cores of $10^{-2} \, m^2$ cross-section and currents within the discharge in excess of 100 A have been obtained (Eckert 1971). Increasing the cross-section of the laminated iron core to $4 \times 10^{-2} \, m^2$ enabled the use of mains frequency (60 Hz) power and operation at pressures up to 500 Pa was accomplished (Eckert 1974b). The application of this device to the production of hydrazine from gaseous ammonia gave disappointingly low yields, caused it was suggested, by the inability to effect a sufficiently fast quench on the products of reaction or to extract the hydrazine from the discharge region. It is understood that research concerning this device has now ceased (Eckert 1978).

3.7.4. The Combination of d.c. and High Frequency Discharges

A limited number of investigations have been made into the feasibility of combining a high frequency and a d.c. discharge. The superposition of a d.c. arc between two axially mounted electrodes and a high frequency discharge was reported by Reboux (1963a). A 300 A, 15 kW d.c. arc was superimposed on a 3 kW induction coupled discharge operating at 7 MHz in argon. A visibly detectable expansion of the discharge took place on the addition of the d.c. arc and a larger torch was subsequently constructed with a 50 kW output, of which only 7 kW was taken from the r.f. supply (Reboux 1963b, Galtier et al 1963). In all cases the d.c. power was superimposed on an already existing induction coupled discharge and no information regarding the coupling of r.f. energy into the d.c. arc could be obtained. The major advantages sought from this device were increased discharge stability and power input, which were achieved and research into this device ceased shortly after the work was published (Foëx 1975).
Radio frequency power at 4 MHz was coupled into a plasma jet issuing from a d.c. plasma torch (Vermeulen et al 1966). An analysis was given showing that the temperature distribution could theoretically be controlled by varying the frequency of the electromagnetic field and that an approximately uniform temperature distribution in the plasma may be obtained. Experimental verification was inconclusive, largely because of the misinterpretation of the spectroscopic data (chapter 2.6.). It was also reported by Thorpe et al (1968), that enhancement of a d.c. discharge between two electrodes could be observed by an increase in the luminosity, when the r.f. power at an operating frequency of 4 MHz was coupled to the discharge. This work was carried out as part of a government contract to investigate induction coupled discharges in hydrogen atmospheres and although the economic advantages of obtaining a large volume discharge using d.c. power as the major source of power input were postulated, no further research in this direction has been published by these workers.

A mathematical model of the coupled d.c. and induction coupled discharge has been put forward (Schreiber et al 1973). Calculations based on this model indicated that a coupled discharge could generate a plasma zone of more uniform temperature than could be obtained with either a d.c. or an induction coupled discharge alone. This model did not, however, give an insight into the process of initiation of the discharge or its stability.
3.8 Summary of the Characteristics of Arc Heating Devices Proposed for Use in Chemical and Metallurgy Synthesis

The design of plasma reactors for chemical and metallurgical synthesis has major problems, including the reactant by-passing the discharge region, the non-uniformity of temperature, and the overall control of residence time and quench rate.

Gases approaching a discharge expand due to the rise in temperature, causing the flow lines to diverge and hence a large proportion of the gas will by-pass the heated region which behaves as a viscous semi-impermeable medium. Using the mass, momentum and energy balance equations, an estimate can be made of the fraction of the gas entering the discharge zone as a function of the temperature and the fraction of the flow area occupied by the discharge. For example, in an arc of 2.9 kW input power burning in an axial flow of air, mass flow rate $2.17 \times 10^{-3}$ kg/s, and filling approximately 50% of the cross-sectional area of the reactor, only 10% of the gas is estimated to enter the luminous zone (Lawton 1967).

Arc discharges usually incorporated in high power reactor design have to be stabilised by aerodynamic or magnetic methods, or by thermal constriction of the arc in a narrow passage through which the gas flows. High energy losses can therefore be incurred, especially if constriction is used to stabilise the discharge, and an extreme non-uniform temperature distribution is formed with temperature gradients of the order of $10^3$ K/mm.

In chemical synthesis where the rates of reaction and the concentrations of different species are sensitive to the temperature, the reactants by-passing the discharge and the non-uniform
temperature distributions can reduce the expected product yields substantially. Various methods have been investigated to improve the uniformity of the temperature distribution in the reaction zone of a plasma in thermal equilibrium and to limit the amount of reactant by-passing the hot zone. The problem has been approached in two ways; the arc has maintained its inherent constricted form and the uniformity of heat transfer increased by means such as magnetic rotation of the arc, or attempts have been made to obtain a large volume, uniform temperature plasma or diffuse discharge.

High voltage arc heaters are characterised by their high working voltage, long arc length and relatively low arc current. The discharge chamber is small in order to stabilise the long arc and because of the large interior surface of the heater exposed to the arc high losses to the walls of the torch are incurred. This type of arc heater can be used in the transferred mode where the relatively low electrode losses, due to the low arc current, and the high arc temperatures associated with this device may be advantageous. High efficiencies are claimed when operating in the transferred mode as the overall length of the transferred arc is many times the length of the arc column within the heater.

Plasma torches, based on those commonly used in industry for welding and cutting, have found little industrial application for chemical processing when used in the non-transferred mode. The steep radial temperature and viscosity gradients especially associated with this type of arc heater have reduced the product yields because of the difficulties in the particle entrainment into the discharge region and because of the short residence times due to the high gas velocities used. The entrainment of particles into the discharge region can be increased by feeding the particles into the arc just above the cathode.
region thereby making use of magneto hydrodynamic forces to draw the particles into the discharge region. This method of particle injection is often referred to as a forced convection cathode.

The use of a d.c. plasma torch in the transferred mode has been proposed for a number of applications including metal melting. Precessing the plasma torch in this mode increases, it is claimed, the arc stability and the heat transfer to any particulate feedstock.

Enhanced thermal contact between the plasma and solid reactants can be achieved in a centrifugal plasma furnace which can be heated by d.c. plasma torches in either non-transferred or transferred modes. This type of furnace is not suitable for continuous material throughput and additional losses are encountered in rotating the furnace.

Three phase carbon arc heaters have been used industrially for the production of acetylene since 1963 and similar units are employed in the Ionarc process for small scale plasma treatment of ores. The Ionarc process uses consumable carbon electrodes but commercial units are available using water-cooled copper electrodes or d.c. plasma torches to replace the carbon electrodes. Particle entrainment into the hottest regions of the discharge is still a major problem when using these devices. In a three phase arc system the position of the three discharges relative to each other and to the central axis of the reactor is unstable leading again to excessive reactant by-passing and low product yields. Increased stability can be achieved by use of three d.c. transferred arcs between three separate d.c. plasma torches acting as anodes and one central d.c. plasma torch acting as the common cathode. Although a relatively large stable volume of plasma was produced and a forced convection
cathode system of particle injection used to enhance particle entrainment into the discharge, the problems of reactant by-passing and poor particle entrainment were still significant. As yet the product yields have been too low and specific power consumption too high for any commercial acceptance of this process.

Magnetically rotated arc heaters are commercially available and have been used on a pilot plant scale for the production of acetylene, ferrochrome, spheroidization of magnetite grit and for the production of liquid silicon. Small arc lengths are associated with this type of arc heater allowing the use of a.c. power but reducing the residence times available. This type of arc heater still has the problems of poor particle entrainment and excessive reactant by-passing but it can produce high heat transfer rates due to the production of free stream turbulence and rapid rotational gas flow.

The augmentation of a combustion flame by electric discharges has been investigated but as yet no industrial process using such a device is known. High heat transfer rates have been obtained using a magnetically rotated arc augmented flame device and this has the most commercial potential. However the problem of uniformly distributing the electric power input throughout the flame has not been solved.

The induction coupled discharge is the only form of plasma device which produces a relatively large diameter diffuse discharge and is capable of high power operation. Commercial exploitation has been hindered however by problems of particle entrainment due to the double vortex flow pattern, poor discharge stability and the need for expensive and inefficient r.f. valve oscillators if the operating frequencies usually associated with induction coupled discharges (above 1 MHz) are used.
Low frequency operation (below 10 kHz) within the range of the more efficient and less expensive static inverter power supplies has been achieved but only under research conditions because of the large power requirements and the problems encountered in discharge initiation. At operating frequencies of 1 MHz and above the axial temperature of an induction coupled discharge is less than 10% below the maximum temperature. Low frequency operation increases the diameter of the discharge and the non-uniformity of the radial temperature distribution. Incorporating a d.c. discharge along the central axis of a low frequency induction coupled discharge would reduce this temperature non-uniformity. The combination of an induction coupled discharge and a centrally mounted d.c. arc has only been briefly investigated using high operating frequencies. The stability of the combined device was however significantly better than the induction coupled discharge alone and a relatively large volume of plasma was formed with more than 80% of the input power taken from the d.c. source. A combination of a low frequency induction coupled discharge and an axially positioned d.c. discharge could therefore reduce the disadvantages associated with the industrial application of induction coupled plasmas and was worthy of further investigation.
CHAPTER 4

Preliminary Investigations and Analysis

The purpose of the preliminary investigations was to ascertain the main factors which influenced the coupling of d.c. and high frequency discharges. An analysis of the efficiency of coupling between d.c. arcs and an r.f. power source operating in the H type mode was developed and high frequency discharges operating in the E type mode were investigated experimentally.
4. Preliminary Investigations and Analysis

There are two different modes of operation for high frequency discharges which depend on the method of coupling energy from the oscillatory circuit. Most of the published literature is concerned with high frequency discharges operating in the H type mode i.e. induction coupled discharges, which are used on a laboratory scale for spherodizing particles, spectroscopic sources and chemical processing. Initial investigations into the combination of d.c. arcs and high frequency discharges were therefore associated with induction coupled discharges.

Operating frequencies of 4 MHz and above are common for induction coupled discharges although their future industrial use would be more likely if operating frequencies could be reduced to 10 kHz or below. Where discharges have been operated at low frequencies, larger diameter discharges have been formed necessitating the use of higher input powers. To investigate the formation of a large volume of ionised gas by the combination of d.c. power and high frequency power, below the megahertz range, requires a compromise between reducing the frequency by a significant amount whilst keeping the power needed within a laboratory scale. An r.f. frequency of 450 kHz was chosen as this provided a reduction in frequency of one order of magnitude from those normally associated with induction coupled discharges. The total discharge power requirements would then be of the order of 50 kW (Cannon 1962).

Induction coupled discharges operating at 4 MHz and above are commonly initiated by coupling the high frequency energy into a low current pilot arc or even a high voltage spark. The failure of the initial attempts to obtain efficient coupling of r.f. energy at 450 kHz
into relatively high current d.c. arcs, up to 100 A, was thus unexpected (Hobson 1974). A thorough analysis of the problem was therefore required before further progress could be made.

4.1. Analysis of the Coupling of R.F. Power in an H Type Mode into a D.C. Electric Discharge

The interaction of a conductor with an alternating magnetic field to ultimately produce heat within the conductor i.e. induction heating, is a common industrial process used for heat treatment, through heating of billets, metal melting and similar applications. The theory detailed in Appendix 1 is adapted from the theory of induction heating of metals. The distribution of the induced eddy currents is treated in terms of discrete circuit parameters which can be reflected into the primary circuit, that is the tank circuit of the vacuum tube oscillator, using transformer theory.

Previously theories have been developed to explain the phenomena associated with induction coupled discharges based solely on the coupling efficiency between the work coil and the plasma load. Using a pilot arc technique to initiate the induction coupled discharge means that the power source must be able to supply sufficient energy to the pilot arc to cause it to expand thus forming the discharge and also sufficient energy to sustain the larger diameter induction coupled discharge after its formation. The value of the tank circuit impedance varies with these two loading conditions, the range of variation increasing with a decrease in operating frequency. Little attention has been paid in the past to the effects of the mismatch between the tank circuit impedance and that required for maximum power transfer from the valve due mainly to the need to specify the particular work coil used.
To understand the problems associated with a reduction in the operating frequency, however, an overall coupling efficiency of the high frequency power source must be investigated. The overall coupling efficiency between an r.f. valve oscillator and a load \( \eta \), includes the efficiency of the high voltage transformer and rectifier \( \eta_1 \), the efficiency of power conversion from d.c. to a.c. within the valve \( \eta_2 \); the efficiency of power transfer between the valve and the tank circuit \( \eta_3 \), and the efficiency of power transfer from the tank circuit to the load \( \eta_4 \).

Commerclally used power transformers and solid state rectifiers have efficiencies of the order of 95% throughout their operating range and therefore have little effect on the overall coupling efficiency.

The efficiency of power conversion from the high voltage d.c. power input of a valve to the a.c. power output \( \eta_2 \), depends on the operating characteristics of the valve and the value of the grid bias voltage. In induction heating applications the valve oscillators are operated in Class C mode (May 1949, Simpson 1960) in which the conduction angle of the valve can vary typically between 20° and 180°. The efficiency of power conversion falls steadily from about 90% at a conduction angle of 20° to 66.7% at a conduction angle of 180°. However, the power output from the valve increases with the conduction angle and a compromise must be made between a large power output from a given valve and efficient power conversion. The conduction angle is usually designed, by means of the grid bias voltage used, to be in the range of 120° to 150° with an efficiency of power conversion of approximately 75% (May 1949).
A rigorous analysis of the efficiency of power transfer from the tank circuit of the induction heater to the plasma load $\eta_{T}$, would require the simultaneous solution of Maxwell's field equations and the energy equations. An energy balance of a discharge equates the rate of change of energy in a unit volume with the divergence of the heat transfer by conduction, the power radiated, and the electromagnetic power dissipated by the applied electric field. Because the electrical conductivity, thermal conductivity and radiation source strength are strongly dependent on temperature (Yos 1963, 1967, Emmons 1967,) these equations have to be solved numerically even in the simplest case of cylindrical symmetry and zero flow.

An analytical treatment of the problem can be made however by ignoring the axial electric field of the d.c. discharge (Appendix 1). The plasma is considered similar to a solid cylindrical conductor, that is with a constant electrical conductivity, along the length and across the cross-section, placed along the axis of the work coil. Experimental evidence exists supporting the use of this type of coupling model with a plasma load (Sprouse 1965, Keefer 1967). Assuming that the work coil makes up the whole of the tank circuit inductance then the variation of efficiency of power transfer from the tank circuit to the load $\eta_{T}$, and the ratio of tank circuit impedance $Z_{T}$, to oscillator output impedance $Z_{G}$, can be calculated for any work coil, operating frequency and workpiece electrical conductivity Fig 4.1., and Fig 4.2.

The efficiency of power transfer from the valve to the tank circuit $\eta_{3}$, is determined from the valve characteristics and load line
Fig. 4.1 The efficiency of power transfer from the tank circuit to a load as a function of the load diameter, electrical conductivity and operating frequency. The nine turn work coil was 80 mm long 80 mm in diameter.

and varies with the ratio of tank circuit impedance $Z_T$, to oscillator output impedance $Z_G$, in a manner similar to that predicted by the maximum power transfer theorem of circuit analysis, as shown in Fig. 4.3. The maximum power transfer to the tank circuit is
Fig. 4.2 Ratio of tank circuit impedance to oscillator impedance for various values of load diameter. The nine turn work coil was 80 mm long and 80 mm in diameter.
Fig. 4.3. Percentage of power transferred to the tank circuit for various ratios of tank circuit impedance $Z_T$ to oscillator impedance $Z_G$. 
obtained when the tank circuit impedance is equal to the oscillator impedance. However if this ratio only varies between 0.6 and 1.8 more than 90% of the maximum power is transferred to the tank circuit and the tank circuit is matched.

Operation of an induction heater in a grossly mismatched condition may lead to the valve failing to oscillate or to the overloading of the anode or grid circuits. Within these two limits, however, an estimate of the overall coupling efficiency can be made by neglecting the losses in the input transformer and solid state rectifier, assuming that the efficiency of power conversion within the valve $\eta_1$ is 75%, estimating the efficiency of power transfer from the valve to the tank circuit $\eta_3$ from Fig. 4.3 and calculating the efficiency of power transfer from the tank circuit to the load $\eta_4$ using the equivalent circuit analysis of Appendix 1.

The incorporation of the effects of a mismatch between the generator and the load increase the complexity of the analytical solution to the coupling of r.f. power into a load. Any induction heating problem can, however, be solved by the equivalent circuit technique, to give the efficiency of the power input to a load and guidance as to the correct operation of the generator, providing the dimensionless flux factors $P$ and $Q$ can be determined, (Appendix 1 and Chapter 2.3) and the details of the work coil are specified.

