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MULTIPLE ELECTRIC ARC DISCHARGES

by

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A DOCTORAL THESIS

Submitted in partial fulfilment of the requirements for the award of Ph.D. of the Loughborough University of Technology, 1984.

Supervisor: Dr. J. S. Harry

Department of Electronic and Electrical Engineering

by R. Knight, 1984.
SUMMARY

The conditions under which stable separate and coalesced multiple parallel arcs can be operated from a common power supply have been investigated and analysed. Results indicate that any number of stable parallel arcs can be maintained provided each arc is individually stabilised.

Multiple electrode configurations relevant to industrial plasma processes have been investigated including coalesced discharges with multiple, individually stabilised, anodes and cathodes and discharges with multiple cathodes and a common anode.

The results have been applied to a number of plasma processes including a horizontal multiple discharge system, capable of producing large volumes of ionised gas with a high degree of uniformity, a plasma furnace incorporating multiple dc plasma torches operating from a single power supply, and a high-current, non-consumable, multiple cathode assembly for use in dc arc furnaces.

A horizontal multiple arc system and a plasma furnace incorporating three plasma torches have been designed at the University and are in use for processing material at Cambridge University and in industry respectively.
ACKNOWLEDGEMENTS

I am deeply grateful to my supervisor and friend, Dr. J. E. Harry, for his encouragement, advice, guidance and patience throughout this work.

I am grateful to SERC for the financial support over the years which made this work possible. I would also like to thank the numerous technicians who have supported me and constructed equipment.

Finally, my thanks go to my parents, my fiancee Pam and to my 'edge'.
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Power dissipated in the stabilising resistors in multiple arc heaters.  

Magnetically rotated arc heaters suitable for gas heating or material processing.  

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CHAPTER 6  
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8.4 Variation of electrical parameters during a melting cycle.  
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APPENDIX 5  
A5.1 Graphite savings due to the use of multiple electrodes.
LIST OF SYMBOLS

SI units have been used wherever possible throughout this text. Non SI units occur only as duplicates (for example lb/in² or PSI) for clarity.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>c</td>
<td>velocity of light in vacuo (3 x 10⁸)</td>
<td>(m/s)</td>
</tr>
<tr>
<td>d</td>
<td>arc diameter</td>
<td>(m)</td>
</tr>
<tr>
<td></td>
<td>electrode separation</td>
<td>(m)</td>
</tr>
<tr>
<td></td>
<td>diameter of multiple graphite electrodes</td>
<td>(m)</td>
</tr>
<tr>
<td>f</td>
<td>frequency of supply</td>
<td>(Hz)</td>
</tr>
<tr>
<td>h</td>
<td>coefficient of heat transfer</td>
<td>(W/m²/K)</td>
</tr>
<tr>
<td></td>
<td>Planck's constant (6.626 x 10⁻³⁴)</td>
<td>(J)</td>
</tr>
<tr>
<td>j</td>
<td>current density</td>
<td>(A/m²)</td>
</tr>
<tr>
<td>k</td>
<td>thermal conductivity</td>
<td>(W/m²/K)</td>
</tr>
<tr>
<td></td>
<td>Boltzmann's constant (1.38 x 10⁻²³/8.6 x 10⁻⁵)</td>
<td>(J/K/eV)</td>
</tr>
<tr>
<td>l</td>
<td>arc length</td>
<td>(m)</td>
</tr>
<tr>
<td>n</td>
<td>number of multiple electrodes</td>
<td>(--)</td>
</tr>
<tr>
<td>r</td>
<td>arc radius</td>
<td>(m)</td>
</tr>
<tr>
<td>r₀,₁,₂</td>
<td>resistance of sections of coalescing arcs</td>
<td>(Ω)</td>
</tr>
<tr>
<td>t</td>
<td>time constant</td>
<td>(s)</td>
</tr>
<tr>
<td>A</td>
<td>area</td>
<td>(m²)</td>
</tr>
<tr>
<td>B</td>
<td>magnetic flux density</td>
<td>(T)</td>
</tr>
<tr>
<td>D</td>
<td>diameter of single graphite electrode</td>
<td>(m)</td>
</tr>
<tr>
<td>E</td>
<td>electric field strength</td>
<td>(V/m)</td>
</tr>
<tr>
<td>E₁,₂</td>
<td>energy difference between excited atomic or ionic states</td>
<td>(eV)</td>
</tr>
<tr>
<td>F</td>
<td>force</td>
<td>(N)</td>
</tr>
<tr>
<td>I</td>
<td>current</td>
<td>(A)</td>
</tr>
<tr>
<td>Iₘ</td>
<td>mean value of current</td>
<td>(A)</td>
</tr>
<tr>
<td>Iₜ</td>
<td>total current in a circuit with multiple parallel arcs</td>
<td>(A)</td>
</tr>
<tr>
<td>Iₙ,₂</td>
<td>current in individual branches of a coalescing arc circuit</td>
<td>(A)</td>
</tr>
<tr>
<td>L</td>
<td>inductance</td>
<td>(H)</td>
</tr>
<tr>
<td>M</td>
<td>electrode erosion rate</td>
<td>(kg/C)</td>
</tr>
<tr>
<td>R</td>
<td>electrical resistance</td>
<td>(Ω)</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Unit</td>
</tr>
<tr>
<td>--------</td>
<td>------------------------------------------</td>
<td>-----------------</td>
</tr>
<tr>
<td>$R_L$</td>
<td>resistance per unit length</td>
<td>($\Omega/m$)</td>
</tr>
<tr>
<td>$R_O$</td>
<td>resistance common to two parallel arc circuits</td>
<td>($\Omega$)</td>
</tr>
<tr>
<td>$R_S$</td>
<td>stabilising resistance</td>
<td>($\Omega$)</td>
</tr>
<tr>
<td>$R_{ac(n)}$</td>
<td>ac resistance of n multiple electrodes connected in parallel</td>
<td>($\Omega/m$)</td>
</tr>
<tr>
<td>$S$</td>
<td>heat conduction potential</td>
<td>(-)</td>
</tr>
<tr>
<td>$T$</td>
<td>temperature</td>
<td>(K)</td>
</tr>
<tr>
<td>$m$</td>
<td>mass</td>
<td>(Tonne)</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>$V_S$</td>
<td>supply voltage</td>
<td>(V)</td>
</tr>
<tr>
<td>$P_L$</td>
<td>power dissipation per unit length</td>
<td>($W/m$)</td>
</tr>
<tr>
<td>$Z$</td>
<td>impedance</td>
<td>($\Omega$)</td>
</tr>
<tr>
<td>$Z_C$</td>
<td>impedance common to two parallel arc circuits</td>
<td>($\Omega$)</td>
</tr>
<tr>
<td>$\delta$</td>
<td>skin depth</td>
<td>(m)</td>
</tr>
<tr>
<td>$\lambda$</td>
<td>wavelength</td>
<td>(nm)</td>
</tr>
<tr>
<td>$\mu_0$</td>
<td>permeability of free space ($4\pi \times 10^{-7}$)</td>
<td>($H/m$)</td>
</tr>
<tr>
<td>$\nu$</td>
<td>frequency</td>
<td>(Hz)</td>
</tr>
<tr>
<td>$\rho$</td>
<td>resistivity</td>
<td>($\Omega.m$)</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>electrical conductivity</td>
<td>($S/m$)</td>
</tr>
<tr>
<td>$\omega$</td>
<td>angular frequency</td>
<td>($Rads/s$)</td>
</tr>
</tbody>
</table>
CHAPTER 1

INTRODUCTION
The electric arc operating at atmospheric pressure is important as a relatively low cost, high intensity, high temperature source of energy and its use has enabled chemical and metallurgical processes to be carried out which could not be carried out in any other way. Arc processes have advantages over non-electrical methods of heating, such as combustion, since reduced contamination of the products may be obtained.

Electric arcs are used at powers ranging from a few kilowatts to hundreds of megawatts at currents from ten amps to more than a hundred thousand amps, operating in oxidising, reducing and inert atmospheres at pressures ranging from near vacuum to hundreds of atmospheres. Temperatures in the range six thousand kelvin to in excess of thirty thousand kelvin can be produced depending on the current and operating conditions.

Electric arcs are utilised in a wide range of industrial processes including welding, plasma torches, arc furnaces and arc lamps. Principal applications include cutting, welding, spraying coatings and the large-scale melting of metal in the steel industry. Other applications include the use of arc lamps for illumination and laser excitation.