4.1.1. Work-coil Design

The induction heater used in these investigations was a Hyforce 12 kW unit with an output frequency range 340 kHz to 470 kHz and typical operating conditions of the valve and circuit values are shown in Table 4.1.
Typical Operating Conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anode voltage</td>
<td>7 kV</td>
</tr>
<tr>
<td>Anode current</td>
<td>2.25 A</td>
</tr>
<tr>
<td>Peak fundamental anode current</td>
<td>4 A</td>
</tr>
<tr>
<td>Peak voltage across tank circuit</td>
<td>5.95 kV</td>
</tr>
<tr>
<td>Max. power in tank circuit</td>
<td>12 kW</td>
</tr>
<tr>
<td>Dynamic load resistance</td>
<td>1490 Ω</td>
</tr>
</tbody>
</table>

Inductance of Series Tank Circuit \( (L_L) \)

<table>
<thead>
<tr>
<th>Turns</th>
<th>Inductance ( (\mu H) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>2.6</td>
</tr>
<tr>
<td>3</td>
<td>1.26</td>
</tr>
</tbody>
</table>

Permanent Series Tank Resistance \( (R_L) \)

<table>
<thead>
<tr>
<th>Turns</th>
<th>Resistance ( (\Omega) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>23.10^{-3}</td>
</tr>
<tr>
<td>5</td>
<td>16.10^{-3}</td>
</tr>
<tr>
<td>3</td>
<td>10.10^{-3}</td>
</tr>
</tbody>
</table>

Tank Circuit Capacitance \( (C) \) = 22.5 10^{-9} F

Table 4.1 Typical operating conditions of the valve oscillator used in chapter 4.1.

The power input to the work piece is proportional to the square of the work coil turns per unit length. For maximum power density the spacing between the turns must be kept to a minimum restricted by the necessity to avoid breakdown between the turns under working conditions. The work coils used with this generator are constructed from 6 mm O.D. water cooled copper tubes with a minimum spacing between turns, based on practical experience, of approximately 3mm.

The need to electrically insulate the discharge from the work coil requires the introduction of a refractory tube between the work coil and the discharge. Induction coupled discharges require their diameters to be in excess of 3.5 times the skin depth, chapter 2.5.1.
and therefore a discharge with an average temperature of 8000 K in argon would have a diameter of approximately 60 mm. The thickness of the refractory tubes and the need to water cool tubes where the heat transfer from the discharge would otherwise cause melting, restricts the ratio of the discharge diameter to work coil diameter to a minimum of 0.7 (Thorpe et al 1968). The minimum diameter of the work coil considered in this analysis is therefore 80 mm.

4.1.2. Results of Analysis of Coupling R.F. Power in H Type Mode into an Electric Discharge

The design of the initial work coils was based on calculations of the overall coupling efficiency into a load with an average temperature of 8000 K and a diameter of 60 mm. This load approximated to the steady state discharge expected when comparing induction coupled discharges at this frequency (Chapter 2.5.1.). Table 4.2. shows the calculations for typical work coils of diameters ranging from 80 mm to 150 mm and with the appropriate series matching inductances included within the tank circuit.

Using the same work coil configurations the analysis was then applied to a load with a constant electrical conductivity of 4500 S/m and a diameter of 8 mm which is the equivalent conductor developed in Chapter 2.3. for a 100 A d.c. arc in argon. The results, also in Table 4.2., show that the overall coupling efficiency was extremely small, less than 0.3 % and that the generator was operating in a severely mismatched condition.
Table 4.2 Results of analysis of coupling energy at 450 kHz from an induction heating work coil into axially mounted d.c. arcs.

The initiation of an induction coupled discharge by means of a low current pilot arc or high voltage spark discharge requires that sufficient power can be initially coupled into the outer regions of the auxiliary discharge to start a runaway expansion leading to the formation of the induction coupled discharge. The analysis has shown that using operating frequencies of 450 kHz or less, the initial coupling into an auxiliary discharge is less than 0.3%. In
order to successfully initiate an induction coupled discharge at 
450 kHz using a pilot arc technique, an induction heater is required 
with an output power many times that needed to sustain a steady 
state discharge.

This was therefore the reason for the failure of the initial attempts 
to achieve significant coupling between a r.f. power source at 450 kHz 
and d.c. arcs in argon up to 100 A (Hobson 1974).

The efficiency of power transfer between the tank circuit and a d.c. 
arc load, for any particular work coil geometry, may be increased 
by increasing the operating frequency of the r.f. power supply, the 
electrical conductivity of the d.c. arc or its diameter, Fig 4.1. The 
overall coupling efficiency, however, is also dependent on the matching 
between the tank circuit impedance and the output impedance of the 
r.f. generator, which in turn is a function of the work piece, the 
work coil and the coupling between them. Assuming that sufficient 
r.f. power can be coupled to a d.c. arc to form a large diameter 
combined discharge then the effective inductance of the tank circuit 
would be reduced whilst its effective resistance would be increased, 
thus reducing the tank circuit impedance.

Increasing the operating frequency from 450 kHz to 6.5 MHz 
increases the efficiency of power transfer from the tank circuit to 
the load by more than five times, and reduces the predicted diameter 
of the combined discharge, based on known diameters of induction 
coupled discharges at this higher operating frequency, to between 
30 mm to 40 mm. The range of values of the load matching 
parameter $\frac{Z_T}{Z_o}$ between initiation and steady state operation are 
subsequently reduced by up to an order to magnitude compared with 
those using an operating frequency of 450 kHz. Thus high overall
coupling efficiencies can be achieved at both the initiation of
coupling into the d.c. arc and when the larger diameter combined
discharge is formed if an operating frequency of 6.5 MHz is used.

Seeding a gas with small particles of easily ionisable material such
as sodium, potassium or caesium can increase the electrical
conductivity of the gas. If seeding is arranged to be predominantly
in the outer regions of an arc then the increase in electrical
conductivity there can effectively increase the diameter of the arc.
The introduction of seed material lowers the impedance of the arc,
decreasing the arc voltage, the voltage gradient and the temperature
of the arc column. Any increase therefore in coupling efficiency
brought about by an increase in the arc diameter has to offset the
decrease in coupling due to the lower electrical conductivity within
the central regions of the arc. The electrical conductivity of argon
seeded with potassium has a maximum of the order of 400 Sm\(^{-1}\) at
4000 K (Frost 1961). Assuming however, that the overall conductivity
of a seeded argon arc is 10\(^3\) Sm\(^{-1}\), i.e. that associated with the central
zones of an unseeded arc, then even if the effective diameter of a
100 A d.c. arc in argon was doubled by the use of seeding, the
analysis developed in this chapter shows that the overall coupling
efficiency would still be less than 5\%. Therefore, little advantage
is indicated if seeding is used to enhance the overall coupling
efficiency when using a pilot arc technique to initiate an induction
coupled discharge. Contamination of the products of any chemical
synthesis carried out in a seeded arc is also an inherent and severe
restriction of its use. It is more suitably applied to arcs augmenting
combustion flames where the contamination due to the seed material
is small when compared with that from the combustion products
themselves.
The diameter of a d.c. arc can be increased by the reduction of the working pressure, the elimination of the convection effects in the outer regions of the arc and by increasing the arc current. The diameter of an arc is inversely proportional to the working pressure and low pressure initiation techniques have been used successfully with low frequency induction coupled discharges (Dymshits et al 1965, Vogel et al 1971). Construction of the torch would, however, be increased in complexity and if continuous operation at low pressures is envisaged then high throughput vacuum systems would have to be used so that commercially viable throughputs of material could be obtained.

The elimination of convection effects in the outer regions of the arc is the basis on which the rotating wall plasma furnace (Whyman 1967) was designed. Such a device could in principle be useful in the initiation of a d.c. and r.f. coupled discharge at low frequencies, but the rotating wall furnace suffers from disadvantages (Chapter 3.4.) limiting the possibility of scaling up this process to powers and reactor sizes required by industrial applications.

For arc currents between 100 A and 400 A experimental evidence exists (Nicolai 1970) which indicates that the diameter of an arc is approximately proportional to the square root of the arc current. However overall coupling efficiencies of less than 10 % are predicted by the analysis for arc currents up to 400 A in argon and an operating frequency of 450 kHz. Whilst it may be possible to achieve efficient coupling of r.f. energy at 450 kHz if a sufficiently high current power supply, in excess of 2000 A, could be used, scaling up this method such that efficient coupling at frequencies low enough for the use of the more efficient static inverter power supplies would not be practical.
The major problem of initiation of a low frequency induction coupled discharge is the need to produce a sufficiently large volume of ionised gas into which the r.f. energy can be initially coupled. Excepting the inherent filamentary form of a single d.c. arc, one method of producing a large volume of ionised gas would be to combine a number of single arcs into a multiple arc system. Such systems have been developed and are used in 3 phase arc furnaces, mercury arc rectifiers and plasma torch furnaces with two or more torches supplied from separate power supplies, chapter 3. All of these systems use separate arcs with only one common electrode or point of coupling. To produce a large integral volume of ionised gas it is necessary that the arcs should mix but interaction between the arc supply circuits is known to occur causing instability (Hoyaux 1968).

However, the use of a multiple arc system to produce a large volume of ionised gas into which r.f. power can subsequently be coupled has distinct advantages over the other methods proposed. Contamination of the discharge is confined to that produced by electrode evaporation, atmospheric pressure operation can be used, and the power input and volume of the discharge can readily be scaled up by an increase in the number and separation of the power sources used.

Fundamental investigations were therefore carried out on two parallel fronts.

1. An r.f. power source operating at a frequency of 6.5 MHz, (to avoid any initiation problems) was used in combination with d.c. arcs in argon to form a large volume discharge. The characteristics of a combined discharge were then investigated, experimental verification of the analysis developed in this chapter was carried out,
and design criteria for a discharge vessel suitable for a combined discharge was established (Chapter 5).

2. A study of the interaction of d.c arcs within multiple arc systems was carried out so that a large integral volume of ionised gas could be produced enabling efficient coupling of r.f. energy at relatively low frequencies (Chapter 6).

4.2: The E Type Mode of High Frequency Discharge

An alternative form of high frequency discharge also exists which has an axial electric field and current flow and operates in what is known as the E type mode (Chapter 2.5). A simplified analysis (Mironer et al 1963) of this form of discharge shows that at high frequencies power generation occurs in the outer regions of this discharge, as in the H type mode of operation. When considering the combination of high frequency and d.c. discharges, however, the coupling efficiency from the high frequency power source to the discharge in this case is directly proportional to the ratio of the resistance of the discharge and the resistance of the connecting leads. The resistance of the discharge can be easily increased by various means including increasing its length. Hence efficient power transfer to the discharge formed in the E type mode can be obtained at any operating frequency.

Little information is available on the E type high frequency discharge, particularly at pressures approaching atmospheric and at discharge powers of several kilowatts. As a result the preliminary investigations would not be complete without an assessment of the applicability of high frequency discharge in the E type mode with or without the
superposition of a d.c. arc to form a large volume of ionised gas.

The principal parameters which govern the production of a high frequency device working in the E type mode are:

(i) the power input required to sustain the discharge,
(ii) the operating frequency,
(iii) the working pressure of the system.

An estimate of the power input required to maintain an E type high frequency discharge up to atmospheric pressure was obtained from an analysis of an a.c. column initially put forward by Edels et al (1965) and later adapted for high frequency discharges by Eckert (1971) (Chapter 2.5). The power dissipated per metre length $P_L$ from an arc column in a cylindrical discharge tube is

$$P_L = 7.84 \ S_0 \quad (4.1)$$

In an argon plasma at atmospheric pressure and a temperature of $10^4 \ K$ the value of the heat conduction potential on the axis $S_0$ is equal to $2.06 \ kWm^{-1}$ (Emmons 1967). The maintenance of a 300 mm long discharge requires therefore of the order of 5 kW power input.

The conductance of a low frequency a.c. discharge changes during each cycle and will become zero over part of each cycle if the decay time of the discharge is small. However, a.c. discharges in argon at atmospheric pressure attain an approximately constant conductivity at frequencies above 1 kHz. An operating frequency of 450 kHz was therefore chosen so that a direct comparison could be made with the results of experiments carried out with high frequency discharges operating in the H type mode (Hobson 1974).
The system was designed to be capable of working over a range of gas pressures from below 50 Pa up to atmospheric pressure. This enabled the discharge to be initiated more easily and its characteristics to be studied over this pressure range.

As no other data was available on typical discharge diameters the initial choice of a 70 mm internal diameter discharge tube was based on that suitable for use with induction coupled discharges at 450 kHz and atmospheric pressure.

4.2.1. Initial E Type Discharge Assembly

The discharge vessel shown in Fig 4.4 consisted of a 300 mm long cylindrical glass tube of 70 mm internal diameter and enclosed at either end by a brass electrode. Argon was fed to a gas plenum chamber constructed as part of the upper electrode and entered the discharge chamber through nine 6 mm diameter holes spaced equidistant around a 25 mm pitch circle centred on the mid-point of the electrode. The pressure was measured using a Bourdon tube type vacuum gauge connected to a copper pipe which was located within the upper electrode.

The outlet from the discharge tube was taken through a 25 mm diameter orifice at the centre of the lower electrode and connected to the input of a rotary vacuum pump, which had a throughput capability at S.T.P. of $10^{-2} \text{m}^3/\text{s}$. The gas flow rate was measured using a variable area flowmeter connected at the outlet of the vacuum pump.
Fig. 4.4. Initial E type discharge assembly

The electrical circuit of the high frequency supply is shown schematically in Fig. 4.5a and the tank circuit was completed when the discharge was ignited. The r.f. current was measured by a thermal ammeter connected to the output of a ferrite cored current transformer and r.f. voltage was measured using a high resistance in series with an r.f. ammeter both in parallel with the discharge.
Fig. 4.5. Electric circuits used with E type discharge
(a) h.f. power source
(b) high voltage breakdown supply
(c) high current d.c. supply

High voltage breakdown of the gap between the electrodes at pressures below 100 Pa was initiated by the circuit shown in Fig. 4.5b. Once the breakdown of the gap had occurred the application of the high frequency field formed a stable E type discharge and the initiating voltage was subsequently disconnected.
Fig. 4.6. E type discharge at a pressure of 1000 Pa and argon flow rate $5 \times 10^{-4}$ m$^3$/s.

A relatively diffuse discharge was formed Fig. 4.6 and could be maintained at pressures up to 2000 Pa and argon flow rates up to $7 \times 10^{-4}$ m$^3$/s. Over this range the r.f. current remained essentially constant for any particular value of pressure and argon flow rate Fig. 4.7. An increase in either the pressure or the flow rate above these values caused the discharge to adopt a more filamentary and unstable nature. This was accompanied by excessive electrode
Fig. 4.7a Variation of r.f. current and voltage in initial E type discharge assembly as a function of
(a) Argon flow rate
(b) Pressure

vaporisation of the discharge vessel which limited the duration of each trial and made visual evaluation of the nature of the discharge very difficult. Further progress in the investigation of the E type high frequency discharge necessitated therefore an improved discharge vessel.
Fig. 4.7b Variation of r.f. current and voltage in initial E type discharge assembly as a function of
(a) Argon flow rate
(b) Pressure
4.2.2. The Second E Type Discharge Assembly

The design of the second electrode assembly Fig. 4.8 was essentially the same, only on a larger scale, as that used initially. Modifications were made, however, including more efficient water cooling of the electrodes, larger gas inlet and outlet orifices, an increase in the internal diameter of the discharge tube to 150 mm and the incorporation of a water-cooled calorimeter to cool the gas prior to the rotary vacuum pump.

Fig. 4.8. Second E type discharge assembly.
At low pressures, up to 2500 Pa, there was no evidence of electrode evaporation and stable discharges were obtained which at high power levels and low gas flow rates expand to approximately the same cross-sectional area as the tube itself.
Fig. 4.9b Variation of r.f. current and voltage in second E type discharge assembly as a function of
(a) Argon flow rate
(b) Pressure

The discharge was similar to that formed within the first discharge assembly with the r.f. current again being constant for any particular value of gas pressure and flow rate, Fig. 4.9. The more efficient water cooling incorporated within this second discharge assembly
Fig. 4.10 Discharge diameter in second E type discharge assembly as a function of r.f. power input.

extended the duration of each experiment and enabled the diameter of the discharge to be estimated from visual and photographic observations. A reduction in the r.f. power input reduced both the diameter and the intensity of the discharge.
Fig. 4.11 Discharge diameter in second E type discharge assembly as a function of gas pressure and flow rate.

An approximately linear relationship between r.f. power input and the discharge diameter, existed. The variation of discharge diameter with r.f. power input, gas pressure and flow rate is shown in Fig. 4.10.

Increasing the gas pressure above 2500 Pa a transition occurs between the relatively large diameter low intensity discharge to one of smaller diameter, less than 10 mm, but greater intensity. On the formation of the small diameter discharge arc roots are clearly visible and electrode evaporation is evident. The value of pressure required to cause the transition depends on the gas flow rate and r.f. power input. The variations of discharge diameter and current density with gas pressure and flow rate are shown in Fig. 4.11 and Fig. 4.12.
r.f. voltage = 140 V
Argon flow rate = \(6.6 \times 10^{-4} \text{ m}^3/\text{s} = 0\)
\(8.3 \times 10^{-4} \text{ m}^3/\text{s} = \triangle\)
\(10 \times 10^{-4} \text{ m}^3/\text{s} = \Delta\)

Fig. 4.12 Variation of discharge current density in second E type discharge assembly with gas pressure and flow rate.

The r.f. voltage remained constant as the pressure was increased but the r.f. current did vary with pressure, Fig. 4.13. The turning point shown in Fig. 4.13 corresponds to the transition to a smaller
Fig. 4.13 Variation of r.f. current in second E type discharge assembly with gas pressure and flow rate.

diameter discharge. For any particular value of gas pressure and flow rate, an increase in the r.f. power was also more likely to bring out a transition to a constricted form of discharge, Fig. 4.14.

In order to scale up the discharge assembly an increase in either the pressure, gas flow rate, or r.f. power input would have to be carried out. However, the results of Fig. 4.10 - Fig. 4.14 indicate that this would mean an increase in the likelihood of a transition to a constricted form of discharge. A high frequency E type discharge therefore suffers similar disadvantages of large temperature gradients and poor particle entrainment as d.c. or low frequency a.c. arcs when applied to the fields of chemical and metallurgical synthesis.
Fig. 4.14 Variation of discharge diameter in second E type discharge assembly with r.f. power input, gas pressure and flow rate remaining constant.
4.2.3. Superposition of D.C. Power on a High Frequency E Type Discharge

The superposition of d.c. power on a high frequency H type or induction coupled discharge could enhance its suitability for industrial application within the fields of chemical and metallurgical synthesis (Chapter 3.8). Using similar reasoning the superposition of d.c. power to a high frequency E type discharge may also be beneficial. Although attempts to create a large volume, high temperature plasma using an E type discharge alone were not successful, the effect of superimposing d.c. power on to the high frequency discharge was not known and was therefore investigated for the sake of completeness.

At low pressures, about 100 Pa, the addition of d.c. currents up to 5A increases the d.c. voltage across the discharge in a manner similar to that associated with an abnormal glow discharge region (Chapter 2.2). Increasing the d.c. current further reduces the stability of the discharge and a sudden transition occurs with the formation of an intense but relatively small diameter discharge. On the formation of this small diameter discharge the d.c. current rises significantly, the actual magnitude being dependent on the stabilising resistance, and the r.f. power input falls. The variation of d.c. current and voltage is shown in Fig. 4.15. Typical values of d.c. current, d.c. voltage and r.f. power input after the formation of a constricted discharge for various gas pressures and d.c. supply voltages are shown in Fig. 4.16.
Fig. 4.15 Variation of d.c. arc current and voltage when superimposed on a low pressure E type high frequency discharge.
rf. voltage = 130 V
Argon flow rate = 6.6 x 10^-4 m³/s
d.c. supply voltage = 220 = O
200 = Δ

Fig. 4.18a Variation with gas pressure and d.c. supply on the formation of a constricted discharge of:

(a) r.f. power
(b) d.c. current
(c) d.c. voltage
Fig. 4.16b Variation with gas pressure and d.c. supply on the formation of a constricted discharge of
(a) r.f. power
(b) d.c. current
(c) d.c. voltage

rf. voltage = 130 V
Argon flow rate = 6.6·10⁻⁵ m³/s
d.c. supply voltage = 200 V
220 V = 0
r.f. voltage = 130V
Argon flow rate = 6.6 \times 10^{-4} \text{ m}^3/\text{s}
d.c. supply voltage = 220 \text{ V}
= 200 + \Delta

Fig. 4.16c Variation with gas pressure and d.c. supply on the formation of a constricted discharge of
(a) r.f. power
(b) d.c. current
(c) d.c. voltage
The value of d.c. current which causes the transition to a constricted discharge is dependent on the pressure, flow rate and r.f. power input but within the ranges investigated it varied only between 5 A and 10 A. The addition of a d.c. current of only 10 A, contributing as little as 1.5 kW to a total discharge power of 7.5 kW, was sufficient to cause the formation of a constricted discharge at pressures and flow rates of 500 Pa and 7.10^-4 m^3/s. This is far below those associated with a similar transition in an E type discharge alone.

4.2.4. Analysis of the E Type Discharge

In order to explain the experimental findings in the previous sections a simplified analysis has been applied to the high frequency discharge operating in the E type mode based on a constant conductivity model of the discharge Fig. 4.17. The effect of the skin depth phenomenon on the characteristics of the discharge was assessed from the normalised power density distribution across the cross-section of the discharge.

Assuming a constant conductivity model of the discharge the value of the axial electric field strength at any radial point \( E_z(r) \), is given by (Brown et al 1948).

\[
E_z(r) = E_z(0) \sqrt{\frac{\text{ber}^2 \left( \frac{\sqrt{2} r}{\delta} \right)^2 + \text{bei}^2 \left( \frac{\sqrt{2} r}{\delta} \right)^2}{\text{ber}^2 \left( \frac{\sqrt{2} a}{\delta} \right)^2 + \text{bei}^2 \left( \frac{\sqrt{2} a}{\delta} \right)^2}}
\]
Fig. 4.17 Constant conductivity model of an E type high frequency discharge.

where $E_z(0)$ is the electric field strength on the discharge axis and $a$ the arc radius. The power density at any point within the discharge $P$, is given by

$$P = \sigma E_z^2(r)$$  \hspace{1cm} (4.3)

and the average power density is

$$P_{av} = \frac{2}{\pi a^2} \int_0^a r \sigma E_z^2(r) \, dr$$  \hspace{1cm} (4.4)
Substituting $E_z(r)$ from equation (4.2) and integrating, $P_{av}$ becomes

$$P_{av} = \frac{\sqrt{2} a}{\sqrt{\delta}} \sigma E_z^2(0) \left[ \frac{\text{ber} \frac{v_2 a}{\delta} \text{bei} \frac{v_2 a}{\delta} - \text{bei} \frac{v_2 a}{\delta} \text{ber} \frac{v_2 a}{\delta}}{\left( \text{ber} \frac{v_2 a}{\delta} \right)^2 + \left( \text{bei} \frac{v_2 a}{\delta} \right)^2} \right]$$

The normalised power density distribution is therefore,

$$\frac{P}{P_{av}} = \frac{a}{\sqrt{2} \delta} \left[ \frac{\text{ber} \frac{v_2 r}{\delta} \text{bei} \frac{v_2 r}{\delta} - \text{bei} \frac{v_2 r}{\delta} \text{ber} \frac{v_2 r}{\delta}}{\left( \text{ber} \frac{v_2 r}{\delta} \right)^2 + \left( \text{bei} \frac{v_2 r}{\delta} \right)^2} \right]$$

To evaluate the normalised power density distribution at any particular operating frequency estimates had to be made of the diameter of the discharge and the electrical conductivity.

At pressures of 100 Pa the diameter of the discharge was approximately 40 mm. decreasing as the pressure increased. The temperature of a discharge increases with gas pressure (Chapter 2), being of the order of 7000 K for discharges in argon at atmospheric pressure. The normalised power density distribution for various operating frequencies was calculated therefore assuming a discharge diameter of 40 mm and an electrical conductivity of 1000 S/m which corresponds to a discharge temperature in argon of 7000 K, Fig. 4.18. At frequencies in excess of 10 MHz power generation occurs in the outer regions of the discharge but at frequencies below 1 MHz the power generation is approximately uniform throughout the discharge.
Fig. 4.18 The radial distribution of the normalised power density in an E type discharge in argon.

Thus the skin depth phenomenon will have negligible effect on the characteristics of the discharge and by analogy with the characteristics of a d.c. arc it is to be expected that an E type discharge with an operating frequency of 450 kHz would take up a constricted form as the pressure increases towards atmospheric.

4.2.5. Conclusions from Analysis and Experimental Investigations of the E Type High Frequency Discharge

Experimental investigations, supported by a simplified analysis, have shown that E type high frequency discharges operating at frequencies of 450 kHz and below adopt a constricted form at pressures above 2000 Pa, argon flow rates greater than $10^{-3}$ m$^3$/s and r.f.
power inputs above 4 kW. An increase in any one of these three parameters requires a decrease in the other two if constriction is to be avoided, therefore limiting the scale up possibilities of this system.

The addition of d.c. current to the discharge reduced the values of pressure and argon flow rate at which a constricted discharge was formed.

The use of a high frequency E type discharge, with or without the superposition of a d.c. supply, as a method of creating a large volume high temperature discharge was therefore abandoned.
A large volume discharge using a combination of r.f. and d.c. power was formed and its characteristics studied. The experimental results of the overall efficiency of coupling were correlated with those predicted by the analysis of chapter 4.1. and design criteria established for this type of discharge vessel.
5. High Frequency and D.C. Coupled Discharge

Efficient coupling of r.f. power at 450 kHz into a d.c. arc was far more difficult than had been anticipated (Hobson 1974) but the analysis given in Chapter 4.1. indicated that a high efficiency of coupling could be obtained using an operating frequency greater than 4 MHz. A discharge vessel was therefore designed and constructed in which r.f. power at 6.5 MHz, as this was readily available, was superimposed on d.c. arcs up to 100 A in an argon atmosphere. A large volume of ionised gas was formed and the characteristics of a combined r.f. and d.c. discharge studied. The design of the vessel was similar to that postulated previously (Thorpe 1966b, Schreiber et al 1973) and an experimental evaluation of the design as well as a verification of the analysis of chapter 4.1. was carried out.

5.1. Construction of the Discharge Vessel

The discharge vessel Fig. 5.1, was made in four separate parts, an upper section in which the discharge was formed, an annular shaped copper electrode which was the anode of the d.c. supply, a lower section which enabled the tail flame of the discharge to be observed, and lastly a water cooled calorimeter to enable the gas stream to leave the discharge vessel at ambient temperature.

The upper section, shown schematically in Fig. 5.2, had an outer Pyrex tube and an inner silica tube, to withstand the high temperature gradients envisaged, with cooling water passed between them to enable higher power operation to be achieved without damage to the vessel. Commercially available silica tubes have relatively large
Fig. 5.1 The r.f./d.c. discharge vessel
Fig. 5.2 Schematic diagram of Upper Section of Discharge Vessel

tolerances on their diameter and thickness. Each end of the tubes had therefore to be sized in order to obtain the uniform diameter and smooth surface required for rubber O-rings to be used to provide the water tight seals.
The gas injection plate within the upper end-piece, Fig 5.3, had 4 mm diameter holes equally spaced on a 35 mm pitch circle. The holes were inclined at approximately fifteen degrees to the face of the injection plate and as the gas entered the discharge region a vortex flow was formed aiding the stability of the discharge.

The cathode of the d.c. arc consisted of a 25 mm diameter carbon electrode which was passed through a hole in the centre of the upper end-piece. The anode was of an annular shape, Fig 5.4, and was
Fig. 5.4 The anode

made separate from the end-pieces of the upper and lower sections to enable easy replacement in the case of excessive erosion due to the high heat transfer rates from the tail-flame of the discharge and the anode root.

In the calorimeter, Fig. 5.5, the gas from the discharge region passed down nine water cooled copper pipes before exhausting to the atmosphere. The temperature of the gas leaving the calorimeter was less than 1°C above ambient.
5.2. Power Supplies

The high frequency power source was a commercially available 25 kW induction heater with a nominal operating frequency of 6.5 MHz. The electrical circuit of this induction heater is shown schematically in Fig. 5.6 and details of the valve characteristics and typical operating parameters are shown in Table 5.1. The induction heater used two identical valves, type STC 203R, connected in a push-pull arrangement so that the power output and the output impedance of the generator.
Fig. 5.6 Electrical circuit of induction heater

were twice that of a single valve generator (May 1949, Simpson 1960).

The effective tank circuit capacitance was 175 pF and the work coil, made from 8 mm O.D. copper tubing with 5 turns of 120 mm diameter and length 70 mm, completed the parallel resonant tank circuit.

The electrical circuit of the d.c. power supply is shown schematically in Fig. 5.7. A 415 V variable output auto transformer rated at 25 kVA supplied a full wave rectifier, the output of which was smoothed by a large inductance. The arc was stabilised by a 4Ω, high current,
TYPICAL OPERATING CONDITIONS OF VALVE

TYPE STC 203R

- Anode voltage: 6 kV
- Anode current: 2.5 A
- Peak fundamental anode current: 4.4 A
- Peak voltage across single valve: 5.1 kV
- Maximum power from valve: 11.2 kW
- Matched tank circuit impedance: 1350 Ω

TWO IDENTICAL VALVES OPERATING
IN PUSH-PULL ARRANGEMENT

- Peak voltage across tank circuit: 10.2 kV
- Peak fundamental anode current: 4.4 A
- Maximum power in tank circuit: 22.4 kW
- Matched tank circuit impedance: 2700 Ω
- Tank circuit capacitance: 175 pF

Table 5.1 Operating parameters of induction heater used in Chapter 5.

Resistance and lead through capacitors were incorporated in the d.c. supply to eliminate any high frequency interference.

The induction heater had moving coil instruments indicating the grid current, anode current and anode voltage of each valve. The d.c. voltage and current were measured directly from the waveforms.
Fig. 5.7 Electrical circuit of d.c. power supply shown on an oscilloscope and readings taken using moving iron meters.

5.3. Evaluation of the Heat Transfer Mechanisms and Overall Energy Balance within the Discharge Vessel

Commercial application of a r.f. and d.c. coupled discharge depends on the efficiency of power transfer to the gas stream and the suitability of scaling up the discharge vessel design to an industrial size.

The dominant heat transfer mechanisms to the individual sections of the discharge vessel have been evaluated from which the effect on the discharge of any change in the design parameters of the vessel may be assessed.
Table 5.2 Summary of previous experimental measurements of energy balance within induction coupled discharges

The performance of this discharge vessel has also been established by means of an overall energy balance. Each section of the discharge vessel was independently water cooled with facilities to measure the individual water flow rates and temperature rises thus enabling an energy balance to be carried out by calorimetric methods.

5.3.1. Radiation Losses

A limited number of experimental attempts have previously been made to measure the radiation losses from induction coupled discharges, and details of the results obtained are summarised in Table 5.2. The radiation losses depend, however, on many factors including the discharge tube radius, the power level, the gas and its flow rate.
The magnitude of the losses measured has varied from more than 30% (Reed 1961) down to zero (Dresvin et al 1971). The operating parameters of the discharge described in this chapter are similar to those used by Dresvin and his co-workers who measured negligible radiation losses from their discharge.

The radiation losses from this particular discharge vessel were measured using a method similar to that proposed by Reed (1961a). The temperature rise of a black vessel positioned to intercept over 30% of the total radiation from the discharge also indicated negligible radiation loss from the discharge vessel over the complete range of r.f. and d.c. powers used (up to 2.5 kW in each case).

Experimental temperature measurements on induction coupled discharges of similar operating frequencies, power levels and discharge tube diameters to the ones used, indicate that the discharge has a maximum temperature of approximately 8000 K (Ebihara 1973). Theoretical calculations of the radiation losses from an atmospheric pressure argon plasma have also been carried out (Mensing et al 1969). Using these results and assuming a maximum discharge temperature of 8000 K, the radiation loss was $10^6 \text{ W/m}^3$ which represents less than 250 W or less than 5% of the power input to the discharge.

In conclusion the experimental and theoretical assessments of the radiation loss from the discharge both indicated that this was less than 5% of the power input to the discharge and it was neglected in the subsequent energy balance investigations.
5.3.2. Heat Transfer to the Upper Section of Discharge Vessel

The heat transfer to the cooling water of the upper section consisted of radial heat conduction from the discharge directly to the walls of the discharge vessel and heat transfer through the carbon cathode due to conduction from the discharge directly or by arc root mechanisms.

At arc currents of above 10 A, the effect of electron emission and radiation on the cooling of the cathode is small and the energy input to the cathode fall region is dissipated by conduction through the electrode and evaporation of the electrode material. The conduction losses for a d.c. carbon arc in air have been measured (Holm 1949) and were approximately 10% of the energy input to the cathode fall region. For a 60 A arc, assuming a cathode fall potential of 10 V, the power input to the cathode fall region is 600 W and hence the conduction heat transfer to the electrode was less than 60 W and could be neglected.

Over the range of argon flow rates used, $3 \times 10^{-4} \text{ m}^3/\text{s}$ to $13 \times 10^{-4} \text{ m}^3/\text{s}$, the position of the discharge remained essentially within the work coil or downstream from it and hence it was at least 20 mm away from the end of the carbon cathode. The conduction losses from the r.f. and d.c. coupled discharge to the electrode were thus negligible in comparison with the radial conduction to the walls of the vessel which were less than 15 mm from the discharge and over 80 times the surface area.

Radial heat conduction from the discharge was therefore the major heat transfer mechanism to the upper section of the discharge vessel. Any change in the design parameters of this type of vessel, with regard to scaling up the device, could be assessed therefore by considering the effect on the radial heat conduction mechanism alone.
Fig. 5.8 Effect of argon flow rate and power input on the heat transfer to upper section of the discharge vessel.