Arc devices and processes can generally be divided into two types, those utilising free-burning arcs, such as welding and arc furnaces, and those in which the arc is forcibly constricted, either by gas flows (vortex stabilisation) or by the presence of cooled surfaces (wall constriction), such as plasma torches. Arc welding and melting processes have been developed gradually during the last century, however, the fundamental principles remain unchanged. Three-phase arc furnaces rated at 163 MVA with capacities up to 400T, for example, have been used for bulk steelmaking in recent years. The dc plasma torch was invented by Mathers in 1911 and remained largely unused until the 1950s when its usefulness as a tool for spraying refractory coatings onto metal and ceramic substrates, and for simulating the re-entry conditions experienced by spacecraft returning to earth were realised. The present day plasma torches have largely been developed as a result of improvements and work carried out by Gage and co-workers at Union Carbide in the period 1955 to 1970. Since the 1950s applications of plasma torches have expanded to include cutting of metals such as stainless steel up to 50 mm thick typically, fabrication processes such as welding and spraying, more advanced re-entry simulation for interplanetary probes and the space shuttle, gas heating for chemical synthesis, and metal melting. Torches rated at up to 10 MW, carrying currents up to 10 kA, are now commercially available.
Arc and plasma heating processes are likely to become increasingly important and widespread in the future due to depletion, and high costs, of alternative fuels such as oil and gas, the shortage of raw materials and subsequent need to recycle and reclaim, and the increased efficiency of production offered by single-stage processes including the direct reduction of ores to metal and melting scrap, which are ideally suited to plasma and arc processes. The main industrial energy source is likely to be electricity ultimately and arc processes offer an efficient method of energy utilisation. Plasma processes also offer additional advantages including increased melting efficiency, reduced electrical interference, quieter operation and greater stability over arc processes. One possible method of further increasing the power input and rate of heating in arc processes is to use several arcs. Some existing processes including welding, plasma furnaces and three-phase arc furnaces incorporate several arcs, generally in configurations where the arcs remain separate and do not interact, or coalesce, but these invariably use separate power supplies for each arc, with resulting high capital costs. The ability to operate stable separate and coalesced multiple arcs from a common power supply would have a number of advantages, such as reduced capital costs of the power supply for a given total power input, and would enable larger volumes of ionised gas to be produced than at present, allowing increased throughputs of feedstock to be obtained.

This thesis is a study of the theory and applications resulting from the operation of multiple parallel arcs from a single power source. Applications include the production of large volumes of ionised gas for more efficient and uniform heating of gases and particulate materials, plasma furnaces incorporating multiple dc plasma torches for increased power inputs and melting efficiency and the development of non-consumable electrodes for use in dc arc furnaces to eliminate the cost of the electrodes from the final cost of the steel produced. The structure of, and interrelation between, the chapters of the thesis are shown in Fig. 1.1.
<table>
<thead>
<tr>
<th>(1) Introduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2) Review of arc processes</td>
</tr>
<tr>
<td>(3) Review of measurement techniques applicable to electric arc discharges</td>
</tr>
<tr>
<td>(4) Review of arc heaters and applications of electric arc discharges for gas heating and material processing</td>
</tr>
<tr>
<td>(5) Preliminary investigations of multiple arc discharges</td>
</tr>
<tr>
<td>(6) Investigation of the conditions for simultaneous operation of multiple electric arcs from a common supply</td>
</tr>
<tr>
<td>(7) Investigation of the intensity distribution of large volume multiple arc discharges</td>
</tr>
<tr>
<td>(8) Applications of multiple electric arc discharges</td>
</tr>
<tr>
<td>(9) Discussion, conclusions and recommendations</td>
</tr>
</tbody>
</table>

**References**

**Appendices**

1) An annotated bibliography of literature relevant to the theory and applications of electric arcs and arc heaters.

2) Network analysis by the method of determinants.

3) Computer program for the solution of the Ayrton equation.

4) Specification of scanning monochromator used to investigate the intensity distributions of multiple arc discharges.

5) Reduction in electrode volume requirements resulting from the use of multiple electrodes.
A review of arc theory relevant to a study of the operating conditions of multiple parallel arcs is presented in Chapter 2. Parts of the arc, including the electrode regions and arc column, are described together with typical characteristics of arcs operating at atmospheric pressure and a summary of the criteria to be satisfied for stable operation. This chapter also includes a review of existing examples and applications of multiple arcs.

Measurement techniques applicable to the determination of the temperature or temperature distribution of arcs operating at atmospheric pressure are reviewed in Chapter 3. These include electrostatic (Langmuir) probes, and magnetic probes. However, particular emphasis is placed on non-contact methods including single exposure and high-speed cine photography and spectroscopy.

Industrial plasma devices operating at power levels in excess of 100 kW are reviewed in Chapter 4. This review is considered from the operating principle rather than power of the devices and covers re-entry simulators including those utilizing multiple electrodes, plasma torches and furnaces, and magnetically rotated arc heaters.

The preliminary investigations of the characteristics of a horizontal multiple arc discharge system are described in Chapter 5 including the determination of possible electrode configurations, a photographic study of the different discharges produced and the use of a conducting paper analogue to model the discharges.

Experimental tests and results and theoretical analysis carried out during the investigation of the conditions under which stable separate and coalesced multiple arcs can be operated from a common supply are described in Chapter 6.

The application of a spectroscopic method of determining intensity distribution to coalesced multiple arc discharges produced by the horizontal multiple arc system described in Chapter 5 is explained in Chapter 7 with particular emphasis on the geometry of the discharges and the repeatability of the results.

The application of multiple arcs in two areas related to industrial processes is described in Chapter 8. Firstly, the design, development and operation of a plasma furnace, in industry, incorporating three dc plasma torches operating in the transferred mode from a common power supply,
and secondly the use of multiple electrodes in ac and dc arc melting and smelting furnaces including the design and construction of a high-current, non-consumable, multiple electrode assembly for use in dc arc furnaces.

The results and conclusions of this work, together with recommendations for further research, are summarised in Chapter 9.
CHAPTER 2

REVIEW OF ARC PROCESSES
"An arc is a discharge of electricity, between electrodes in a gas or vapour, which has a voltage drop at the cathode of the order of the minimum ionising or minimum exciting potential of the gas or vapour." (Compton, 1927).

The general features, properties and characteristics of arcs are described in this chapter, including the arc roots, the arc column, the conditions for stable operation, the effect of self and applied magnetic fields, and the conditions under which multiple arcs can be operated.

2.1 Electric arc discharges.

Several reviews of electric discharges, and more specifically arcs, have been published (Finkelnburg et al, 1956; Olsen, 1963; Papoular, 1965; Nasser, 1971; Meek et al, 1978). Electric arcs and other discharges, such as glows, have also been discussed in several monographs (Cobine, 1958; Somerville, 1959; Ecker, 1961; Von Engel, 1965; Rieder, 1967; Hoyaux, 1968; Grosse et al, 1968; Howatson, 1976; Hirsh et al, 1978).

The characteristics of an arc depend on the gas pressure, gas, electrode material and geometry, and the characteristics of the electrical supply. Three principal discharges exist, the Townsend, glow and arc discharges. The voltage-current characteristics of these discharges at low pressure are shown in Fig. 2.1. The characteristic of the arc at atmospheric pressure is identical to the low-pressure curve. A Townsend discharge exists up to $10^{-5}$ A, a glow discharge exists between $10^{-4}$ A and $10^{-1}$ A and a contracted, filamentary, low voltage, high temperature arc is produced at currents in excess of 1 A. An arc is a self-sustaining discharge which may be formed by transition from a glow (Fig. 2.1), by contacting and separating the electrodes or by pre-ionising the discharge gap with an externally applied high-voltage spark. The transient spark, and the Townsend and glow discharges are generally low pressure phenomena and are not relevant to a study of arcs at atmospheric pressure, although some
Fig. 2.1 Electric discharge characteristics at 133 Pa (after Guile, 1971).

A comparison between the glow and arc discharges will be made.

An arc can be divided into three sections: the cathode and anode regions (including the arc roots), and the arc (positive) column. Undefined transition regions occur between these zones.

2.2 The arc cathode.

Arc cathode materials can be described as either thermionic, which includes graphite and tungsten, or cold-cathode materials, which includes copper and iron. The principal feature which distinguishes an arc from a glow discharge is the voltage drop at the cathode, which is approximately 10 V in an arc compared with approximately 300 V in a glow. This characteristically low fall voltage in an arc depends on the electrode material and generally varies over a range between 8 V and 16 V although values as low as 4 V have been measured for arcs between carbon electrodes.
(Dickson et al, 1967). Measured values of fall voltage for some common electrode materials are summarised in Table 2.1.

The cathode fall region is believed to be due to the presence of a positive-ion space charge (Cobine, 1958). Electrons emitted from the cathode are highly mobile and it is claimed that they are rapidly accelerated through this region faster than positive ions from the arc column, resulting in an excess of positive ions. Thermal effects may also contribute since steep electric field and temperature gradients exist in the transition region. The thickness of the fall region is thought to be approximately one electron mean-free-path length (Mackeown, 1929; Howatson, 1976; Pfender, 1978) and values have been measured generally in the range $4.2 \times 10^{-5}$ mm (Dickson et al, 1967; Dekker, 1970) to $1 \times 10^{-2}$ mm (Somerviille, 1959) although a value as high as 0.1 mm has been suggested (Finkelnburg et al, 1951). The measured values were obtained using Langmuir probes (chapter 3) and Mason (1937) showed that severe errors could arise in measurements of the very narrow fall region because the probe cooled the discharge. The electric field strength is high in the fall zone due to the narrowness of the region and estimated values range between $3.5 \times 10^{4}$ V/mm for a refractory electrode (Cobine, 1958) and $10^{6}$ V/mm for a cold-cathode material (Guile, 1971).

The transition between the cathode root and arc column is not abrupt. The current density in the column is typically 0.5 A/mm$^2$ but may be as high as $10^5$ A/mm$^2$ at the cathode (Guile, 1971), and the electric field strength varies between 2 V/mm in the column to $10^6$ V/mm at the cathode. High temperature gradients also exist since the column temperature is typically $15 \times 10^3$ K but the temperature of the cathode is limited by the boiling point of the material and is generally less than $4 \times 10^3$ K (Table 2.2).
<table>
<thead>
<tr>
<th>Material</th>
<th>Current (A)</th>
<th>Cathode fall (V)</th>
<th>Anode fall (V)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>up to 20</td>
<td>9 - 11</td>
<td>11 - 12</td>
<td>Von Engel et al, (1934)</td>
</tr>
<tr>
<td>Carbon</td>
<td>-</td>
<td>10</td>
<td>20</td>
<td>Mason, (1937)</td>
</tr>
<tr>
<td>Carbon</td>
<td>-</td>
<td>10</td>
<td>-</td>
<td>Finkelnburg, (1948)</td>
</tr>
<tr>
<td>Tungsten</td>
<td>up to 6</td>
<td>16.1</td>
<td>-</td>
<td>Kesaev, (1965)</td>
</tr>
<tr>
<td>Copper</td>
<td>up to 20</td>
<td>8 - 9</td>
<td>2 - 6</td>
<td>Von Engel et al, (1934)</td>
</tr>
<tr>
<td>Copper</td>
<td>up to 6</td>
<td>16</td>
<td>-</td>
<td>Kesaev, (1965)</td>
</tr>
<tr>
<td>Iron</td>
<td>up to 300</td>
<td>8 - 12</td>
<td>2 - 10</td>
<td>Von Engel et al, (1934)</td>
</tr>
<tr>
<td>Iron</td>
<td>up to 6</td>
<td>15.1</td>
<td>-</td>
<td>Kesaev, (1965)</td>
</tr>
</tbody>
</table>

Table 2.1 Measured cathode (and anode) fall voltages for arcs in air at atmospheric pressure.
2.2.1 Cathode emission processes.

An arc is maintained by the emission of electrons from an area on the cathode known as the arc root. The diameter of the cathode root is a function of the arc current up to a critical value (Thouret et al., 1951), and is typically 0.5 mm² in a thermionic arc. Materials with high melting points, usually greater than $3 \times 10^3$ K, such as carbon (graphite) and tungsten can be heated by positive ions from the arc column to temperatures at which thermionic emission produces sufficient electrons to supply the arc current. Under these conditions the current density of the electrons emitted is given by the Dushman equation (Dushman, 1923; 1930).

If a material with a relatively low boiling point, such as copper, is used as an arc cathode, the surface of the material cannot be raised to a high enough temperature without melting for thermionic emission to produce all the electrons required to account for the measured current. These materials are known as non-thermionic or cold-cathode emitters. The characteristics of the two types of electron emission have been extensively reviewed (Guile, 1971) and are summarised in Table 2.3.

<table>
<thead>
<tr>
<th>Electrode material</th>
<th>Gas</th>
<th>Current (A)</th>
<th>T. cathode (K)</th>
<th>T. anode (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>Air</td>
<td>2 - 12</td>
<td>$3.5 \times 10^3$</td>
<td>$4.2 \times 10^3$</td>
</tr>
<tr>
<td>Carbon</td>
<td>Nitrogen</td>
<td>4 - 10</td>
<td>$3.5 \times 10^3$</td>
<td>$4.0 \times 10^3$</td>
</tr>
<tr>
<td>Copper</td>
<td>Air/nitrogen</td>
<td>10 - 20</td>
<td>$2.2 \times 10^3$*</td>
<td>$2.4 \times 10^3$</td>
</tr>
<tr>
<td>Iron</td>
<td>Air/nitrogen</td>
<td>4 - 17</td>
<td>$2.4 \times 10^3$*</td>
<td>$2.6 \times 10^3$</td>
</tr>
<tr>
<td>Tungsten</td>
<td>Air</td>
<td>2 - 4</td>
<td>$3.0 \times 10^3$</td>
<td>$4.25 \times 10^3$</td>
</tr>
</tbody>
</table>

Table 2.2 Arc cathode and anode temperatures at atmospheric pressure (after Von Engel et al., 1934).

* Arc root temperatures greater than the melting point of the electrodes.
<table>
<thead>
<tr>
<th>Thermionic cathodes</th>
<th>Non-thermionic cathodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operate at high temperatures generally in excess of $3.5 \times 10^3$ K.</td>
<td>Operate over a wide range of temperatures generally less than $3 \times 10^3$ K.</td>
</tr>
<tr>
<td>Low current density $(10 - 100 \text{ A/mm}^2)$</td>
<td>High current density $(10^4 - 10^5 \text{ A/mm}^2$ or higher)</td>
</tr>
<tr>
<td>Slow moving or fixed cathode spot.</td>
<td>Rapidly moving cathode spot.</td>
</tr>
<tr>
<td>No evidence of excess pressure on cathode spot.</td>
<td>Pressure on cathode spot above ambient; indicated by depression of liquid metal.</td>
</tr>
</tbody>
</table>

Table 2.3 Characteristics of emission processes at an arc cathode (after Guile, 1971).

Various techniques have been used to determine the current density at the cathode root, including measurement of the area of arc tracks on electrodes, and the area of tracks produced by arcs deflected by a transverse magnetic field, and photographic methods. All these methods are subject to errors because arc tracks are produced by positive ions and by heat conducted and radiated from the arc column so that the eroded area may be much larger than the arc root, and the luminous area photographed on an electrode is likely to be larger than the area emitting electrons. Both these errors will result in under-estimation of the current density. A summary of reported values is given in Table 2.4, and the maximum current density is approximately $100 \text{ A/mm}^2$ at a thermionic cathode and $10^6 \text{ A/mm}^2$ at a cold-cathode.

Cold-cathode emission is sometimes referred to as field emission, but this is not strictly accurate since, under certain conditions, for example at currents below about 10 A, field emission can take place from carbon and tungsten electrodes (Cobine, 1958). The theory of field emission
<table>
<thead>
<tr>
<th>Cathode material</th>
<th>Current (A)</th>
<th>Current density ($a/mm^2$)</th>
<th>Method of measurement</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>-</td>
<td>4.7</td>
<td>Imaging arc root on a screen</td>
<td>Guntherschulze, (1922)</td>
</tr>
<tr>
<td>Tungsten</td>
<td>2.6</td>
<td>$0.74 \times 10^3$</td>
<td>Area of tracks</td>
<td>Cobine et al, (1948)</td>
</tr>
<tr>
<td>Tungsten</td>
<td>200</td>
<td>$0.22 \times 10^3$</td>
<td>Photographically</td>
<td>Somerville et al, (1949)</td>
</tr>
<tr>
<td>Tungsten</td>
<td>less than 10A</td>
<td>$10^3$</td>
<td>-</td>
<td>Thouret et al, (1951)</td>
</tr>
<tr>
<td>Tungsten</td>
<td>greater than 10A</td>
<td>10</td>
<td>-</td>
<td>Thouret et al, (1951)</td>
</tr>
<tr>
<td>Tungsten</td>
<td>30</td>
<td>$0.45 \times 10^3$</td>
<td>Area of tracks under influence of magnetic field</td>
<td>Dunkerley et al, (1955)</td>
</tr>
<tr>
<td>Copper</td>
<td>2.6</td>
<td>$1.24 \times 10^3$</td>
<td>Area of tracks</td>
<td>Cobine et al, (1948)</td>
</tr>
<tr>
<td>Copper</td>
<td>200</td>
<td>$0.35 \times 10^3$</td>
<td>Photographically</td>
<td>Somerville et al, (1949)</td>
</tr>
<tr>
<td>Copper</td>
<td>-</td>
<td>$10^4$</td>
<td>Photographically</td>
<td>Froome, (1946-1950 inc.)</td>
</tr>
<tr>
<td>Thermionic</td>
<td>greater than 10A</td>
<td>$10^2$</td>
<td>-</td>
<td>Guile, (1971)</td>
</tr>
<tr>
<td>Non-thermionic</td>
<td>greater than 10A</td>
<td>$10^5$</td>
<td>-</td>
<td>Guile, (1971)</td>
</tr>
</tbody>
</table>