The effect of argon flow rate and power input on the overall heat transfer to the walls of the vessel is shown in Fig. 5.8. An increase in the flow rate increased the heat transfer only slightly with the major effect of the increase in flow rate being on the stability of the discharge.
Fig. 5.9 Percentage of total discharge power transfer to upper section of discharge vessel

Increases in d.c. arc current and anode voltage of the r.f. supply increased the power input to the discharge causing significant increases in the heat transfer to the walls of the vessel. However, the percentage of
the total power input to the discharge which is lost to the walls of the vessel decreased with an increase in discharge power, Fig. 5.9. This was due to an increase in the power input to the gas stream and hence an increased heating efficiency was achieved at higher discharge powers.

5.3.3. Heat Transfer to the Anode

The two processes involved in the heat transfer to the anode were the d.c. arc root mechanisms, and the radial conduction of heat directly from the discharge or its tail flame. The magnitude of the heat losses to the anode for various argon flow rates, and d.c. arc currents is shown in Fig. 5.10, using an r.f. voltage of 2 kV.
To separate the effects of the arc root mechanism and the radial conduction from the discharge the position of the discharge relative to the anode must be taken into consideration. For argon flow rates greater than $8.10^{-4} \text{ m}^3/\text{s}$ the discharge extended downstream of the work coil and into the anode region. The heat conduction to the anode was then calculated assuming that it increased with the discharge power input in the same ratio as the heat conduction to the upper section of the vessel, Fig. 5.11. The heat transfer attributable to the arc root mechanisms was approximately 180 W and 360 W for d.c. arc currents of 30 A and 60 A respectively. These values varied little with argon flow rate or r.f. power input and were always directly proportional to the d.c. arc currents and correlated well with anode fall voltages for copper electrodes, Table 2.4.
When scaling up the discharge vessel therefore the heat transfer due to the arc root mechanisms could be estimated from its direct proportionality to the d.c. arc current whilst any change in the design parameters of the discharge vessel would affect the heat transfer to the anode by radial conduction in a manner similar to that within the upper section of the vessel.

5.3.4. Power Input to the Gas Stream

The temperature of the emergent gas at the exit of the calorimeter was approximately that of the surroundings. The sum of the heat losses to the lower chamber and the calorimeter was therefore equal to the power input to the gas stream.

The gas entered the discharge region tangentially and the vortex flow pattern formed not only stabilised the discharge but also aided in the mixing between the hot and cold regions of the gas flow downstream of the discharge. The variation with argon flow rate of power input to the gas stream as a fraction of the total discharge power is shown in Fig. 5.12. Decreasing the flow rate below $5 \times 10^{-4}$ m$^3$/s reduced the stability of the discharge and caused excessive heat transfer to the walls of the upper chamber thus reducing the heating efficiency of the discharge vessel. Increasing the gas flow rate increased the heating efficiency but at very high flow rates the power input was insufficient to maintain the discharge although the presence of a d.c. arc of 60 A enabled the combined discharge to exist at flow rates more than 50% higher than those which would extinguish an induction coupled discharge alone.
Fig. 5.12 Percentage of power input transferred to gas stream

Although the power input to the gas stream only varied between 30 % and 50 % an increase in the r.f. power input, and to a lesser extent the d.c. power input, increased both the actual power input to the gas stream and its fraction of the total input power. The variation of the percentage of the total discharge power in the gas stream with r.f. power input to the discharge is shown in Fig. 5.13. Increasing the r.f. power input increased the discharge diameter and hence the ratio of the discharge diameter to the surrounding tube diameter thereby reducing the fraction of the gas flow by-passing the discharge.
An attempt was made to correlate the experimental results with an analysis of the phenomenon of the gas by-passing the discharge region initially put forward by Lawton (1967). The diameter of the discharge, measured photographically, was approximately 40 mm and varied by less than 10% over the range of power inputs investigated. Applying the analysis, and assuming a discharge temperature of 8000 K, then less than 10% of the argon gas would pass through the discharge region. The experimental results show, however, that between 10% and 20% of the argon gas flow passed through the discharge. The
discrepancy was due mainly to the omission from the analysis of the radial inflow inherent within an induction coupled discharge, and the enhanced mixing of the hot and cold regions of the gas stream brought about by the vortex flow pattern within the discharge. The use of this analysis to predict with any acceptable degree of accuracy the percentage of gas flow by-passing the discharge cannot be justified and its use as an aid to the design of future discharge vessel of this type must be restricted to generalisations.

5.4. Discharge Characteristics

The d.c. discharge was initiated by short circuiting the electrodes with a thin copper wire which melted when the d.c. current passed through it, forming in its place a d.c. discharge. Once a d.c. discharge had formed the high frequency power was applied creating in most cases a relatively large volume discharge, Fig. 5.14.

The formation of a large volume discharge depended on the argon flow rate, and the d.c. and r.f. power inputs. The characteristics of the different discharges formed and the interaction of the two power supplies will now be discussed.

5.4.1. D.C. Arc Characteristics

A major constraint in the design of this discharge vessel was the provision of a d.c. power source able to supply a high current arc of sufficient length such that the electrodes of the d.c. supply did not interact significantly with the work coil of the r.f. supply. Investigations were carried out with the full range of open circuit voltages, electrode
Fig. 5.14 Large volume discharge formed in r.f/d.c. discharge vessel.

It was found that an electrode separation of 150 mm and a d.c. open circuit voltage of 300 V, gave a stable arc between 10 A and 60 A for argon flow rates of $3.10^{-4}$ m$^3$/s to $13.10^{-4}$ m$^3$/s and this could be used satisfactorily with a work coil 70 mm long.

The relationship between the arc voltage and arc current for an electrode spacing of 150 mm is shown in Fig. 5.15 for various argon flow rates.
The gas entered the discharge region in such a way as to form a discharge stabilising vortex and hence the argon flow rate had a great effect on the arc characteristics. At low gas flow rates the arc was relatively unstable and the values of the arc current and voltage varied accordingly. For argon flow rates above $5 \times 10^{-4} \text{ m}^3/\text{s}$ the arc was stable and for increased gas flow rates the shape of the arc characteristic was constant, giving a family of curves Fig. 5.15, in which the arc voltage required for any arc current increased with argon flow rate.
5.4.2. High Frequency Discharge Characteristics

A high frequency discharge was initiated by forming a d.c. arc, superimposing the high frequency power and subsequently disconnecting the d.c. power supply. No auxiliary power supply was therefore required and providing the d.c. power was reduced slowly a smooth transition into an induction coupled discharge was obtained.

A stable operating region existed for the induction coupled discharge dependent on the work coil geometry, argon flow rate and power input to the discharge, Fig 5.16. Within the stable operating region lines of constant anode voltage of the r.f. supply corresponded approximately to constant values of r.f. power input to the discharge. The magnitude of the power input increased as the anode voltage increased.

For low flow rates and high discharge powers excessive heat conduction occurred to the upper section of the discharge vessel which would have led to failure of the silica tube if prolonged operation was attempted. Increased argon flow rates increased the r.f. power input required to maintain the discharge and this defined the lower boundary of the stable operating region of the discharge, Fig 5.16. Operation outside this boundary extinguished the discharge.

5.4.3. The Characteristics of the High Frequency and D.C. Coupled Discharge

The characteristics of the combined discharge depend greatly on the magnitude of the r.f. power input. If the r.f. power input was sufficient to sustain an induction coupled discharge alone at a particular argon flow rate, i.e. within the stable operating region
Fig. 5.16 Operating characteristic of the induction coupled discharge of Fig. 5.16, then superimposing d.c. current of between 10 A and 60 A had little effect on the r.f. power input to the discharge Fig. 5.17, although the intensity and total power input to the discharge was increased, Fig. 5.18. Similarly with the same range of r.f. power inputs, the d.c. voltage and current characteristics maintained essentially the same shape as in the absence of any r.f. power but
Fig. 5.17 Variation of r.f. power input with d.c. current superimposed on an existing induction coupled discharge.

An increase in r.f. power input reduced the voltage required for any particular d.c. current, Fig. 5.19. The reason the power sources interact in such a manner is due to the power input to an induction coupled discharge being predominantly within the outer regions of the discharge, and hence mainly dependent on the discharge temperature within this region. The application of d.c.
power along the axis of the high frequency discharge would have only a minor effect on the temperature distribution within the outer regions of the discharge and hence only a minor effect on the power taken from the high frequency supply, which is consistent with the experimental results obtained.

Measurements from still photographs of the discharge using Ilford H.P. 4 film at f. 22 with one millisecond exposure, showed that the
diameter of the discharges formed was approximately 40 mm and varied by less than 10% throughout the range of argon flow rates and discharge powers used. Using the analysis given in chapter 4.1. and assuming that the discharge could be approximated by a solid conductor of electrical conductivity 1640 S/m and a diameter of 40 mm, the overall efficiency of power input to the discharge was calculated, Fig. 5.20. The experimental values of the overall
Theoretical calculation based on solid conductor diameter = 4.0 mm and electrical conductivity = 1640 S/m corresponding to a mean discharge temperature in argon of 8000 K (see appendix I).

Fig. 5.20 Overall efficiency of high frequency power input as a function of total discharge power.

Efficiency of power input to the discharge, measured calorimetrically, are also shown in Fig. 5.20, and agreement to within 8% is achieved between the theoretical and experimental results.

The r.f. and d.c. power sources interacted in a completely different manner if the magnitude of the r.f. power input was below that required to sustain an independent induction coupled discharge. The characteristics of the combined discharge were dependent on the...
Fig. 5.21 Effect of a d.c. current on r.f. power input to combined discharge.

value of d.c. current, with a reduction in the d.c. current causing a reduction in the intensity of the discharge and the r.f. power input Fig. 5.21. The overall efficiency of power input to the discharge from the high frequency supply was measured calorimetrically, Fig. 5.22. Using the analysis given in chapter 4.1., and assuming that the diameter of the discharge was proportional to the r.f. power input, the value of the overall coupling efficiency was calculated and
Theoretical calculation based on solid conductor with electrical conductivity = 1640 S/m corresponding to a mean discharge temperature of 8000K.

Fig. 5.22 Overall efficiency of coupling as a function of discharge diameter for low values of r.f. power input.

is also shown in Fig. 5.22. Agreement to within 5% is achieved between the theoretical and experimental results.

The close agreement between the experimental and theoretical results achieved with d.c., induction coupled, and combined discharges means that the analysis of chapter 4.1., may be applied with confidence to ascertain the coupling efficiency and load matching parameters of any high frequency power supply used to generate a large volume discharge.
5.5. Design Criteria for a High Frequency and D.C. Coupled Discharge Vessel

Having evaluated the heat transfer mechanisms in each section of the discharge vessel, this information must now be correlated with the characteristics of the discharges and a generalised design procedure formulated.

5.5.1. Initial Requirements Affecting the Design

The interacting factors affecting the design of the discharge vessel are indicated in Fig. 5.23. The particular application defines the required mean temperature of the discharge, the mass throughput and the minimum residence time and hence the maximum flow rate that can be tolerated.

The power input to the discharge can be estimated from the mean temperature of the discharge, the mass throughput and gas flow rate, assuming that an allowance is made for the efficiency of power input to the gas stream. The results obtained with the discharge vessel described in the previous sections of this chapter show that between 30 % and 50 % of the discharge power can be contained in the gas stream. The discharge powers used were relatively small being less than 6 kW. Increasing the discharge power input would increase its diameter and the heat losses due to the containment of the discharge as these are predominantly by radial conduction to the surrounding walls. An increase in discharge diameter would, however, reduced the fraction of the mass flow by-passing the heated region and the results indicated that this is the dominant factor leading to an increase in the percentage of the total power input within the gas stream above the 50 % already obtained at low power levels.
Fig. 5.23 Factors affecting the design of a r.f./d.c. discharge vessel.

5.5.2. Design of D.C. Supply

In plasma torches used in cutting and welding applications the arc is of a constricted nature whereas in the discharge vessel investigated the diameter of any d.c. arc envisaged is an order of magnitude less than the diameter of the inner surrounding tube. The characteristics of the discharge therefore are more closely associated with those
of a free-burning arc. Many basic construction principles and design criteria are, however, similar to those occurring in the more common forms of plasma torch and these will not be dealt with in detail.

5.5.2.1. Efficiency of D.C. Power Input

The efficiency of power input to the gas stream from the total power input to the discharge depends on the magnitude of the power losses at the arc roots. The percentage of total d.c. 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. Assuming cathode and anode fall voltages of 10 V and 6 V respectively, the results indicate an efficiency of approximately 60%. Increasing the electrode spacing and gas flow rate did increase the efficiency as would changing the gas from argon to either nitrogen, oxygen or hydrogen, because of the increased voltage gradient within the arc column, and efficiencies in excess of 90% are possible.

Insufficient information is available to enable an optimum ratio of open circuit voltage to arc voltage to be predicted. Where a high efficiency and good utilisation of the power supply 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 can be used as was the case in these investigations.
5.5.2.2. Electrode Design

The choice of electrode material is dependent on the application and the power levels envisaged. The anode will almost certainly be made from copper, to enable high arc currents to be used, and water cooled to dissipate the heat losses due to the arc root and by radial conduction from the discharge itself. The results show that the anode fall voltage is of the order of 6 V (Chapter 5.3.3) and that the heat dissipation is equal to the product of the arc current and this anode fall voltage. The radial conduction from the discharge is dependent on the temperature and the proximity of the vessel walls. With the particular design investigated the losses were no more than 10% of the total discharge power input and decreased with an increase in power input.

The use of carbon as the cathode material eliminated the need for a separate water cooling supply but in applications where contamination of the discharge by evaporated electrode material must be kept to a minimum, water cooled copper electrodes with thoriated tungsten, zirconium or hafnium inserts must be used as in the case of cathodes in plasma cutting torches.

The distance between the electrodes was determined by the need to eliminate any interaction between the electrodes and the work coil of the r.f. supply. A clearance of approximately 20 mm was required between the lower end of the work coil and the anode in order to prevent electrical breakdown between them. Smaller distances could be tolerated, however, by the use of suitable insulating material. A similar clearance was required between the work coil and the carbon cathode to reduce the wasteful coupling of r.f. energy and to
eliminate any effect that the presence of a relatively cold cathode in close proximity to the discharge might have on its stability.

Although the electrode separation was of the order of 150 mm, few problems of discharge initiation were encountered even though a relatively crude melting wire technique was used. In higher powered industrial discharge vessels moveable electrodes are envisaged which could be either initially short circuited and subsequently moved apart to draw out the arc or moved close enough to each other to make the use of high voltage ignition units feasible.

Having set the electrode separation the arc voltage can be estimated using the cathode and anode fall potentials given in Table 2.4., and a discharge column voltage gradient of approximately 1V/mm for arc currents in argon of the order of 100 A. The arc current can now be determined from the total d.c. input power to the discharge and arc voltage. An example of the use of this design procedure is given in Appendix 2.

5. 5. 3. Determination of Operating Frequency and Discharge Vessel Diameter

The volume of a discharge is determined by the material throughput and the minimum residence time within the heated region required by a particular application.

The diameter of a discharge is dependent on the operating frequency, the power input especially that from the high frequency supply, and the heat losses. The dimensions of the combined discharge followed closely the characteristics of an induction coupled discharge alone
and hence the minimum diameter of discharge that can exist at any particular frequency is 3.5 times the skin depth (Chapter 2.5). The minimum diameter of discharge in argon is shown in Fig. 5.24, for various operating frequencies and discharge temperatures.
The overall efficiency of the combined discharge when operating within its stable operating region, Fig. 5.16, was essentially constant but when using r.f. power inputs below those required for stable operation the overall efficiency decreased with d.c. power input, Fig. 5.21. Because of the high capital and running costs associated with high frequency power supplies, a design criteria is postulated in which the operating frequency is chosen to give the maximum overall efficiency for the lowest value of power input at any particular discharge diameter i.e. the operating frequency is chosen such that the minimum discharge diameter shown in Fig. 5.24, is only slightly less than the discharge diameter required.

Single refractory tubes can be used at discharge power levels up to 5 kW in which case the diameter of the discharge vessel can be made only slightly greater than the discharge diameter thereby reducing the by-passing of the discharge region. At higher power levels some form of external cooling is required increasing the overall diameter of the discharge vessel. The diameter of the work coil of the high frequency supply is therefore always at least 1.5 times the diameter of the discharge, (Chapter 3.7.).

5.5.4. Operating Parameters of the High Frequency Supply

The majority of combined discharges investigated had d.c. power inputs of between 30 % and 60 % of the total discharge power input. Discharges were, however, formed with up to 80 % of the total discharge power supplied by the d.c. source and as the commercial viability of any combined discharge assembly is dependent on a relatively large d.c. power input then the high frequency power inputs should be no more than 20 % of the total power requirements.
Having assessed the required r.f. power input to the discharge, taking into consideration the fraction of the total discharge power input that appears in the gas stream, the values of the major components of a suitable high frequency supply now have to be calculated.

The length of the discharge is dependent on the flow rate and the residence time required by the particular application. The length of the work coil is usually made equal to the length of the discharge and the diameter of the work coil is limited by the practical constraints placed on the design of the discharge vessel diameter.