Table 2.4 Estimated values of current density at the cathodes of arc discharges.
imposes the condition that the current density at the cathode, due to electrons and positive ions, must be greater than $10^5 \text{ A/mm}^2$, which does not agree with measured values (Table 2.4) although more recent measurements (Kensav, 1964) have indicated that this may be the case. Field emission has been discussed in a monograph by Cobine (1958) and in a review of arc electrode processes by Guile (1971), in which several theories put forward to explain the emission of electrons from cold-cathodes have been described. Different theories appear to apply to specific experimental conditions and it is likely that no single mechanism applies in all cases.

2.2.2 Formation of multiple emitting spots on arc cathodes.

Two types of cathode root have been reported on refractory electrodes such as tungsten and carbon (Thouret et al, 1951). At currents less than approximately 10 A the arc column contracts very sharply at the cathode, producing a small cathode root with a high current density, typically greater than $10^3 \text{ A/mm}^2$. This type of arc has been described as a burning-spot arc (Somerville, 1959; Finkelnburg et al, 1956). At higher currents the arc root changes to a different form, characterised by a less contracted root and a current density of the order of $10^3 \text{ A/mm}^2$. The two modes of operation occur due to a transition from non-thermionic emission at currents below about 10 A, to thermionic emission at higher current. Below 10 A the current is insufficient to heat the cathode to the temperature required for thermionic emission to occur and the material behaves similarly to copper and other cold-cathode emitters. When the current is increased, the temperature becomes sufficient for thermionic emission of electrons to supply the current. Materials like tungsten can also operate in the non-thermionic mode at higher currents if the electrode is intensively cooled so that the cathode root contracts and the current density increases (Zhukov et al, 1976). The increased current density may result in increased evaporation of the electrode and its eventual destruction at high currents (section 2.2.3). An arc cathode emitting thermionically has a single arc root which is either stationary or moves very slowly over the surface of the electrode (Cobine, 1958; Guile, 1971), probably depending on the shape of the electrode.
Conversely, a cold-cathode root is comprised of a number of very small, highly mobile, emitting spots at arc currents above 10 A (Somerville, 1959; Guile, 1971; Pfender, 1978). These spots move at random over the surface of the cathode and are continually created and extinguished (Guile, 1971). A detailed study of the stability and movement of cathode spots on a mercury cathode has been carried out (Kesaev, 1964) and the results may also be applied to solid cathodes. The random movement of the cathode spots is likely to increase the errors in measurements of the current density at the cathode (Table 2.4) and results may be an order of magnitude too low. The number of emitting spots is reported to be proportional to the current (Djakov, 1970) which indicates that the current per spot is constant and values as low as 0.03 A (Secker et al, 1969) and as high as 10 A to 17 A (Wright, 1968) have been reported for arcs on highly polished and dull non-thermionic cathodes respectively, in air at atmospheric pressure, indicating that surface finish and oxide layers may affect the formation of multiple cathode spots. Each cathode site may only be capable of emitting electrons for a very short time (Guile, 1971) which may be due to the removal of oxide layers from the surface. The oxide layers act as preferential emitters of electrons because the ionisation energies of the oxides are lower than that of the substrate. When a cathode spot is extinguished the total current must either be distributed among the remaining spots or flow from new spots excited by positive ions bombarding the cathode, particularly at irregularities on the surface. The lifetime of multiple spots has been reported to be between approximately $2 \times 10^{-6}$ s (Basharov et al, 1966) and $10^{-9}$ s (Engelbrecht, 1942), the latter value arising from tests which showed that interruption of the supply for $10^{-9}$ s caused extinction of arcs, and because frequencies in excess of $10^9$ Hz have reportedly been generated by arcs (Prinzler, 1965).

The mechanism of multiple root formation on non-thermionic cathodes is not fully understood. Multiple arc spots have been reported in vacuum arcs at currents in the range $6 \times 10^3$ A to $10 \times 10^3$ A (Guile, 1971) where the arc spots are more widely spaced than at high pressures and are claimed to be entirely separate roots, each carrying currents of approximately 100 A, although values as high as 500 A for copper have been claimed (Basharov et al, 1966). A vacuum arc is different from an arc in air.
at atmospheric pressure since the existence of the arc is dependent on
the vaporisation of material from the cathode to form the plasma in the
arc column because there is insufficient gas to ionise and maintain the
arc. Electrode vapour in the contraction zones, close to the multiple
spots, is claimed to act as a series resistor connected to each spot
(Grosse et al, 1968) which would individually stabilise the multiple
roots (section 2.5.3). Up to 50 simultaneous cathode spots have been
reported in vacuum circuit-breakers operating at 5000 A (Grosse et al, 1968).
Vapour from the electrodes is less important for maintenance of arcs at
atmospheric pressure than vacuum arcs and, under these conditions, it is
possible that multiple roots may be maintained by the oxide layer at the
emitting sites. This oxide layer is rapidly removed by positive ions
incident on the surface of the cathode, which may account for the short
lifetime of the spots, but can be reformed when the surface reoxidises
after the arc is extinguished. The surface of arc cathodes operating
in reducing atmospheres are reportedly cleaned up (Guile, 1966) because
no new oxide layers are formed.

2.2.3 Erosion of arc cathodes at high currents.

One of the main factors limiting the scale-up of arc heaters is erosion
of the cathodes due to the high current density at the cathode root on
tungsten electrodes at high currents. A current limit of approximately
1000 A has been suggested for thoriated tungsten cathodes
(Boldman et al, 1962) but, in recent years, several arc heaters have been
developed for operation at currents of the order of 5000 A and 10000 A is
claimed to be attainable (chapter 4). Erosion of the cathode may become
so high at these currents that the lifetime of the cathode becomes too short
for continuous operation for periods in excess of 100 hours. The design of
some high power arc heaters (TASC and Westinghouse for example, chapter 4)
enables very high currents to be used. These heaters utilise copper
cathodes and ac, and use gas streams or magnetic fields, or both, to move
the arc roots over the surface of the electrodes in order to distribute
the thermal load and reduce erosion. The use of cold cathode materials
(section 2.2.1) in plasma torches is generally considered to be undesirable because of the need to move the cathode root over the surface of the electrode in two planes, which complicates the design and increases the cost.

The rate of erosion of tungsten and copper electrodes at high currents has been investigated by several authors. Results, together with the calculated erosion for one hour's operation at 1000 A and 10000 A, are shown in Table 2.5. The highest values of erosion rate (Holm, 1949) were calculated from energy balances at the cathode. Erosion at 1000 A and 10000 A calculated from these values (Table 2.5) is not compatible with generally accepted erosion rates, indicating errors in the model used by Holm. Harry (1969) measured the rate of erosion of a copper electrode at 200 A and reported that it was an order of magnitude lower than the minimum value proposed by Holm which also suggests errors in the earlier work.

Some authors (Kimblin, 1974) claim that the erosion rate of the cathodes of vacuum arcs (expressed as mass/coulomb) is independent of the arc current due to the division of high-current cathode roots into a number of spots, each carrying approximately 100 A (section 2.2.2). This implies that the erosion of the cathode is directly proportional to the current and is in agreement with results obtained by Holm at currents in excess of 1000 A (Holm, 1949). Conversely, Fey et al (1979) have reported that the erosion rate (per coulomb) of copper electrodes in a magnetically rotated ac arc heater varies linearly with current at atmospheric pressure and can be described by an equation of the form:

$$M = kI^{2.24}$$

where $M$ is the erosion rate (mass/coulomb), $I$ is the arc current (kA) and $k$ is a constant dependent on the size of the electrodes ($k = 0.12$ for 100 mm diameter electrodes). The main causes of cathode erosion are evaporation of material due to the high current density at the arc root, and high rates of heat transfer from the hotter arc column. Heat transfer to the cathode depends on the arc current, the size of the cathode and the gas used (Zhoukov et al, 1976). The use of diatomic gases increases the heat transfer due to the heat of dissociation (section 2.4.2).
<table>
<thead>
<tr>
<th>Material</th>
<th>Current (A)</th>
<th>Erosion rate (mm³/coulomb)</th>
<th>Calculated erosion for 1 hour's operation (mm³)</th>
<th>Comments</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>1000 A</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10,000 A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tungsten</td>
<td>1000</td>
<td>8 x 10⁻⁵</td>
<td>2.86 x 10⁵</td>
<td>Erosion rates calculated from energy balance at the cathode. Calculated erosion is extremely high, even at 1000 A.</td>
<td>Holm, (1949)</td>
</tr>
<tr>
<td></td>
<td>10000</td>
<td>1 x 10⁻⁴</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3.6 x 10⁶</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tungsten</td>
<td>-</td>
<td>greater than 5.16 x 10⁻⁵</td>
<td>18.57</td>
<td>Erosion acceptable up to 10,000 A.</td>
<td>Guile, (1971)</td>
</tr>
<tr>
<td>Tungsten</td>
<td>1000</td>
<td>5.16 x 10⁻⁷</td>
<td>1.85</td>
<td>Order of magnitude lower than previous values. Erosion rate measured at currents up to 1000 A.</td>
<td>Zhukov et al, (1976)</td>
</tr>
<tr>
<td>Copper</td>
<td>1000</td>
<td>1 x 10⁻²</td>
<td>3.6 x 10⁵</td>
<td>Erosion rates calculated from energy balance at the cathode. Calculated erosion is extremely high.</td>
<td>Holm, (1949)</td>
</tr>
<tr>
<td></td>
<td>10000</td>
<td>2 x 10⁻¹</td>
<td>-</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7.2 x 10⁶</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Copper</td>
<td>-</td>
<td>7.81 x 10⁻⁴ to 9.73 x 10⁻³</td>
<td>2.81 x 10³ to 3.5 x 10⁴</td>
<td>Calculated erosion is high above 1000 A.</td>
<td>Cobine, (1959)</td>
</tr>
<tr>
<td>Copper</td>
<td>10 to 10000</td>
<td>1.11 x 10⁻² to 4 x 10⁴</td>
<td>4 x 10⁴ to 1 x 10⁵</td>
<td>Erosion high above 1000 A.</td>
<td>Reece, (1963); Plyuto et al, (1955); Mitchell, (1970); Rondeel, (1973); Zinblin, (1973)</td>
</tr>
<tr>
<td>Copper</td>
<td>45</td>
<td>4.9 x 10⁻⁵ to 7.4 x 10⁻⁴</td>
<td>0.176 x 10³ to 2.6 x 10³</td>
<td>Magnetically rotated arc. Calculated erosion is acceptable up to 1000 A.</td>
<td>Guile et al, (1974)</td>
</tr>
<tr>
<td>Copper</td>
<td>200</td>
<td>1.11 x 10⁻⁴</td>
<td>0.4 x 10³</td>
<td>Magnetically rotated arc heater. Calculated erosion is acceptable up to 1000 A.</td>
<td>Harry, (1969)</td>
</tr>
<tr>
<td>Copper</td>
<td>250 to 12400</td>
<td>4.9 x 10⁻⁴ to 7.3 x 10⁻³</td>
<td>1.76 x 10³ to 2.61 x 10⁵</td>
<td>Magnetically rotated arc heater. Excessive erosion at 1000 A.</td>
<td>Pay et al, (1979)</td>
</tr>
</tbody>
</table>

Table 2.5 Erosion of tungsten and copper cathodes.
Resistance heating of the cathode has been considered by Rich (1961) who reported that 38% of the total energy dissipated by resistance heating in the cathode was concentrated in the hemisphere beneath the arc root with corresponding power densities in the cathode spot zone of the order of $5 \times 10^5 \text{ W/mm}^2$ which would cause rapid vaporisation of the cathode. Zhoukov et al (1976) have also reported on the effects of resistance heating of the cathode and claim that the temperature within the cathode may exceed that of the arc root at high currents if the bulk of the electrode is inadequately cooled. This can lead to the destruction of the cathode (Ziber et al, 1975). Overefficient cooling of the cathode can also lead to its failure (Zhoukov et al, 1976) because the arc contracts at the cathode which increases the current density and temperature of the cathode.

If the current density at the cathode root of an arc electrode is constant at high currents then a doubling of the current would double the surface area of the arc root. The radius of the root would only be increased by a factor of $\sqrt{2}$, however the surface area of the hemisphere beneath the arc root would also be doubled (i.e. proportional to the current) and the volume of the hemisphere would be increased by a factor of $2 \sqrt{2}$. The relationships indicate that the surface area of the hemisphere in the cathode through which heat losses occur increases proportional to the current, and that the volume of the hemisphere increases at a greater rate than the current. Resistive losses in the cathode increase proportional to $I^2$, i.e. by a factor of 4 when the current is doubled, so that the power density in the hemisphere will increase. This analysis indicates that arc cathodes may be destroyed at high currents, but may be subject to errors due to the non-uniformity of the current density over the area of the arc root, particularly on cold-cathode materials (Harry, 1969).

Studies carried out by Zhoukov et al (1976) during the development of high-power plasma torches for smelting steel in East Germany (chapter 4) have indicated that semi-enclosed (flat-surface) tungsten cathodes can be used up to 2000 A and that rod type cathodes should be used at higher currents in order to maintain satisfactorily low erosion rates. This type of plasma torch and the Tetronics torch (chapter 4) both use this latter type of cathode and operate with argon as the stabilising gas. Higher erosion of the electrodes can be tolerated in the high-power magnetically-rotated arc arc heaters developed by Westinghouse (Fey et al, 1979) (chapter 4) due to the larger surface area of the electrodes than in plasma torches.
2.3 The arc anode.

The anode region of electric arcs has not been investigated as much as the cathode and column because it is less important for maintaining the arc and consequently less work has been published on the subject although anode phenomena have been described by Somerville, (1959), Cobine (1958), Grosse et al (1968) and Pfender (1978).

The primary function of the anode is to provide a sink for the arc current carried by the electrons emitted from the cathode in order to maintain the discharge. The anode does not emit a significant amount of positive ions, except in the Beck arc (Beck, 1921; Finkelnburg, 1949) which uses electrodes cored with rare-earth compounds such as cerium oxide. Current flow to the anode is almost entirely due to electrons, whereas both positive ions from the arc column and emitted electrons carry the current at the cathode. The anode is generally hotter than the cathode and the anode root is less contracted because no emission process occurs, which requires a contracted root (section 2.2.1) and tends to cool the cathode. The temperature of the anode may reach the boiling point of the material, or its oxide, resulting in erosion of the electrode, but a hot anode is not essential for maintaining an arc and water-cooled anodes are often used, for example in plasma torches (chapter 4), to reduce erosion and contamination of the discharge.

A fall voltage exists over a distance of the order of an electron mean-free-path (10^-2 mm) (Somerville, 1959) close to the anode due to the formation of an electron space charge (Cobine, 1958). Anode fall voltages have been measured using similar techniques to those applied at the cathode (section 2.2), including probes, and the results are subject to the same errors due to the narrowness of the anode fall and the effect of the probe on the discharge. Results vary between 2 V and 12 V (Table 2.1) although values between 35 V (Somerville, 1959) and 1 V (Busz-Peuckert et al, 1955) have been measured for carbon anodes.

Positive ions are produced by electron collisions in the fall region and accelerated towards the cathode under the influence of the applied voltage. A concentration gradient of positive ions exists in the fall region, from zero at the surface of the anode to the equilibrium level, in the arc column,
where the concentrations of electrons and ions are equal. The ionic component of the total current is only approximately 1% (Pfender, 1978) due to the high mobility and velocity of the smaller electrons and the relatively small number of ions flowing. The generation of charge carriers in the anode fall region is reported to be due to two different mechanisms; field ionisation and thermal ionisation (Pfender, 1978) and these processes have been described by Bez et al., (1954(a) and (b), 1955(a) and (b)) and Ecker, (1961).

The current density at the anode is less than at the cathode due to the larger arc root. Measurements of current density are subject to errors due to the relatively small diameter of the root and a range of values has been reported (Table 2.6).