If the high frequency power supply is already in existence then once the work coil dimensions have been decided on the overall coupling efficiency can be calculated using the analysis set out in Chapter 4.1 and Appendix 1 and hence an estimate of the required power rating of the r.f. supply can be made. If, however, the high frequency power source is to be specified completely the procedure is more involved and in order to reduce the calculations required various approximations can be made and the following procedure adopted.

The effective resistance of the discharge load to the high frequency supply for a one turn work coil, $R_x$, is calculated using the equivalent circuit analysis developed in Chapter 4.1. The number of turns per unit length $N$, required on the work coil to produce a power input $P_w$, per unit length of the discharge can then be found from

$$N^2 I_c^2 = \frac{P_w}{R_x} \quad \left(\text{A}^2 \text{ m}^{-2}\right) \quad (5.1)$$
where \( I_c \) = high frequency current in work coil (A)
\( l_c \) = length of work coil (m)

In medium and low frequency power supplies used in induction heating the work coil is usually designed to operate at a fixed voltage but in r.f. valve oscillators, the work coil is designed for a fixed current which is typically of the order of 100 A.

Neglecting any leakage reactance of the work coil and assuming the discharge diameter to be equal to 3.5 times the skin depth, \( \delta \), the term \( R_x l_c \) of equation (5.1) can be simplified using equation (A.14) of Appendix 1,

\[
R_x l_c = \frac{7.12}{\sigma} \quad (\Omega \cdot \text{m})
\]  

(5.2)

The electrical conductivity of the discharge \( \sigma \), is a function of the gas and its temperature and pressure. Fig. 5.25 shows the number of work coil turns per unit length of a discharge in argon at atmospheric pressure and a temperature of 8000 K for various values of work coil current \( I_c \).

Having chosen the number of work coil turns, the work coil efficiency and the size of the tank circuit capacitance can be calculated, again following the analysis developed in Chapter 4.1. Using the characteristics of the valve chosen the overall efficiency of power conversion may then be evaluated. The rating of the high frequency power unit can then be found and the specification of the operating parameters of the high frequency power supply is complete.
Fig. 5.25 An estimate of the number of work coil turns required per unit length.

An example of the use of the design criteria outlined in this section is given in Appendix 2.

5.6. Summary of Results

A large volume of ionised gas was formed, diameter approximately 40 mm, using a combination of d.c. and high frequency (6.5 MHz) power. D.C. power inputs between 35% and 80% of the total
discharge power were used and the values of overall coupling
efficiency correlated to an accuracy within ± 8 % to those predicted
by the analysis developed in chapter 4.1.

The characteristics of the d.c., high frequency and coupled discharges
were studied and found to be greatly dependent on the argon flow rate,
due to the vortex flow pattern within the discharge vessel, and the
magnitude of the r.f. power input. With r.f. power inputs greater
than those required to sustain an induction coupled discharge alone,
under the same conditions, the diameter of the discharge remained
essentially constant even with the addition of d.c. power inputs up to
80 % of the total discharge power. For lower r.f. power inputs the
diameter of the discharge depended on the magnitude of the d.c. arc
current and power input and in both cases good agreement was
found between the experimental results and theoretical predictions
based on the analysis developed in chapter 4.1.

Overall energy balances of the high frequency and d.c. coupled
discharges were carried out. Radiation losses were less than 5 %
of the total discharge power input over the range of power inputs
investigated (less than 6 kW) and average discharge temperatures
of less than 8000 K were estimated. The percentage of power input
to the gas stream varied between 30 % and 50 % which was high
considering that the discharge occupied less than 35 % of the cross-
sectional area of the vessel.

The heat transfer mechanisms within each section of the discharge
vessel were evaluated and used, along with an extension of the
analysis of chapter 4.1. and the discharge phenomena reviewed in
chapter 2, to establish a generalised design procedure for this
type of discharge vessel. An example of the use of this design
procedure is given in Appendix 2.
CHAPTER 6

Multiple Arc Systems

Fundamental information on the behaviour of coalescing multiple arcs was obtained and a horizontal multiple arc configuration was developed which formed a large volume discharge of an apparently diffuse nature.
6. Multiple Arc Systems

The efficient coupling of electrical energy from a medium frequency source to a plasma requires an initial discharge of large diameter and high overall electrical conductivity. One possible method of obtaining an initial large volume of ionised gas is to use a multiple arc system (Chapter 4.1.2).

Various multiple arc systems have been developed including 3 phase arc furnaces, arc welding processes, mercury arc rectifiers and plasma arc furnaces, but all use separate arcs with only one common electrode or point of coupling. To produce a large integral volume of ionised gas it is necessary that the arcs should mix. Under these conditions interaction between the arc supply circuits occurs causing instability and, due to the negative gradient of the arc dynamic resistance, all the current will eventually be carried by one arc.

6.1. Conditions for Multiple Arc Operation

Two separate arcs connected to the same power supply cannot normally exist without individual stabilising impedances because of the negative dynamic resistance of the arc.

Fig. 6.1 shows two parallel arcs supplied from the same power source, where $R_o$ is the common resistance and $R_1$ and $R_2$ are the individual stabilising resistances. There is no quantitative data available on the optimum values of stabilising impedance required for a given application but the minimum condition for arc stability for a single arc is given by the Kaufmann criterion (Chapter 2.4.).
Fig. 6.1 Equivalent circuit of two parallel arcs supplied from the same power source

For the parallel arcs of Fig. 6.1 an equivalent minimum stability criterion can be formulated where the stabilising resistance $R_s$ (Equation 2.19) is replaced by $2R_0 + R_1$ or $2R_0 + R_2$.

The stability of two arcs in parallel is further complicated by the interaction between the individual arcs through the common resistance $R_0$ in the supply circuit. Fig. 6.2 and Fig. 6.3 shows the arc characteristics and load lines of the supply circuit for each arc. The lines AB show the variation of the voltage across the parallel arc system $V^1$, against the current in each arc and each has a gradient of $-R_0$. Lines CD show the variation of the voltage across each arc against current and have gradients of $-R_1$ or $-R_2$ respectively.
Fig. 6.2 Arc characteristics and power supply load line for arc 1 of parallel system.

Fig. 6.3 Arc characteristic and power supply load line for arc 2 of parallel arc system.
A sudden decrease in the current in arc 1 of $\Delta I_1$, assumed to be caused by some external factor, will increase the voltage $V^I$ across the two parallel arcs by $R_0 \Delta I_1$ volts, Fig. 6.2. The individual stabilising impedance of arc 1 will act so as to restore the current in arc 1 to its original value $I^1$, but at the same time the increased voltage across the parallel arcs of $V^I + R_0 \Delta I_1$ will increase the current in arc 2. Assuming that the equilibrium time for each arc is the same then when the current in arc 1 is restored to its original value, the current in arc 2 will be increased by $\Delta I_2$. Assuming that the arc characteristic in the region of the operating point $P_2$ to be a straight line of the same gradient as the arc characteristic at $P_2$, i.e. $\left( \frac{dv}{dl} \right)_{P_2}$, then $\Delta I_2$ can be expressed mathematically as

$$
I_2 = \frac{R_0 \Delta I_1}{R_2 + \left( \frac{dv}{dl} \right)_{P_2}} \tag{6.1}
$$

Providing $R_0$ is less than $R_2 + \left( \frac{dv}{dl} \right)_{P_2}$, the oscillations within the system will die away and the situation will remain stable. If $R_0$ is greater than $R_2 + \left( \frac{dv}{dl} \right)_{P_2}$ then an unstable situation will exist in which any fluctuation in the value of the current in one arc will cause a runaway condition in which one arc will carry an increasing proportion of the total current and the current in the other will decrease until it is extinguished. By similar reasoning it can be shown that for stability $R_0$ must also be less than $R_1 + \left( \frac{dv}{dl} \right)_{P_1}$.

For low current arcs the gradient of the arc characteristic is negative and hence the stability criterion based on the interaction between the arcs is severe. On increasing the current the gradient
of the arc characteristic tends towards zero and for very high current arcs can in certain cases become positive with a subsequent reduction in severity of the arc interaction stability criterion. It becomes possible therefore at high arc currents to operate two or more arcs in parallel if each is connected by its own stabilising impedance, even if the common resistance is much larger. This occurs for example in parallel connected mercury arc rectifiers which have been used for railway network rectification.

Tests carried out with horizontal d.c. arcs of between 15 mm and 25 mm length and up to 20 A showed that parallel arcs could be maintained with high values of individual stabilising resistances and essentially no common resistance. When the arcs coalesced however, an unstable situation resulted and one of the arcs was extinguished even though the individual stabilising resistances were approximately one order of magnitude greater than the resistance of the arc.

The interaction of 2 electric arcs supplied from the same power source but with separate stabilising resistors can be represented by the equivalent circuit shown in Fig. 6.4. R is the stabilising resistor which is assumed to be the same for each arc. The arcs are each represented by two separate resistors corresponding to the separate current paths from each electrode and a resistance \( r_{0} \) common to both arcs corresponding to the common region in which they coalesce. If a small increase in the arc path corresponding to \( r_{2} \) occurs, for example due to a change in arc length, the current in this part of the arc will decrease resulting in a small increase in voltage at \( \sigma' \). Normally for a single arc this would restore the arc to its
stable operating point. In this case however the current will increase in the part of the first arc corresponding to $r_1^1$. Due to the negative dynamic arc characteristic the increased arc current in arc 1 results in a higher arc current and more stable operating conditions and since not restoring voltage is available for arc 2 the current in $r_2^2$ will decrease further until the part of the arc corresponding to $r_2^2$ is extinguished.

Interaction between the arc supply circuits can be avoided if the power supplies are totally isolated from each other. This is relatively difficult and cumbersome with batteries or separate power supplies but can be more easily achieved using a transformer with separate secondary windings. In this case the isolation is not infinite but the mutual coupling between the secondary windings of the transformer will normally be very small.
6.2. Horizontal Multiple Arc Assembly

A multiple arc system was designed and constructed using a transformer with six separate output windings. The electrode holder is shown in Fig. 6.5 and enables 6 pairs of electrodes up to 10 mm diameter to be used. The radial position of each electrode can be adjusted simultaneously with the circumferential movement of a lever, allowing the electrode tips to be positioned on a pitch circle varying from approximately 15 mm to 120 mm diameter. The centre of the electrode holder was removed to allow the discharge to be photographed from below.

The single phase transformer had a primary winding for 230 V, 50 Hz rated at 60 kVA with six separate secondary windings with outputs of 24 A at 415 V. The output of each secondary winding was rectified with a bridge rectifier and smoothed and a series stabilising inductance connected on the input side of each rectifier bridge. The electrical circuit is shown in Fig. 6.6. The arcs were initiated with the electrodes on the minimum pitch circle using a graphite block to short circuit the electrodes and draw out an arc.

6.2.1. Initial Measurements and Observations

Three electrode configurations with an electrode separation measured across a diameter of about 40 mm were examined and are shown in Fig. 6.7. The electrodes were initially connected in diametrically opposed pairs, Fig. 6.7a. A large volume of ionised gas was observed
Fig. 6.5 Electrode holder for the horizontal multiple arc system.

filling the region between the electrodes. Regions of higher luminosity and greater stability could be seen between the adjacent electrodes of opposite polarity i.e. $A^+ F^-$, $A^- F^+$.

A peripheral ring of ionised gas formed by separate arcs between adjacent electrodes was obtained with the electrode configuration shown in Fig. 6.7b. No ionised gas was apparent in the central region.
Fig. 6.6 Electrical circuit used with horizontal multiple arc system.
Using the electrode configuration shown in Fig. 6.7c a large volume of ionised gas was formed similar to that formed by electrode configuration of Fig. 6.7a but in this case the more intense regions between adjacent electrodes of opposite polarity were not so apparent. The difference in behaviour of the different electrode systems can be considered in terms of the difference in path lengths and the effects of alternative paths provided by the ionised gas. For example if we consider electrode $A^+$ in Fig 6.7a, then one possible conducting path is across the diameter $A^+ - A^-$. However, a number of alternative paths also exist, $A^+ - B^-$, $A^+ - C^-$ etc.

In order for the system to be consistent i.e. the same value of current leaving electrode $A^+$, enters electrode $A^-$, then the conducting paths between $A^- - B^+$, $A^- - C^+$ etc should also be considered. The highest voltage gradients when using electrode configuration of Fig. 6.7a will exist between $A$ and $F$ electrodes resulting in the formation of a well defined conducting path between these electrodes. The voltage gradients between the electrodes of supplies $B$, $C$, $D$ and $E$ are all of the same order and smaller than that associated with supplies $A$ and $F$. This is consistent with the greater luminosity seen between electrodes $A$ and $F$ and the higher current values in their supply circuits. The experimental results of the arc voltage and current measurements for different supply circuits using electrode configuration of Fig. 6.7a are shown in Table 6.1.

The electrode configuration shown in Fig 6.7c results in the highest voltage gradients between $A^+ - C^-$ and $F^+ - D^-$ but the lowest voltage gradients between $C^+ - A^-$ and $D^+ - F^-$. The voltage gradients associated with the electrodes of the supplies $B$ and $E$ being intermediary in each case. The combined effect is again to form a large
Fig. 6.7 Electrode configurations of horizontal multiple arc system

a) Diametrically opposed pairs
b) Alternate electrodes of opposite polarity
c) Pairs at right angles to each other.
Table 6.1 Arc voltage and current values for different supply circuits of horizontal multiple arc system.

(a) With electrode configuration of Fig. 6.7a
(b) With electrode configuration of Fig. 6.7c
volume of ionised gas but in this case the tendency to form a well
defined or dominant conducting path between certain electrodes is
reduced. Arc voltage and current measurements for different supply
circuits are also shown in Table 6.1. Because of the symmetry of
the electrode configurations results for only three electrode pairs are
given.

For the electrode configuration shown in Fig. 6.7b a relatively high
electric field exists between $A^+ - F^-$, $B^+ - A^-$, $C^+ - B^-$ etc., i.e.
adjacent electrodes. This provides a well defined conducting path
between the electrodes around the periphery and no ionised gas was
observed in the central region for this configuration.

In addition to the effect of the various conducting paths on the uniformity
of the discharge, electromagnetic forces exist between the discharges
resulting in attraction or repulsion. In the case of Fig. 6.7a these
tend to be balanced. In Fig. 6.7b however, they tend to repel, forcing
the arcs outwards to the periphery of the discharge while in Fig. 6.7c
they attract towards the centre of the discharge aiding the formation
of a large volume of ionised gas.

Fig. 6.8 shows a photograph taken from the side of the electrode
assembly and the effects of convection are apparent, producing a
large tail flame above the plane of the electrodes. Ilford F.P. 4 roll
film was used with an aperture setting of f11, an exposure of 8
milliseconds and at a distance of 0.5 m from the centre of the electrode
assembly.
Fig. 6.8 Side view of the horizontal multiple arc discharge.

Steenbech (1932) confirmed experimentally that a buoyancy force was responsible for the upward bending of a single horizontal arc column. For given values of gas pressure and arc current, if the electrode separation was increased the single horizontal arc would become convex in shape. Beyond a limiting value of electrode separation, dependent on arc current, the arc would take on a hair-pin shape with the subsequent increase in arc voltage and decrease in arc stability. More recent work (Handa 1971) indicated a maximum horizontal electrode spacing of 10 mm for a stable single 10 A d.c. arc in air.
The buoyancy force is due to the difference in densities of the gas inside and outside the arc column. If the external gas temperature increases, as it effectively does with a multiple arc system, then the buoyancy force acting on the discharge would decrease and hence the stability would be increased. Experimental results using the horizontal multiple arc system showed however that it was still not possible to sustain a stable horizontal multiple arc discharge with an electrode separation in excess of approximately 30 mm for arc currents of the order of 10 A. The gas, at flow rates between $3 \times 10^{-4}$ m$^3$/s and $13 \times 10^{-4}$ m$^3$/s, was fed into the discharge region from above thereby also acting against the buoyancy force.

This source of instability and restriction in the diameter of discharge would have to be overcome if a horizontal multiple arc discharge on its own were to be scaled up for commercial use in the fields chemical and metallurgical synthesis. Similarly the restriction in the discharge diameter reduces the effectiveness of multiple arc systems of this form in initiating medium and radio frequency induction coupled discharges.

6.2.2. Current Distribution within the Discharge

The first step in the investigation of the current distribution within the discharge was to ascertain any electrical interaction between the supply circuits on the formation of the discharge. The open circuit voltage between the positive and negative electrodes of each supply was constant while that between electrodes of different supplies was zero. When the arcs were ignited however, a voltage was measured between the positive of one supply and all the negative electrodes indicating some form of interaction between the supplies. To test
whether the effect of mutual coupling between the secondary windings of the transformer was the cause of this interaction the voltage measurements were repeated with the arcs replaced by independent resistors of a similar value. The voltage between the positive electrode of one supply and the negative electrode of another supply could not be detected. The effect of mutual coupling between the secondaries of the transformer was therefore negligible and the interaction between the supply circuits was due solely to the discharge.