<table>
<thead>
<tr>
<th>Anode material</th>
<th>Current (A)</th>
<th>Current density (A/mm²)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>4</td>
<td>1.2</td>
<td>Cobine, (1958)</td>
</tr>
<tr>
<td>Carbon</td>
<td>10</td>
<td>0.65</td>
<td>Cobine, (1958)</td>
</tr>
<tr>
<td>Carbon</td>
<td>low current</td>
<td>0.4</td>
<td>Somerville, (1959)</td>
</tr>
<tr>
<td>Carbon</td>
<td>up to 20</td>
<td>0.4</td>
<td>Grosse et al, (1968)</td>
</tr>
<tr>
<td>Copper</td>
<td>50 - 150</td>
<td>3</td>
<td>Schoek et al, (1961)</td>
</tr>
</tbody>
</table>

Table 2.6 Measured values of current density at the anode of an arc.

Generally the current density at a carbon anode is independent of the arc current provided that the arc root does not occupy the whole of the cross-section of the anode (Somerville, 1959). If the current is increased in this limiting condition the phenomenon of hissing occurs, which is reported to be due to overloading and contraction at the anode root (Somerville, 1959; Grosse et al, 1968). The anode root is believed to be comprised of a number of small spots, similar to the cathode root on a non-thermionic electrode (section 2.2.2), and as the current is increased the current density rises to approximately 100 A mm⁻² (Grosse et al, 1968) which causes thermal overloading and evaporation of the anode material which is characterised by a hiss. The frequency of the noise produced is
dependent on the thermal conductivity of the carbon (Grosse et al., 1968) and the arc voltage and current oscillate between 5 V and 30 V (Grosse et al., 1968) and 3 A and 13 A (Finkelnburg et al., 1956) respectively at a frequency of approximately 1 kHz. Higher frequency (50 kHz) oscillations in voltage and current, superimposed on the 1 kHz hiss, are generated by movement of the small spots within the anode root and current densities as high as 500 A mm\(^{-2}\) have been reported (Somerville, 1959).

The existence of contracted (spot) and uncontracted (diffuse) anode roots has been reported (Grosse et al., 1968; Pfender, 1978). Spot anodes are claimed to be most likely to occur in arcs operating in oxidising atmospheres when the arc root wanders randomly over the surface of the anode at high velocities (Pfender, 1978) although the conditions for operation with a single spot are not fully understood. Anode spots may be produced as a result of evaporation of the electrode producing surface irregularities which can act as preferential arcing sites. The formation of diffuse anode roots is reported to be due to the influence of the cathode jet (section 2.4.4) on the anode region such that in relatively short arcs the cathode jet extends to the surface of the anode and increases the supply of heat and reduces the contraction so that the arc column attaches to the anode over a larger area (Pfender, 1978). The cathode jet may not extend to the anode and a fall region, contraction zone and anode spot will be formed. Diffuse anode roots have been reported in arcs operating at currents in excess of 30 A in inert gases and nitrogen (Grosse et al., 1968).

2.4 The arc column.

The main part of an arc discharge, between the electrodes, is known as the arc column and is characterised by a lower axial electric field strength and current density than the electrode regions. The column can be regarded as the useful part of the arc in the investigation of the production of a large volume discharge for gas heating since power dissipated in the arc column will be transferred to the process, whereas the anode root is the useful part in welding and transferred-arc processes such as cutting and metal melting. The power developed in the arc column depends on the voltage drop in the column, the current, and the length of the discharge.
2.4.1 Arc column characteristics.

The static voltage-current characteristic of a dc carbon arc of constant length was first determined by Ayrton (1902) (Fig. 2.2). Constant arc length is difficult to obtain in practice due to erosion of the electrodes and convection currents which increase the length of the arc, particularly in horizontal arcs.

\[ V_{arc} = A + BL + \frac{C + DI}{I} \]  

(2.2)

where \( A, B, C \) and \( D \) are constants, which have been tabulated (Cobine, 1958) and depend on the gas used. The Ayrton equation only applies to materials other than carbon over a very limited range of current.
Nottingham (1923) found that an atmospheric pressure arc of constant length could be represented by

$$V_{\text{arc}} = a + \frac{b}{I^n}$$

(2.3)

for a number of different electrodes. The exponent $n$ is proportional to the absolute boiling temperature of the anode, or its oxide, such that

$$n = 2.62 \times 10^{-4} T$$

(2.4)

The value of $n$ is also dependent on the gas and pressure and decreases from 0.54 in argon at atmospheric pressure to 0.35 at $2 \times 10^6$ Pa (Suits, 1934).

The electric field strength, or voltage gradient, in an arc column is typically 1 V/mm, but this depends on the gas, gas pressure, electrode material, cooling of the arc, applied magnetic fields and the arc current. These parameters affect the diameter, and therefore resistance, of the arc so that the arc voltage and voltage gradient also change, the electrode fall voltages being approximately constant. Air, and other gases used for discharges, have a positive temperature coefficient of electrical conductivity such that as current is increased the temperature and electrical conductivity increase and the voltage and electric field strength decrease. (Fig. 2.3).

The relationships between electric field strength in the column and arc current in the range 1 A to 10 A, and gas pressures between $10^3$ Pa and $5 \times 10^6$ Pa have been investigated by Suits (1939a) to give

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

and

$$E \propto P^m$$

(2.5)

where $n$ is the same constant as used by Nottingham in equation (2.3), and $m$ is equal to 0.31 for a carbon arc in nitrogen. Identical values were obtained for tungsten and copper electrodes (Cobine, 1958). Further investigations of the variation of electric field, $E$, with current have been carried out (Strom, 1946; King, 1961) in the current range $10^{-4}$ A to $10^5$ A.
Fig. 2.3 Arc column voltage gradient as function of current at atmospheric pressure. (After Suits, 1939a).

The current density in the arc column is difficult to measure because the current-carrying region is not rigidly defined. Measured values of current density at atmospheric pressure are given in Table 2.7.

<table>
<thead>
<tr>
<th>Current density (A/mm²)</th>
<th>Gas</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.06</td>
<td>Nitrogen</td>
<td>Suits, (1939a)</td>
</tr>
<tr>
<td>0.32</td>
<td>Argon</td>
<td>Suits, (1939a)</td>
</tr>
<tr>
<td>1.0</td>
<td>Air</td>
<td>Pfender, (1978)</td>
</tr>
<tr>
<td>2.0</td>
<td>Air</td>
<td>King, (1954)</td>
</tr>
</tbody>
</table>

Table 2.7 Measured values of current density in the arc column.
The radius of the arc column was reported to be constant between 20 A and 200 A (King, 1954) indicating a mean current density of 2 A/mm$^2$ at 200 A. The radius of the column was reported to be proportional to current above this value. Nicolai (1970) determined the dimensions of the arc column photographically and claimed that the diameter of the arc was proportional to the square root of the current in the range 190 A to 400 A at air pressures between $2 \times 10^3$ Pa and $10^5$ Pa.

The voltage gradient in the column of a free-burning arc is a function of the electrical conductivity of the ionised gas in the column. Heat transfer occurs mainly by conduction within the column and convection at the periphery and is proportional to the radius of the arc. As the current is increased, the radius also increases and at a given current two extreme values can occur. At large cross-sections the temperature and therefore the electrical conductivity would be relatively low and a high voltage-gradient would be required to maintain the flow of current. Conversely at small cross-sections, the temperature and electrical conductivity would be high but, due to the small cross-section (high resistance), a high voltage-gradient would again be required. An arc cross-section must exist between these two extremes such that the voltage gradient is a minimum. This is known as Steenbeck's principle of minimum voltage (Von Engel et al, 1932; Steenbeck, 1932) and can be expressed as

$$\frac{dE}{dT} = 0 \quad \text{or} \quad \frac{dE}{dr} = 0 \quad (2.6)$$

which implies that at a given current and boundary conditions the current-carrying region of a stationary, symmetrical arc has a radius or temperature such that the electric field strength of the arc is a minimum. Some agreement between this theory and experimental observations has been reported (Kirchstein et al, 1937; Steenbeck, 1940).
2.4.2 Thermal properties of the arc column.

The thermal characteristics of the arc column are governed by the transport properties, such as thermal conductivity, of the gas used. Monatomic gases like argon ionise to give

\[ \text{Ar} \xleftrightarrow{} \text{Ar}^+ + e^- \quad (2.7) \]

but polyatomic gases such as nitrogen undergo dissociation into atoms before ionisation which increases the energy content or enthalpy (Fig. 2.4).

\[ \text{N}_2 \xleftrightarrow{} 2\text{N} \xleftrightarrow{} 2\text{N}^+ + 2e^- \quad (2.8) \]

An arc can be initiated more easily in a monatomic gas due to the lower ionisation potential, but a higher arc voltage is required to dissipate the same power as an arc carrying the same current in a diatomic gas. Similarly an arc operating in a diatomic gas requires a higher supply voltage than an arc of equal length in a monatomic gas due to the higher voltage gradient (Fig. 2.3).

The thermal conductivity of monatomic gases always increases with temperature but the thermal conductivity of diatomic gases, such as nitrogen, is characterised by a number of peaks (Fig. 2.5). The peaks occur at the temperatures corresponding to molecular dissociation, single ionisation and double ionisation (King, 1957). The dissociation of nitrogen molecules governs the thermal conductivity of air between 5000 K and 7000 K. The energy of dissociation is released when atoms of a partially dissociated gas diffuse to the cooler regions of an arc where recombination takes place. The reverse process, accompanied by the absorption of energy from the power supply, takes place within the electrically conducting region of the arc. Dissociation processes make up the largest proportion of the total thermal conductivity and increase up to approximately 7000 K when it approaches 100%, i.e. all the molecules are dissociated. Above this temperature the thermal conductivity of nitrogen decreases sharply until the temperature reaches 11,000 K when it begins to increase again due to ionisation of the atoms. A stable arc cannot be maintained between 7000 K and 11,000 K due to the negative dynamic characteristic of the
Fig. 2.4  Variation of the specific enthalpy of commonly used plasma gases with temperature.
thermal conductivity which causes a runaway transition. When the axial temperature exceeds 11,000 K a high temperature core is formed due to the increased temperature gradients. The formation of a core has been reported at currents in the range 40 A - 60 A in air at atmospheric pressure (King, 1957). A second core may also be formed when the temperature exceeds 20,000 K due to a peak in the conductivity of electron-ion pairs between approximately 14,000 K and 20,000 K but this only occurs at much higher currents (greater than 100 A) (King, 1954). The minimum temperature of an arc cannot be readily defined, although a lower limit of approximately 4000 K is often used, however the electrical conductivity of arcs seeded with potassium salts shows a maximum at approximately 3500 K (Lawton, 1975). The concentrations of electrons in argon and nitrogen at 4000 K are $(1.272 \times 10^{10} \text{ cm}^{-3})$ and $(1.10 \times 10^{10} \text{ cm}^{-3})$ respectively, which is a difference of only 15%. An arc column at atmospheric pressure contains approximately equal numbers of positive ions and electrons which can be described by a single temperature if the discharge is in thermal equilibrium. The existence of thermodynamic equilibrium simplifies the determination of parameters, such as temperature, by spectroscopic methods, (chapter 3).

Fig. 2.5  Variation of thermal conductivity of nitrogen with temperature. (Ernst et al, 1973).
2.4.3 An energy balance.

An arc can be considered as a cylindrical conductor dissipating the electrical energy supplied (Fig. 2.6).

![Diagram of an arc](image)

**Fig. 2.6** Dissipation of power in an arc.

The arc is assumed to be a cylindrically symmetrical radiator. Errors will only be introduced by this approximation at the arc roots and transition regions where the current density is higher than in the column, but the arc column is generally very much longer than the electrode regions and the errors will be small.

The power dissipated by an arc carrying a current $I$ is given by

$$ W = I^2 R = (j \frac{\pi d^2}{4}) R $$

(2.9)

where $j$ is the current density ($\text{Am}^{-2}$), $d$ the diameter of the arc ($\text{m}$) and $R$ the resistance of the arc ($\Omega$).
The power dissipation per unit length of a cylindrical arc is therefore
\[ W_L = (j^2 d^2 / \pi) R_L \]  
(2.10)

where \( R_L \) is the resistance per unit length (\( \Omega \cdot m^{-1} \)). The heat transfer per unit length of the arc can be expressed as
\[ W_L = h \cdot \pi d \cdot dT \]  
(2.11)

where \( h \) is an overall coefficient of heat transfer (\( W \cdot m^{-2} \cdot K^{-1} \)), and \( dT \) is the temperature difference (K). \( W_L \) can be eliminated from these two equations so that
\[ h = j^2 \frac{\pi d^3}{16} \frac{R_L}{dT} = \sigma^2 E^2 \frac{\pi d^3}{16} \frac{R_L}{dT} = \sigma^2 I^2 R_L^3 \frac{\pi d^3}{16 dT} \]  
(2.12)

which indicates that heat transfer from an arc varies as the square of the electrical conductivity (\( \sigma \)) and current (\( I \)); as the cube of the specific resistance (\( R_L \)) and as the fourth power of the diameter (\( d \)). Close to the electrodes, in the contraction zones, the heat transfer will increase proportional to \( j^2 \), which becomes very large, but decrease proportional to \( d^4 \), which becomes small. The effect of these two terms can be determined by considering the arc column and cathode root in a 10 A arc (Table 2.8) which shows that the fourth power term has a slight dominance.

<table>
<thead>
<tr>
<th>Region</th>
<th>Current density j (A/mm²)</th>
<th>Area of arc (mm²)</th>
<th>Diameter of arc d (m)</th>
<th>Product ( j^2 d^4 ) (Am⁻²)² x (m)⁴</th>
</tr>
</thead>
<tbody>
<tr>
<td>Column</td>
<td>1.0</td>
<td>( 1 \times 10^6 )</td>
<td>( 1 \times 10^{-5} )</td>
<td>( 3.56 \times 10^{-3} ) ( 160.6 )</td>
</tr>
<tr>
<td>Cathode</td>
<td>10</td>
<td>( 1 \times 10^7 )</td>
<td>( 1 \times 10^{-6} )</td>
<td>( 1.12 \times 10^{-3} ) ( 157.3 )</td>
</tr>
</tbody>
</table>

Table 2.8 Variation of the effects of \( j^2 \) and \( d^4 \) in the arc column and at the cathode root of an arc.

This analysis represents a simple qualitative model of heat transfer from an arc. A value for \( h \) is difficult to ascribe, since the coefficient includes heat transfer by conduction, convection and
radiation, although the method may be useful to compare heat transfer from arc at different currents when \( d \) remains approximately constant (in a plasma torch for example) and \( I, R_L \), and \( \sigma \) can be measured.

The standard energy balance applied to the arc column is the Elenbaas-Heller equation (1935) which equated the electrical power supplied to heat lost by conduction only and neglected radiative and convective heat transfer. The Elenbaas-Heller equation in cylindrical coordinates is given by

\[
\frac{1}{r} \frac{\partial}{\partial r} \left[ r k \frac{dT}{dr} \right] + \sigma \varepsilon^2 = 0 \quad (2.13)
\]

where \( r \) is the radius (m), \( k \) the thermal conductivity \( (\text{W m}^{-2} \text{K}^{-1}) \), and \( \frac{dT}{dr} \) the radial temperature distribution. If the temperature dependences of \( \sigma \) and \( k \) are known then the temperature profile over the arc channel can be determined, but the equation is difficult to solve analytically because \( \sigma \) and \( k \) are highly non-linear functions of temperature and iterative or numerical solutions are often used. The equation has been expressed in a different form by Maacker (1951)

\[
-2 \pi r k \frac{dT}{dr} = 2 \pi \varepsilon^2 \int_0^R \sigma r \, dr \quad (2.14)
\]

in which the first term represents the conduction of heat from a cylinder of unit length, radius \( r \), and the second term represents the total power dissipated in the cylinder since

\[
I = 2 \pi \varepsilon \int_0^R \sigma r \, dr \quad (2.15)
\]

These equations can be solved if the functions of \( \sigma \) and \( k \) and the boundary conditions are known. The non-linearity of \( k \) can be eliminated (Hoyaux, 1968; Pfender, 1978) by introducing the heat conduction potential \( S \) to replace \( T \) where

\[
S = \int_0^T k(T) \, dT \quad (2.16)
\]
and the equation becomes

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

(2.17)

which is claimed to be easier to solve since several models for the non-linear function \( \sigma (s) \) have been proposed (Dresvin, 1977). Significant errors may be introduced if radiation losses are ignored, since approximately 20% of the input power to an arc carrying several hundred amperes in a nitrogen atmosphere is reportedly lost by radiation (Pelzer, 1958). Much lower losses have been reported at lower currents (Table 2.9) however and the error may only be significant at high currents.

<table>
<thead>
<tr>
<th>Arc current (A)</th>
<th>% Radiation loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.8</td>
</tr>
<tr>
<td>10</td>
<td>1.4</td>
</tr>
<tr>
<td>14</td>
<td>3.0</td>
</tr>
</tbody>
</table>

Table 2.9 Radiation losses from a carbon arc in air (Brinkman, 1937).