To investigate the current distribution within the discharge further a model of the system was constructed assuming the discharge to be a region of constant conductivity and thickness. Six stabilised 10 V d.c. power supplies were connected by resistors corresponding to the arc stabilising resistors to a circular sheet of Teledeltos paper which was used to model the conducting region of the discharge. Measurements of the voltage drop between each electrode pair and the current flowing from each supply were made. These were compared with the experimental results assuming that the anode and cathode fall voltages were each 10 V and independent of the arc current (Cobine 1958) and hence the voltage drop across the conducting path between the electrodes was obtained by subtraction of the anode and cathode fall voltages from the total voltage between the electrodes.

A normalised comparison between experimental results and the results from the model are shown in Table 6.2. Because of the symmetry of each electrode configuration the results for only three electrode pairs are given.
Electrode Configuration of Fig. 6.7a

<table>
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<td>Conductance (S)</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
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Electrode Configuration of Fig. 6.7c

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<td>Conductance (S)</td>
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<td>0.83</td>
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</table>

Table 6.2 A normalised comparison between experimental results and the results from model assuming discharge to have constant electrical conductivity and thickness.

(a) With electrode configuration of Fig. 6.7a.
(b) With electrode configuration of Fig. 6.7c.
The measurements using the analogue correlated most closely with the experimental measurements when the electrode configuration shown in Fig. 6.7c was used. This was to be expected as the model did not take into account the region of higher current between the adjacent electrodes of opposite polarity and this region was more evident when the electrodes were arranged in diametrically opposed pairs. The results for the electrode configuration of Fig. 6.7c indicate again that a uniformly conducting zone is formed by the coalescing discharges.

6.2.3. Investigations of the Diffuse Discharge Formed

Various diagnostic techniques have been considered to investigate the intensity distribution in electrical discharges. Probes have been used to determine the temperature profile in electric discharges (Gick et al 1973). The geometry of the multiple electrode system precludes the use of rotating probes whilst the dimensions of the interelectrode region and the relatively small size of probe required to avoid excessive disturbance means that the use of a water cooled probe would be impossible.

Spectroscopic measurements have been used to measure temperature distributions in electric discharges but require the use of relatively sophisticated equipment and a high standard of optical alignment.

The effect of convection and, in certain electrode configurations, the electromagnetic forces of attraction between the arcs, causes the discharge to adopt a flame-like appearance with essentially a conical shape above the plane of the electrodes. For practical reasons the
observations would have to be made in a direction perpendicular to the plane of the electrodes. Because of the steep temperature gradients associated with high pressure discharges this would mean that the radiation detected would be the sum of that emitted by various elements of the discharge of greatly differing temperatures. Spectroscopic techniques were therefore rejected.

Photographic techniques have been extensively used to study electric discharges (Chapter 2.6) and initial observations of the multiple arc discharge were made by still photographs. Each arc was supplied with a d.c. current of approximately 8 A with corresponding arc voltage of between 50 V - 70 V at an electrode spacing of 20 mm - 25 mm. The photographs were taken with a camera using Ilford H P 4 film at f22 with one millisecond exposure.

The observations were extended by using neutral density filters in order to reduce the light intensity so that only the most intense regions of the discharge were detected (Airey et al 1975). The neutral density filters up to 2.9 ND were added until at approximately 0.1 % transmission no discharge could be detected by the film and over this range of reduction in light intensity each photograph showed a uniformly luminous region, Fig. 6.9.

6.2.3.1. Results Using High Speed Photography

There are a number of possible explanations for what appeared from photographs to be a uniform luminous region other than the existence of a diffuse discharge. The arcs may be subject to rapid movement which because of the persistence of luminosity (Harry 1971) would
Fig. 6.9 Single shot photographs of horizontal multiple arc system.
give the appearance of a diffuse discharge. Similarly the effect of convection within the discharge would draw the ions or excited atoms from the arcs towards the central region of the discharge and again because of the persistence of luminosity result in a uniformly luminous region. The electrodes themselves, especially the anode, are incandescent and if the inter-electrode region is not sufficiently large the proximity of the electrodes may also give rise to uncertainty in any photographic results.

To assess the effects of the persistence of luminosity on the photographic images of the multiple arc system a 10 A d.c. arc between two horizontally mounted carbon electrodes was used to study the magnitude of the persistence of luminosity for low current arcs in air at atmospheric pressure (Harry 1971).

The arc current was interrupted using the thyristor diverter circuit shown in Fig. 6.10, in less than 0.1 milliseconds. The arc was photographed using a Hycam 16 mm high speed camera at 4,000 frames per second and the arc current and voltage waveforms and timing marks at one millisecond intervals were superimposed on the film. The thyristor trigger unit shown in Fig. 6.11 was operated from the camera control unit so that the film drive could be brought up to full speed before the arc was extinguished.

Initial results indicated that the luminosity of the arc gap persisted for between 15 and 20 milliseconds after arc extinction and the ends of the electrodes remained luminous for considerably longer.
Decreasing the lens aperture and the introduction of neutral density optical filters decreased the apparent persistence of luminosity. When the arc was photographed at 4,000 frames per second with an aperture setting of f5.6 the introduction of a neutral density filter ND 1.3, i.e. approximately 5% transmission, reduced the apparent persistence of luminosity to less than two milliseconds. Fig. 6.12 shows the change in light intensity when the arc is interrupted and the voltage and current traces on the high speed film.

The use of neutral density filters may reduce the photographic image to that of only the hottest parts of the arc but it does not distinguish between the radiation from the electrically conducting regions of the arc and than from the after-glow.

The great majority of work carried out on after-glow has taken place at low pressures and with essentially pure gases (Golde et al 1973).
An emission spectrum of the nitrogen afterglow at atmospheric pressure has been published (Stanley 1954), and a comparison made of the intensity against wavelength for this afterglow and a low pressure afterglow. More detailed work was carried out by Noxon (1962) and the emission spectrum of the nitrogen afterglow produced. The spectrum varies greatly with the amount of impurities present, especially traces of oxygen or moisture. It would therefore be extremely difficult to predict with any certainty a narrow band filter which would give a satisfactory image of the multiple arc discharge and have a low persistence of luminosity.
Fig. 6.12 High speed photographs to measure persistence of luminosity of single arc in air.
An experimental comparison of the performance of four filters which enabled the visible spectrum to be divided into four approximately equal sections was carried out with the single horizontal carbon arc. Kodak Tri-x reversal film 7278 was used at a speed of 4000 frames per second and an aperture of f 5.6 in the HYCAM 16 mm high speed camera. The sensitivity of the film itself provided the cut-off point in the infra-red region of the spectrum whilst the filters provided the cut-off point in the ultra-violet. Neutral density filters were used to adjust the percentage transmission level for each system so that a direct comparison could be made.

The persistence of luminosity and the characteristics of the photographic image was noted in each case and the results are shown in Table 6.3 and Fig. 6.13.

The intensity of luminosity from the multiple arc system and that from a single arc were compared using a photometer. The photometer worked on the principle of comparison between the discharge, viewed through filters, and an internal standard light source, and because of the subjective nature of this method no absolute measurements of light intensity were attempted. The intensity of luminosity of the single arc was always greater than that of the multiple arc system and it was considered valid to assume that the value of the persistence of luminosity found from the single arc experiments was greater than that associated with the multiple arc system.

The multiple arc discharge was photographed in exactly the same manner as the single arc with both the Ilford 806 and 828 filters used for each of the configurations shown in Fig. 6.7. The discharge was
Table 6.3 Persistence of luminosity using various optical filters.

<table>
<thead>
<tr>
<th>Ilford Filter No.</th>
<th>Transmission Band (nm)</th>
<th>Persistence of Luminosity (s)</th>
<th>Photographic Image</th>
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<td>828</td>
<td>300 - 400</td>
<td>$0.25 \times 10^{-3}$</td>
<td>Incandescence of electrodes virtually eliminated, discharge only is seen.</td>
</tr>
<tr>
<td>806</td>
<td>420 - 480</td>
<td>$0.25 \times 10^{-3}$</td>
<td>Electrodes can be seen but incandescence effect less than with filters 807 and 808.</td>
</tr>
<tr>
<td>807</td>
<td>510 - 560</td>
<td>$1 \times 10^{-3}$</td>
<td>Incandescence of electrodes obscured the image of the discharge.</td>
</tr>
<tr>
<td>808</td>
<td>560 - 560</td>
<td>$1 \times 10^{-3}$</td>
<td>Incandescence of electrodes obscured the image of the discharge.</td>
</tr>
</tbody>
</table>

Viewed from below using a $45^\circ$ angled mirror such that the high speed camera could be mounted in its correct vertical position. The supply to each pair of electrodes was smoothed such that the ripple was reduced to 5% to prevent fluctuations in the luminosity of the photographic image.

The electrode configuration of Fig. 6.7a showed a relatively uniform luminous region but clearly discernible brighter regions could be seen between the electrodes $A^+$ - $F^-$ and $A^-$ and $F^+$ as expected, Fig. 6.14a.
Fig. 6.13 High speed photographs of single arc using optical filters to reduce persistence of luminosity.
(a) Ilford Filter 806
(b) Ilford Filter 828 + 0.98 ND Filter.
The configuration of Fig. 6.7b showed six small arcs between an anode and its adjacent cathode again as predicted, Fig. 6.14b. The electrode configuration of Fig. 6.7c indicated that a relatively uniform luminous region was formed with no sign of a cold central zone, Fig. 6.14c. The brighter regions between the electrodes of opposite polarity still remained but their relative magnitude was decreased.

6.3. Summary of Results

A stable multiple arc system can be obtained by using power sources electrically isolated from each other. A large volume of ionised gas is obtained, subject to limitations in diameter ( < 30 mm) due to buoyancy forces, which might be used for chemical synthesis and metallurgical reduction processes by itself or to initiate or modify the intensity distribution of medium and radio frequency induction coupled discharges.

Measurements using analogue techniques correlated closely with the actual electrical measurements on the electrode system indicating that the interaction between the various electrode supplies was similar to that expected from a diffuse discharge.

The results of single shot photography with neutral density filters and high speed photographs with persistence of luminosity below 0.25.10^{-3}s indicated that the discharge remained relatively uniform in the region between the electrodes.
(a) Diametrically opposed pairs

(b) Alternate electrodes of opposite polarity

(c) Pairs at right angles to each other.

Fig. 6.14 High speed photographs of horizontal multiple arc system.
CHAPTER 7

Coupling of R. F. Energy into Multiple Arc Discharges

The coupling efficiency of r.f. energy at 450 kHz into a horizontal multiple arc system is evaluated. A vertical multiple arc system is designed including a practical and theoretical prediction of the maximum distance between vertically parallel coalescing arcs. The vertical multiple arc system was used to initiate a d.c. and high frequency (450 kHz) combined discharge.
7. Coupling of R. F. Energy into Multiple Arc Discharges

The problems associated with coupling relatively low frequency electrical energy into a single d. c. arc between two vertically mounted electrodes have been dealt with in detail in Chapter 4.1. Various methods of increasing the initial coupling efficiency were assessed including increasing the operating frequency, seeding the arc, reducing the working pressure and increasing the arc current. However, the use of a multiple arc system to produce a large volume of ionised gas has distinct advantages over other methods proposed, including low discharge-contamination, atmospheric pressure operation and easier scale up possibilities for power input and volume of discharge.

7.1. Coupling of R. F. Energy into a Horizontal Multiple Arc Discharge

The horizontal multiple arc system (Chapter 6.2.) was designed so that fundamental information on the behaviour of coalescing multiple arcs could be obtained. It was not, therefore, the ideal configuration to be used to initiate coupling from a high frequency power source. However, because of its availability and as a relatively large volume diffuse discharge could be formed, the horizontal multiple arc system was initially used to investigate the coupling of r.f. energy at 450 kHz into a multiple arc discharge.

Practical limitations were placed on the design of the work coil in order to avoid contact with the electrodes of the multiple arc system.
It was assumed that turns above and below the electrode plane would be required to provide a more uniform magnetic field within the region of the discharge. A minimum length for a two turn work coil of 50 mm was needed to provide clearance from the electrodes and further turns could be added limited only by the avoidance of breakdown between the individual turns. The minimum diameter of work coil was again restricted to 80 mm (Chapter 4.1.1.).

Experiments were carried out with argon flow rates, from above the discharge, between \(3 \times 10^{-4}\ m^3/s\) and \(13 \times 10^{-4}\ m^3/s\) and multiple arc discharge diameters up to 30 mm using 2 and 4 turn 80 mm diameter work coils. Theoretical analysis (Chapter 4.1.) shows that the coupling efficiency into any subsequently formed induction coupled discharge is greater than 50% with good matching if such work coils are used, (Table 4.2). However, significant coupling of r.f. energy into the multiple arc discharge could not be detected in any of the tests.

An analysis of the efficiency of coupling r.f. energy at 450 kHz into the horizontal multiple arc discharge requires an estimate of the discharge geometry and its electrical properties. The results of Chapter 6 indicate that the horizontal multiple arc system formed a diffuse discharge within the interelectrode region and if the electrode configuration of Fig. 6.7c is used the discharge approximates to a conductor of constant electrical conductivity and thickness (Chapter 6.2.2.). The electrical conductivity of the discharge approximates to that on the axis of a free burning arc of the same current and the thickness to that of the diameter of a single arc (Table 2.7, Chapter 2.3).
Using the analysis of Chapter 4.1, the initial value of coupling efficiency and ratio of the tank circuit impedance to oscillator impedance were calculated for a supply current of 10 A and various work coil geometries and multiple arc electrode spacings, Table 7.1. The results show that in order to obtain an efficiency of coupling greater than 20% a relatively large electrode separation would be required i.e. greater than 40 mm. For this particular horizontal multiple arc system it was not possible to sustain a stable multiple arc discharge with an electrode spacing in excess of 30 mm even for arc currents as small as 10 A. Initial coupling efficiencies of less than 20% could therefore be expected when using the horizontal multiple arc system and because of this and the severe practical limitations associated with the horizontal multiple arc system, its use for initiating coupling to a high frequency power source was abandoned in favour of a vertical multiple arc system.

7.2. A Vertical Multiple Arc System

The major design consideration in the vertical multiple arc system in which the d.c. arcs are positioned in a vertical plane and spaced equally around the circumference of a circle, is the distance apart consistent with practical construction problems and the need for the arcs to coalesce to form a continuously conducting region.

Visual observations of two 20 A arcs in close proximity indicated that the arcs coalesced if the distance between their electrode centres was less than 18 mm. In order to estimate the maximum spacing between coalescing arcs and the dependence of this maximum spacing on arc current an analysis of the electrical conductivity distribution within a vertical multiple arc system was carried out.
<table>
<thead>
<tr>
<th>Diameter of multiple arc discharge (mm)</th>
<th>Number of coil turns</th>
<th>Efficiency of power transfer from tank circuit to load $n_2$ (%)</th>
<th>Overall coupling efficiency $\eta_2$ (%)</th>
<th>Tank impedance to oscillator impedance $Z_T/Z_L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>2</td>
<td>2.4</td>
<td>1.3</td>
<td>3.3</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>4.2</td>
<td>2.4</td>
<td>3</td>
</tr>
<tr>
<td>40</td>
<td>2</td>
<td>23</td>
<td>13</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>33</td>
<td>20</td>
<td>2.6</td>
</tr>
<tr>
<td>60</td>
<td>2</td>
<td>47</td>
<td>33</td>
<td>1.7</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>57</td>
<td>43</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 7.1 The coupling efficiency of electrical energy at 450 kHz into a horizontal multiple arc discharge.
7.2.1. Electrical Conductivity Distribution within a Vertical Multiple Arc System

The steady state energy balance equation for a unit volume of free burning arc (Equation 2.7) equates the heat losses due to conduction, convection and radiation with the electrical power input.

For an arc discharge along the axis of two vertically mounted electrodes the dominant heat transfer mechanism within the electrically conducting regions of the discharge is that of conduction (Chapter 2.3.1.).

If the arcs are considered symmetrical about their axes and the heat transfer in the axial direction is assumed to be negligible in comparison to that transferred radially, then the heat transfer by conduction between coalescing arcs in the same plane becomes one dimensional in the radial coordinate as expressed mathematically in Equation 2.8.

Because of the magnitude of the variation of the thermal conductivity with temperature encountered in atmospheric pressure arcs the product of the thermal conductivity and temperature gradient is replaced by the heat flux potential \( S \), which is defined in Equation 2.9. The energy balance equation then simplifies to Equation 2.10,

\[
- \frac{1}{r} \frac{d}{dr} \left( r \frac{dS}{dr} \right) = \sigma E^2
\]

which can be solved using relaxation techniques (McAdams 1954).
The electric field strength $E$, in the arc column is constant across the diameter of an arc and reliable data is available for the variation of electrical conductivity and heat flux potential against temperature (Emmons 1967). The correlation between arc current in argon and axial temperature is given in (Table 2.7) and the electric field strength was estimated, for arc currents up to 100 A, by the following relationship, (Krinberg 1964)

$$E = 2550 I^{-0.56}$$  \hspace{1cm} (7.1)

Calculations were made of the maximum spacing of the discharge axes in which an electrically conducting path between them is maintained for various arc currents. The results are shown in Table 7.2. For an arc current of 40 A the maximum separation of two coalescing discharges is approximately 14 mm. This simplified analysis did not take into account the convection effects or the interaction of the electromagnetic forces between the arcs of the multiple arc system, both of which should increase the minimum spacing.

7.2.2. Analysis of the coupling of R.F. Energy into a Vertical Multiple Arc Discharge

The coupling of electrical energy at 450 kHz into the vertical multiple arc discharge required the design of the induction heater work coil and an estimate of the work-piece geometry and physical properties.
Table 7.2: Maximum spacing for coalescing discharges

<table>
<thead>
<tr>
<th>Arc current (A)</th>
<th>Maximum spacing (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>7</td>
</tr>
<tr>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>40</td>
<td>14</td>
</tr>
<tr>
<td>100</td>
<td>24</td>
</tr>
</tbody>
</table>
Using the procedure described in Chapter 4.1. and Appendix 1, theoretical analysis of the various possible vertical multiple arc discharge configurations was carried out i.e. hollow cylindrical discharge, single centrally positioned discharge etc.

A hollow cylindrical discharge would give the greatest efficiency of coupling with only a limited number of isolated power supplies available each with a short time rating of only approximately 40 A.

The constant conductivity model for a single free-burning arc (chapter 2.3.) was used to provide a model for the vertical multiple arc discharge. In this model the term \( r_{0.5} \) was used which is defined as the radial distance from the axis of a single free burning arc to the point at which the electrical conductivity has fallen to one half of its value on the axis.

It has been shown (Kolesnikov et al 1964) that a free burning arc at a particular current can be approximated by an electrical conductor of diameter \( 2.2 r_{0.5} \) and electrical conductivity equal to that on the axis of the arc, \( \sigma_{\text{max}} \). The vertical multiple arc discharge was assumed to have an annular cross-section and a constant conductivity equal to that of a single free burning arc carrying the same current as each supply. The diameter of the annulus was assumed to be the same as the diameter of the circle around which the electrodes were placed and the thickness was approximated by the diameter of a single free-burning arc i.e. \( 2.2 r_{0.5} \). Table 7.3 shows the values used in the model of the temperature \( T_{\text{max}} \) and the electrical conductivity \( \sigma_{\text{max}} \), the thickness \( t_v \) of the discharge and the skin depth, \( \delta \), within the discharge at an operating frequency.
<table>
<thead>
<tr>
<th>Arc current (A)</th>
<th>Temperature on axis (K)</th>
<th>Electrical conductivity on axis (S/m)</th>
<th>Equivalent diameter of single free burning arc (mm)</th>
<th>Skin depth (mm)</th>
<th>Ratio of thickness of cylindrical load to skin depth</th>
<th>Ratio of diameter of cylindrical load to skin depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>9,800</td>
<td>2940</td>
<td>1.6</td>
<td>3.5</td>
<td>0.25</td>
<td>2.17</td>
</tr>
<tr>
<td>20</td>
<td>10,340</td>
<td>3350</td>
<td>2.1</td>
<td>4.6</td>
<td>0.35</td>
<td>2.3</td>
</tr>
<tr>
<td>40</td>
<td>10,880</td>
<td>3700</td>
<td>2.5</td>
<td>5.5</td>
<td>0.45</td>
<td>2.4</td>
</tr>
<tr>
<td>60</td>
<td>11,200</td>
<td>4100</td>
<td>2.9</td>
<td>6.4</td>
<td>0.54</td>
<td>2.5</td>
</tr>
<tr>
<td>80</td>
<td>11,430</td>
<td>4370</td>
<td>3.3</td>
<td>7.2</td>
<td>0.63</td>
<td>2.6</td>
</tr>
<tr>
<td>100</td>
<td>11,600</td>
<td>4500</td>
<td>3.6</td>
<td>8.0</td>
<td>0.72</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Table 7.3 Values of parameters used in model of vertical multiple arc discharge for various arc currents.
Table 7.4 Overall coupling efficiency for electrical energy at 450 kHz into the vertical multiple arc discharge.

<table>
<thead>
<tr>
<th>Arc current I (A)</th>
<th>Overall efficiency of coupling η (%)</th>
<th>Ratio of tank circuit impedance to oscillator impedance $\frac{Z_T}{Z_o}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>36</td>
<td>1.67</td>
</tr>
<tr>
<td>20</td>
<td>49</td>
<td>1.2</td>
</tr>
<tr>
<td>40</td>
<td>53</td>
<td>1</td>
</tr>
<tr>
<td>60</td>
<td>57.5</td>
<td>0.8</td>
</tr>
<tr>
<td>80</td>
<td>58</td>
<td>0.63</td>
</tr>
<tr>
<td>100</td>
<td>58</td>
<td>0.53</td>
</tr>
</tbody>
</table>

of 450 kHz. The diameter of the hollow cylindrical load formed by the vertical multiple arc system, $D_v$, was approximately 30 mm and Table 7.3 also shows the ratio of the skin depth, $\delta$, to the discharge thickness, $t_v$, and diameter, $D_v$. 

Maximum power transfer to the tank circuit is achieved when the impedance of the tank circuit, \( Z_T \), is equal to the impedance required by the oscillator, \( Z_G \). Using a work coil of 7 turns, 63 mm long and 80 mm in diameter, the value of the total effective tank circuit impedance was calculated for all values of arc current investigated. Table 7.4. shows the variation of the overall efficiency of coupling power into the discharge and the ratio of tank impedance, \( Z_T \), to oscillator impedance \( Z_G \) for various arc currents. The efficiency of coupling into a vertical multiple arc discharge using 40 A d.c. arcs in argon would therefore be approximately 50 % and the high frequency power source would still have a high efficiency once the combined large volume discharge was formed.

7.2.3. Construction of Vertical Multiple Arc Assembly

A vertical multiple arc system was constructed based on the analysis of the previous sections and supplied by the same transformer and electrical supply that was used in the tests on the horizontal multiple arc system. The electrical supply circuit is shown in Fig. 7.1 and the assembly in Fig. 7.2.

The electrode holder Fig. 7.3 enabled 6 pairs of electrodes of 6 mm diameter to be used and a laminar gas flow of argon was fed to the discharge region through a brass plenum chamber mounted above the torch. The gas flow rate was measured with a variable area flowmeter over the range \( 10^{-4} \) m\(^3\)/s to \( 13 \times 10^{-4} \) m\(^3\)/s.

The insulated electrode holder contained six 10 mm diameter brass clamps, to hold the carbon electrodes which were situated equally spaced on a pitch circle of 30 mm diameter. A 25 mm thick Syndanyo sheet was placed between the electrode holders and the
Fig. 7.1. Electrical circuit used with vertical multiple arc system.
Fig. 7.2 Vertical multiple arc system.
Fig. 7.3 Electrode holder of vertical multiple arc assembly.

discharge region to prevent deterioration of the insulated electrode holder.

A silica tube of 190 mm length and 70 mm internal diameter surrounded the discharge region and electrically isolated the d. c. arcs from the work coil of the high frequency power source. The work coil had 7 turns of 80 mm diameter and a total length of 63 mm. It was constructed of 6 mm external diameter water-cooled copper tubing. This relatively small diameter was chosen to increase the work coil turns per metre or power density available from the high frequency power source above that used in the previous tests (Chapter 4.1.).
The separation of each pair of electrodes could be adjusted simultaneously to a maximum of 100 mm. The arcs were initiated by short circuiting the electrodes and then slowly drawing them apart to form the arcs.

7.2.4. Characteristics of the Vertical Multiple Arc Discharge

The electrodes were initially connected with the anode vertically above its corresponding cathode. Filamentary arcs were formed when the electrodes were withdrawn from the short circuited position. As the arc length was increased the electromagnetic forces of attraction between the individual arcs caused the formation of a narrow conducting region along the central axis of the discharge vessel, although conducting paths to each electrode root still existed. This formation of a narrow conducting region was predominantly dependent on the arc length, although the tendency to form did increase slightly with arc current. Beyond an arc length of approximately 20 mm a reduction of arc current to less than 5 A did not stop the formation of a central conducting zone. Increasing the argon flow rate up to $13 \times 10^{-4}$ m$^3$/s increased the instability of the system and slightly increased the tendency to form a central conducting zone.

Reversing the connections to each alternate electrode pair, such that each arc was then adjacent and diametrically opposite arcs with an opposite direction of current flow, reduced the effect of the electromagnetic forces to form a narrow conducting zone. Adjacent arcs were now repelled and the whole discharge configuration tended to spread apart. The filamentary arcs formed with this second electrical connection to the electrodes showed no tendency to constrict on the axis but moved slightly radially outwards. Fig. 7.4 shows
Fig. 7.4 Vertical multiple arc discharge formed by six electrode pairs in air

A vertical multiple arc discharge with this second electrical connection and in air to facilitate photography of the discharge. The photographs were taken using Ilford H. P. 4 film at f22 with a one millisecond exposure.

The voltage-current characteristics were derived from oscilloscope traces of the arc voltage and current waveforms for both the vertical multiple arc discharge and for a single arc. Electrode
spacings of 7 mm, 20 mm and 40 mm were used with argon flow rates up to $7 \times 10^{-4} \text{ m}^3/\text{s}$. The results are shown in Fig. 7.5.

Increasing the argon flow rates cooled the outer zones of the multiple arc discharge and hence the arc voltage required for a particular arc current was increased, Fig. 7.5a. The arc voltage was also increased with electrode spacing, Fig. 7.5b.

Comparison of the voltage–current characteristic of the vertical multiple arc discharge and a single arc at a constant gas flow showed that at an electrode spacing of 7 mm the two discharges were similar as no coalescing took place within the multiple arc system and the electrode phenomena dominated. Increasing the electrode spacing to 20 mm allowed interaction between the arc columns of the multiple arc system. The conductance of the multiple arc discharge was always greater than that of the single arc, Fig. 7.6, as in the case of the horizontal multiple arc system. The difference in conductance was less for the vertical system, however, as the distance between the individual arcs was greater and hence their interaction less.

7.2.5. Superposition of R.F. Power on Vertical Multiple Arc Discharge

In the production of a large volume discharge by means of the superposition of a d.c. and an induction coupled discharge the principal obstacle encountered was the inability to inductively couple energy in a manner which would enable a reduction in operating frequencies to values more amenable to industrial application. However, when r.f. energy at 450 kHz i.e. an order of magnitude below the operating frequency usually associated with induction coupled discharges, was applied to a vertical multiple arc discharge consisting of 6 d.c. arcs of approximately 10A each and length 40mm interaction could be visually detected by the formation of a large diameter and more intense discharge. The values of anode current, grid current and tank current were also observed to change appreciably when the d.c. current was raised between 8A and 20A for an argon flow rate of $3 \times 10^{-4} \text{ m}^3/\text{s}$. Typical values of the operating parameters of both the d.c. and r.f. power sources are as follows:-
Fig. 7.5 Variation of the voltage and current characteristic of the vertical multiple arc discharge with
a) Argon flow rate
b) Electrode spacing
Fig. 7.6 Comparison of voltage and current characteristic of single arc and vertical multiple arc discharge.
D.C. arc current (each supply) = 20A
D.C. arc voltage = 20V
Total d.c. power input = 2.4kW

Anode voltage = 7.4kV
Anode current = 1.6A

Estimated overall efficiency of coupling (Table 4.2) = 60%

Estimated Total r.f. power input = 6.7kW

The r.f. power input varied insignificantly with d.c. arc current or electrode spacing once the large volume discharge had formed. Investigations were therefore concentrated on the parameters of the multiple arc system i.e. arc length, arc current and gas flow rate to achieve the formation of a large volume discharge.

Below 8A, no interaction could be detected either from the intensity of the discharge or from the values of the induction heater tank circuit current and voltage.

For electrode spacings below 20 mm no change could be detected in the discharge on the application of the r.f. power. Increasing the electrode spacing to in excess of 30 mm, the formation of a more intense and diffuse discharge was seen which occupied a diameter of approximately 30 mm centred on the axis of the torch and a length equal to the electrode spacing. The 12 arc roots could still however be clearly observed. The coupling of r.f. energy increased the conductance of the multiple arc discharge and the voltage/current characteristics for various argon flow rates and electrode spacings were noted in Fig. 7.7.

Fig. 7.7a shows the variation of the voltage/current characteristic with argon flow rate between approximately $3.10^{-4}$ m$^3$/s and $7.10^{-4}$ m$^3$/s for an electrode spacing of 40 mm. The measurements of the voltage and current were taken directly from photographs of the oscilloscope wave forms and the conductance of the discharge increased by approximately 1.5 times on the application of the r.f. power.
Fig. 7.7 Variation of characteristic of vertical multiple arc system in the presence of r.f. power with

a) Argon flow rate  

b) Electrode spacing
and the subsequent formation of the diffuse discharge.

The variation of the voltage-current characteristic with electrode spacing in the presence of r.f. power is shown in Fig. 7.7b. Below an electrode spacing of 20 mm the application of r.f. power had no effect on the discharge whilst above 50 mm the power input caused excessive overheating of the discharge vessel and the multiple arc discharge, without the superposition of r.f. power was not very stable.

To summarise for electrode spacings in excess of 20 mm arc currents in each supply greater than 8A, and argon flow rates between approximately $3 \times 10^{-4}$ m$^3$/s and $7 \times 10^{-4}$ m$^3$/s, it was possible to inductively couple approximately 7kW of energy at 450 kHz into a vertical multiple arc system. The principal objective of inventing a method by which energy can be inductively coupled into a combined discharge in a manner ideally suited to application at relatively low operating frequencies had therefore been achieved.

7.3. Summary of Results.

Attempts to couple r.f. energy at 450 kHz into a horizontal multiple arc discharge proved unsuccessful. Analysis of the overall efficiency of coupling showed that multiple arc discharge greater than 40 mm diameter would be required for efficient coupling. The horizontal multiple arc system used was unable to sustain a stable discharge of diameter greater than 30 mm with subsequent coupling efficiencies below 20%. Because of this and the severe practical limitations associated with this horizontal configuration the use of this form of multiple arc to initiate the coupling of r.f. energy was abandoned.

A theoretical analysis based on that described in Chapter 4 was used to estimate the overall coupling efficiencies between the possible vertical multiple arc discharge configurations and a high frequency power source at 450 kHz. A hollow cylindrical vertical multiple arc discharge system was subsequently designed and constructed and the characteristics of the multiple arc discharge formed by it were established.
The parameters of the multiple arc system i.e. arc current, arc length and gas flow rate, needed to achieve appreciable coupling from the high frequency power source were determined. Inductive coupling of up to 7kW of energy at 450 kHz into the vertical multiple arc system was successfully carried out with the subsequent formation of a large volume discharge. The principle objective behind the multiple arc discharge investigations (Chapter 6 and 7) was therefore achieved.
CONCLUSIONS AND RECOMMENDATIONS

The results and their implications are summarised and possible areas of further research are suggested.
8.1. Summary of Results

The concept of forming a large volume discharge using a number of power sources electrically isolated from each other was formulated.

A vertical multiple arc system was developed and used to initiate a large volume d.c. and high frequency (450 kHz) combined discharge. An order of magnitude reduction in the operating frequency associated with induction coupled discharges of similar power levels has therefore been achieved.

A horizontal multiple arc configuration was developed which formed a large volume of ionised gas of an apparently diffuse nature.

An analysis of the efficiency of coupling between d.c. arcs and induction coupled power sources was developed and for the first time an estimate of the overall coupling efficiency including the effects of load matching was obtained.

A large volume of ionised gas was formed using a combination of d.c. and high frequency (6.5 MHz) power and its characteristics studied. The experimental results of overall efficiency of coupling were correlated with those predicted by the analysis also developed in this thesis.

A review of discharge processes relevant to the understanding of the production of large volume discharges has been presented that is unique in its coverage.
A critical review of the production of thermal plasmas for chemical and metallurgical synthesis has been made enabling the relative merits of the individual methods of production to be considered.

The possibility of using high frequency electrical energy in an E field system for the production of a large volume high temperature discharge was rejected after a theoretical and experimental investigation.

An explanation for the stability of coalescing multiple arcs from the same power source has been put forward.

Fundamental information on the behaviour of coalescing arcs has been obtained and conditions for stable operation suggested.

The characteristics of the vertical multiple arc system were studied and the influence of arc length, arc current and gas flow rate determined with and without the superposition of induction coupled electrical energy.

A steady state analysis of the electrical conductivity distribution within a vertical multiple arc system was carried out using relaxation techniques.

Explanations of the nature of the discharges formed by three horizontal multiple arc configurations have been advanced.

The influence of the electrode configurations on the current distribution within a horizontal multiple arc system has been studied including the use of an analogue modelling technique.
The apparently diffuse discharge formed by the horizontal multiple arc system was investigated using single shot photographs and high speed photographic techniques with low values of persistence of luminosity.

Use of horizontal multiple arc system to initiate a combined d.c. and high frequency discharge has been evaluated.

A theoretical formulation of an equivalent conductor of constant conductivity representative of an arc column has been made.

The problems associated with inductively coupling electrical energy into axially mounted d.c. arcs have been analysed and methods of increasing the overall efficiency of coupling at frequencies of 450 kHz and below were assessed.

The analysis was also applied in the design of the vertical multiple arc system which successfully initiated a large volume discharge.

A discharge vessel enabling a d.c. and high frequency (6.5 MHz) combined discharge to be formed was designed and constructed.

Overall energy balances of the combined discharges were carried out and the effects of changes in the operating parameters determined.

An abrupt change in the characteristics of a combined discharge dependent on the magnitude of high frequency electrical power input was noted for the first time.

The heat transfer mechanisms within each section of a combined discharge vessel were evaluated and used in the establishment of a generalised design procedure for this type of discharge vessel.
8.2. Possible Areas of Future Research

The major achievement of the present work is the discovery of a method of efficiently coupling electrical energy into a d.c. arc configuration which, it is envisaged, can be adapted to operating frequencies within the range of static inverter power supplies with the subsequent reduction in capital and running costs of the process. Estimates have been made of the number of 100 A power supplies needed and the total d.c. power requirements to initiate a combined d.c. and induction coupled discharge for various operating frequencies, Fig. 8.1 and Fig. 8.2. A detailed explanation of the assumptions used in making these estimates is given in Appendix 4. For an operating frequency of 10 kHz, which is within the range of modern static inverters, approximately twenty 100 A d.c. power supplies would be required and a total d.c. power input of approximately 100 kW, giving a discharge diameter in excess of 150 mm. Further progress in the reduction in the operating frequency of a combined d.c. and induction coupled discharge would therefore seem feasible and further research in this area is recommended.

During the course of this present investigation many areas for more detailed research presented themselves but could not be pursued in the depth required if the initial aims outlined in the introduction were to be fulfilled.

Many more aspects of the interaction of coalescing arcs need to be investigated. Only three electrode configurations of the horizontal multiple arc system have been studied although many more are possible; the use of totally isolated power supplies is an extreme case and a clear understanding of the magnitude and position of arc stabilising resistances which can maintain stable coalesced arcs is needed; the steady state theoretical analysis of the electrical
Fig. 8.1 The number of 100A power supplies in vertical multiple arc configuration required to initiate a combined discharge.

Fig. 8.2 Power requirements of vertical multiple arc configuration required to initiate a combined discharge.
conductivity distribution within multiple arc systems could be more accurately and flexibly carried out by computer program; and the spectroscopically measured absolute temperature distribution would aid further investigation into multiple arc systems.

Industrial application of multiple arc systems would also require further research to be carried out. The use of magnetic deflection or a modified gas input arrangement may reduce the instabilities due to buoyancy forces envisaged in large scale horizontal multiple arc systems. Improvements can be made in the design of the combined discharge vessel by analysing the gas flow patterns such that discharge stability and particulate feedstock entrainment are maximised; increasing the efficiency of the d.c. supply; incorporating a d.c. vertical multiple arc configuration to reduce operating frequency requirements; and installing a starting mechanism which can be more easily adapted to industrial use.

In the present economic climate abrupt changes in the price of fuels such as oil and gas are commonplace and a continuous check on the commercial feasibility of plasma processes should be made. Far greater use of plasma and other electrically based industrial processes is envisaged for the future as the awareness of the eventual exhaustion of alternative energies supplies increases and the availability, even in the short term, of alternative fuels becomes even more subject to political pressures and severe economic instabilities.
APPENDICES
APPENDIX 1

A.1. Induction Heating Theory

The theory developed by Baker (1957) and subsequently by Simpson (1960) is based on the calculation of the total magnetic flux linking the turns of the work coil in terms of the magnetic field strength at the surface of the conductor. This is related to the work coil current and voltage required and an equivalent circuit model is derived which can be solved by circuit analysis to give the efficiency of coupling including an estimate of the load matching conditions.

A.1.1. The Equivalent Circuit

The magnetic flux within the air gap between the work-piece and the work coil, \( \phi_g \) (Wb) and that linking the work coil turns \( \phi_c \) (Wb), Fig. A.1, are given by, (Baker 1957)

\[
\phi_g = \mu_0 H_0 A_g \\
\phi_c = \mu_0 H_0 \frac{k_r p_c \delta_e}{2} (1 - j) 
\]

(A.1)

(A.2)

where

\[
\begin{align*}
\mu_0 & = \text{the permeability of free space} \\
H_0 & = \text{the peak magnetic field strength at the surface} \\
& \quad \text{of the conductor (A/m)} \\
A_g & = \text{the air gap cross-section (m}^2) \\
k_r & = \text{the empirical coil resistance factor} = 1.15 \\
(Baker \ 1957)
\end{align*}
\]
Fig. A.1 A typical induction heating load.

\[ p_c = \text{the perimeter of the work coil (m)} \]

\[ \delta_c = \text{the skin depth in copper (m)} \]

The magnetic flux linked directly with a non-magnetic work-piece given by the solution of Maxwell's equation as,

\[
\phi_w = \frac{\sqrt{2} \pi \mu_0 a H_0 \delta}{\text{bei} \frac{\sqrt{2}a}{\delta} - j \text{ber} \frac{\sqrt{2}a}{\delta}} \left[ \frac{\text{bei} \frac{\sqrt{2}a}{\delta} - j \text{ber} \frac{\sqrt{2}a}{\delta}}{\text{ber} \frac{\sqrt{2}a}{\delta} + j \text{bei} \frac{\sqrt{2}a}{\delta}} \right]
\]  

(A.3)
This equation can be simplified to

\[ \phi_w = \mu_0 A_w H_0 (P - jQ) \]  

(A.4)

where \( A_w \) = the area of work-piece (\( m^2 \)), and

\[ P = \frac{\sqrt{2} \delta}{a} \cdot \frac{\text{bei} \sqrt{2} a \cdot \text{ber} \sqrt{2} a}{\text{ber}^2 \sqrt{2} a + \text{bei}^2 \sqrt{2} a} \]  

(A.5)

\[ Q = \frac{\sqrt{2} \delta}{a} \cdot \frac{\text{bei} \sqrt{2} a \cdot \text{ber} \sqrt{2} a + \text{ber} \sqrt{2} a \cdot \text{bei} \sqrt{2} a}{\text{ber}^2 \sqrt{2} a + \text{bei}^2 \sqrt{2} a} \]  

(A.6)

\[ P \text{ and } Q \text{ are dimensionless flux factors, defined in equations } (A.5) \text{ and } (A.6) \text{ respectively, and are functions of the work-piece geometry, resistivity, permeability and the applied frequency. The solutions of equations } (A.5) \text{ and } (A.6) \text{ have been carried out and the values of } P \text{ and } Q \text{ derived for a number of different work-piece and coil geometries including solid and thin walled cylinders, see Fig. A.2, and A.3. (Simpson 1960).} \]

The total magnetic flux linked with the work coil \( \phi_T \) is

\[ \phi_T = \phi_g + \phi_c + \phi_w \]  

(A.7)
Fig. A. 2 Dimensionless flux factors P and Q for a solid cylinder (Simpson 1960). 

hence 

\[ \phi_T = \mu H \left[ A_g + A_w P + \frac{k \rho \delta r}{c} \right] - j \left[ A_w Q + \frac{k \rho \delta c}{2} \right] \]  

(A.8)
Fig. A.3 Dimensionless flux factors $P$ and $Q$ for a thin walled cylinder (Simpson 1960). Use only when $\frac{t}{2a} \leq 0.10$, $\frac{t}{\delta} \leq 0.20$.

The coil voltage, $E_c$, which must be applied to establish the field intensity $H_o$ at the surface of the work-piece is

$$E_c = j \sqrt{2\pi} N_c f \phi_T$$  \hspace{1cm} (A.9)
which can be written therefore as,

\[ E = j\nu_0^2 N \frac{\mu_0 H}{c} \left[ (A + A_P + \frac{k_r P_c \delta_c}{2}) - j(A_w Q + \frac{k_r P_c \delta_c}{2}) \right] \]  \hspace{1cm} (A.10)

If the work coil is assumed to be long in comparison with its diameter then the magnetic field strength inside it, is given by

\[ H_0 = \frac{N_c I_c \sqrt{2}}{l_c} \]  \hspace{1cm} (A.11)

where
\[
\begin{align*}
N_c &= \text{the number of coil turns} \\
l_c &= \text{the length of the work coil (m)} \\
I_c &= \text{the current flowing in the work coil (A)}
\end{align*}
\]

rearranging,

\[ I_c = \frac{H_0 l_c}{\sqrt{2} N_c} \]  \hspace{1cm} (A.12)

From equations (A.10) and (A.12) the impedance of the work coil \( Z_c \) can be found,

\[ Z_c = \frac{2\pi f N_c l_c}{I_c} \left[ (A + A_P + \frac{k_r P_c \delta_c}{2}) + j(A_w Q + A_w P + \frac{k_r P_c \delta_c}{2}) \right] \]  \hspace{1cm} (A.13)
The equivalent circuit for an induction heating load with a long work coil follows from equation (A.13) and is shown schematically in Fig. A.4, where

\[ R_w = \frac{2\pi f N^2 \mu}{l_c} \quad (\Omega) = \text{the reflected work-piece resistance} \quad (A.14) \]

\[ R_c = \frac{2\pi f N^2 \mu}{l_c} \frac{k_p c}{2} \quad (\Omega) = \text{the reflected work-coil resistance} \quad (A.15) \]

\[ X_c = \frac{2\pi f N^2 \mu}{l_c} \frac{k_p c}{2} \quad (\Omega) = \text{the reactance due to work coil flux} \quad (A.16) \]

\[ X_g = \frac{2\pi f N^2 \mu}{l_c} (A_g) \quad (\Omega) = \text{the reactance due to air-gap flux} \quad (A.17) \]

\[ X_w = \frac{2\pi f N^2 \mu}{l_c} (A_w P) \quad (\Omega) = \text{the reactance due to work-piece flux} \quad (A.18) \]

\[ X_1 = X_c + X_g + X_w \quad (\Omega) \quad (A.19) \]

For work coil geometries usually associated with induction coupled discharges, especially at frequencies below the megahertz range (Vogel et al 1971), the reluctance of the external flux path must be taken into account. This is done in the equivalent circuit model by the addition of a parallel inductance \( X_e \) (Baker 1957) where

\[ X_e = \frac{2\pi f N^2 \mu}{l_c} \frac{1}{1.8} \quad (\Omega) \quad (A.20) \]
Fig. A.4 Equivalent circuit for an induction heated load with a long work coil.

The application of basic circuit analysis techniques reduces this equivalent circuit to a form similar to that shown in Fig. A.4 with \( R_w \) and \( X_1 \) are replaced by \( R'_w \) and \( X_o \) respectively, where

\[
R'_w = \frac{R_w X_e^2}{R_w^2 + (X_1 + X_e)^2} \quad (\Omega) \tag{A.21}
\]

and

\[
X_o = \frac{X_e (R_w^2 + X_1^2 + X_e X_1)}{R_w^2 + (X_1 + X_e)^2} \quad (\Omega) \tag{A.22}
\]
Using the equivalent circuit analysis the total effective resistance of the work coil $R'_o$ is the sum of the work coil resistance $R_c$ and the effective resistance of the work piece $R'_w$. The total tank circuit resistance $R_T$ can then be obtained by adding $R'_o$ to the resistance of any leads from the induction heater to the work coil and the resistance of any load-matching series inductance. The efficiency of power transfer from the tank circuit to the work-piece $\eta_4$ is then

$$\eta_4 = \frac{R_w}{R_T}$$

(A. 23)

and the impedance of the tank circuit $Z_T$ is

$$Z_T = \frac{L_T}{C_T R_T}$$

(A. 24)

where $L_T$ is the total effective inductance (H) formulated in a similar manner to $R_T$, and $C_T$ is the tank circuit capacitance (F).
APPENDIX 2

Design of power supplies for use with a combined discharge assembly.

DATA:-

- Power required into gas stream = 6 kW
- Diameter of discharge required = 20 mm
- Discharge temperature = 7000 K
- Residence time = 0.1 s
- Gas flow rate through discharge = $2 \times 10^{-4}$ m$^3$/s

CALCULATIONS:- Following method described in Fig. 5.23, and Chapter 5.5.

(a) HIGH FREQUENCY POWER SUPPLY

- Power required into gas stream = 6 kW
- Efficiency of power input to gas stream = 50 %
- Power input to discharge = 12 kW
- and r.f. power input = 2.4 kW
  (i.e. 20 %)

- Diameter of discharge required = 20 mm
- Diameter of work coil = 60 mm
- Operating frequency (Fig. 5.24) = 6.5 MHz
- Gas flow rate through discharge = $2 \times 10^{-4}$ m$^3$/s
- Total gas flow rate (assume 80 % by-passing) = $10 \times 10^{-4}$ m$^3$/s
Residence time = 0.1 s
Length of discharge = 70 mm
Length of work coil = 70 mm

If high frequency supply is in existence with, for example, the operating parameters as shown in Table 5.1., Then using the analysis of Chapter 4.1., and assuming work coil is whole of tank circuit,

Overall efficiency = 68 %
Power input to high frequency supply = 3.5 kW

If the complete high frequency power source is to be specified then,
Power input/unit length = 3.5 \times 10^4 \text{ W/m}

Assuming for design purposes work coil current of 100 A then,
Number of work coil turns (Fig. 5.25) = 2 turns

Using analysis of Appendix 1, again assuming work coil is whole of tank circuit

Total tank circuit resistance \( R_T \) = 0.2 \Omega
Total tank circuit inductance \( L_T \) = 0.14 \mu\text{H}
Work coil power factor = 0.035
Work coil voltage = 570 V
Work coil volt-amperes = 57 kVA

(b) D.C. POWER SUPPLY

Length of work coil = 70 mm
Electrode separation = 150 mm
Arc voltage = 166 V
D.C. Power input to discharge = 9.6 kW

Efficiency of power input to gas stream ≥ 90 %

Power rating of d.c. supply ≥ 10.7 kW

and Arc current ≥ 65 A
APPENDIX 3

A.3. Related Background Reading

As part of the background work to this thesis many articles were consulted which are not directly referred to in the text. As no compatible state of the art review exists the references are detailed in this bibliography to assist future research workers. They are listed in three sections entitled (1) plasma diagnostic techniques, (2) induction coupled plasmas and (3) chemical and metallurgical applications of plasmas.

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A.4. Low Frequency Application of Vertical Multiple Arc System

The feasibility of using the vertical multiple arc system to couple electrical energy into a d.c. arc configuration at frequencies below those normally associated with induction coupled discharges, has been shown. In order to assess the usefulness of this system to reduce the operating frequency to within the range of the more efficient static inverter sets (Chapter 1) the number, and typical size of d.c. power supplies required must be estimated.

Assuming that each d.c. power supply is capable of 100 A and that a hollow cylindrical electrode configuration is used then the discharge approximates to one of cylindrical shape with a diameter equal to that of electrode configuration, a thickness of 8.8 mm and an electrical conductivity of 4500 S/m (Chapter 7.2.2).

Figures A.2. and A.3. show the values of the dimensionless flux factors $P$ and $Q$ as functions of the ratio of the workpiece diameter to skin depth for various values of the ratio of workpiece thickness to skin depth.

The power input to a workpiece is directly proportional to the flux factor $Q$ (Chapter 4.1 and Appendix 1) and as such has a maximum value dependent on the workpiece dimensions and skin depth $\delta$. As the workpiece thickness is assumed to be constant and equal to 8.8 mm then for any operating frequency there is a diameter of the multiple arc system which will enable the maximum power to
be coupled to the discharge. For an operating frequency of 10 kHz the effective skin depth within the hollow cylindrical load formed by the multiple arc discharge would be 74.5 mm and using Fig. A.3 the maximum value of $Q$ and hence the maximum value of power input is obtained with a discharge diameter of 1.26 m. However, the use of a vertical multiple arc configuration to initiate a combined discharge does not require a system capable of coupling the maximum power input initially. The results of Chapter 7 show that a multiple arc configuration which can initially couple less than 25% of the maximum power available is still sufficient to initiate a large volume discharge. For an operating frequency of 10 kHz therefore a multiple arc configuration of only 150 mm would be required which would necessitate the use of approximately twenty 100 A power supplies. Fig. 8.1 shows the estimated number of 100 A power supplies required to initiate a combined d.c. and induction coupled discharge for various frequencies.

The voltage gradient within the column of a 100 A free burning arc in argon is approximately 0.2 V/mm (Krinberg 1964). Assuming that the length of the discharge is equal to its diameter, as it is in most low frequency induction coupled discharges used to date (Vogel et al 1971), then the power input required to initiate a combined discharge can be calculated and this is shown as a function of frequency, Fig. 8.2.
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