Radiation losses have been included in the Elenbaas-Heller equation by some investigators (Maecker, 1960; Marlotte et al, 1964; Schmitz et al, 1963; Daytov, 1963) and it is claimed (Vetlutskiy et al, 1965) that radiation can be neglected below temperatures of 11,000 K to 12,000 K. Numerical solutions are claimed to be in close agreement with experimental results (Dresvin, 1977) but these iterative methods only converge to a solution after successive approximations. These methods of solution have generally only been applied to arcs in argon where the errors due to radiation are smaller than in arcs in diatomic gases.

Convection losses are reported to be a maximum at the periphery of the electrically conducting region of an arc (Hagenah, 1950) where convection is the dominant mode of heat transfer. The Elenbaas-Heller model does not describe the conditions in this boundary zone and must only be applied to the parts of the arc where thermal conduction approximates to the conditions in the arc.
Radiation and convection losses can cause significant errors when the Elenbaas-Heller equation is used to represent an arc. The only satisfactory method of determining the temperature distribution in an arc is to measure it spectroscopically (chapter 3).

2.4.4 Pinch effect and plasma jets.

Heat is conducted axially and radially from the arc column to the electrodes in the contraction zones close to the electrodes, particularly the anode, and the arc constricts in order to balance the heat losses. Electromagnetic forces also cause a constriction known as a magnetic pinch (Maecker, 1955). The pinch effect is caused by interaction between the arc current and its self-magnetic field (Fig. 2.7).

![Diagram of pinch effect and plasma jets](image)

**Fig. 2.7** Interaction between the arc current and its self-magnetic field.
The radial force produced by the self-magnetic field is balanced by a radial pressure gradient due to the charge carriers such that

\[- j_z \cdot B_\varphi = \frac{\delta P}{\delta r}\]  

(2.18)

where \( j_z \) is the axial current density, \( B_\varphi \) the circumferential magnetic field, and \( \frac{\delta P}{\delta r} \) the radial pressure gradient. This equation shows that the pressure on the axis of a cylindrical arc is proportional to the product of current density and current. An axial pressure gradient consequently exists between the arc roots, where the current density is high, and the arc column where it is much lower. The gradient is highest close to the cathode root, which is small, and produces jets of entrained gas and vapour from the electrodes which are accelerated away from the electrodes. These gas streams are known as the electrode plasma jets. Pinch effect occurs at all magnitudes of arc current but only becomes noticeable at currents above approximately 100 A (Howatson, 1976).

Pinch effect may also be considered as a result of the attraction between parallel current-carrying filaments. A force of attraction exists between two arc columns in close proximity and can cause the arcs to interact or coalesce. The magnitude of the force is given by

\[F = \frac{\mu_0 I_1 I_2}{2 \pi r}\]  

(2.19)

where \( \mu_0 = 4 \pi \times 10^{-7} \frac{H}{m} \), \( I_1 \) and \( I_2 \) are the arc currents (A) and \( r \) is the separation between the arcs (m). The force varies as the square of the current, and will be large at high currents, and inversely as the distance between the arcs so that the force increases when two parallel arcs are moved closer together and a runaway to coalescence may take place (chapter 6). This effect is relevant to the design of multiple arc devices using parallel arcs similar to that used by Boldman et al (1962) (chapter 4) in which three co-axial cathodes and a single anode were used in an arc heater for re-entry simulation.

When two or more arc columns have coalesced, the resultant column will carry a higher current than the individual arcs and the magnitude of the pinch effect at the common arc root will be increased. Large volumes of
ionised gas can be produced by operating multiple arcs carrying approximately 10 A each in close proximity so that the arc columns coalesce (chapter 5). Pinch effect may cause the discharge to contract at higher currents although the reduction in the temperature gradients in the arcs may offset this.

2.4.5 Constriction of arc discharges.

Free-burning arcs, plasma torches and magnetically rotated arc heaters (chapter 4), multiple arcs (section 2.5.3), and induction coupled plasmas are all examples of contracted discharges.

Convection is the dominant mode of heat transfer from the periphery of a free-burning arc and the diameter is governed by Steenbeck's principle (section 2.4.1). When heat losses are increased, for example by an external cooling effect such as a gas stream or a cold wall, the arc column reaches equilibrium at a smaller diameter. The temperature, electrical conductivity and electric field strength are increased by the constriction and, if the current remains constant, the power dissipation increases. Current densities up to $1 \times 10^3$ A/mm$^2$, voltage gradients of 8 V/mm and temperatures up to $50 \times 10^3$ K have been reported for constricted arcs (Skiftstad, 1962).

The force of constriction at the arc roots caused by the magnetic pinch effect (section 2.4.4) is not as strong in the arc column due to the relatively lower current density although it may be significant in highly constricted arcs when the current density in the column approaches that of the arc roots.

Gas flows and cooled surfaces produce increased convection and conduction losses respectively and cause the arc column to constrict. These techniques are used extensively in plasma torches (chapter 4) because axial and vortex gas flows spatially stabilise the arc in addition to constraining it and raising the temperature.

Applied magnetic fields, which have been used to drive arcs along parallel rail electrodes and rotate arcs between coaxial electrodes, also produce constriction because the movement of the arc increases the convection losses. Consider a dc arc between two parallel rail electrodes (Fig. 2.8).
An arc driven along parallel rail electrodes by its self-magnetic field.

The interaction between the arc current and the magnetic field due to the current flowing through the rails produces a force on the arc given by

\[ F = B I l \sin \theta \]  \hspace{1cm} (2.20)

where \( F \) is the force (N), \( B \) the magnetic flux density (T), \( I \) the arc current (A), \( l \) the arc length (m) and \( \theta \) the angle between the arc current and the magnetic field (rad). A functional relationship for the velocity of an arc moving in a magnetic field has been developed (Dautov et al., 1965) and correlated values over a wide range of conditions has resulted in the expression

\[ \frac{U_d}{I} = 4.6 \left( \frac{I}{B \cdot d} \right)^{-0.6} \]  \hspace{1cm} (Adams et al., 1967) (2.21)
where \( U \) is the velocity (m/s) and \( d \) is the separation between the electrodes (m). The magnetic flux density due to a rail is determined from the equation

\[
B = \frac{\mu_0 I}{2 \pi r}
\]

(2.22)

at a distance \( r \) (m) from the rail but the total flux applied to the arc is the sum of the components from the two rails. The magnitudes of the components of flux density produced by the current in each rail are equal mid-way between the electrodes but the total flux density in each half of the interelectrode region is dominated by the component from the closest rail. The forces and velocities of arcs carrying currents of 10 A and 100 A have been calculated at the mid-point of two rails 25 mm apart (Table 2.10).

<table>
<thead>
<tr>
<th>Current (A)</th>
<th>Total magnetic flux (T)</th>
<th>Force (N)</th>
<th>Velocity m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>( 3.2 \times 10^{-4} )</td>
<td>( 8 \times 10^{-5} )</td>
<td>0.533</td>
</tr>
<tr>
<td>100</td>
<td>( 3.2 \times 10^{-3} )</td>
<td>( 8 \times 10^{-3} )</td>
<td>5.33</td>
</tr>
</tbody>
</table>

Table 2.10 Force exerted on, and velocity of arcs moving between two rails 25 mm apart.

The results show that the force increases proportional to the square of the current, whereas the velocity increases linearly with current. This behaviour may vary depending on the arc length since the electrode regions affect short arcs (root domination) more than long arcs (column domination).

Gas flows and magnetic fields tend to increase the constriction and contraction of arcs as the current is increased, and are a disadvantage if a large volume discharge is required. This can be partly offset by the use of low gas flow rates but the higher electromagnetic forces will increase the pinch effect (section 2.4.4) and move arcs at higher velocities (Table 2.10) which will increase the convection losses so that constriction is more likely to occur.
2.4.6 Seeding and augmented flames.

Several methods of increasing the volume of arc discharges have been investigated, including magnetic rotation (chapter 4) and seeding. An arc constricts due to the negative temperature coefficient of electrical resistivity and the effect of circumferential convection losses (section 2.4.5). The addition of alkali metal salts, such as potassium carbonate, which have low ionisation potentials, to an arc produces an increase in electrical conductivity such that the conductivity of the arc is due almost entirely to the seed material and equilibrium is established at temperatures several thousand degrees below that normally required to produce the same degree of ionisation. This reduces the heat losses and lowers the temperature coefficient of electrical conductivity resulting in a less constricted arc.

Fuel-flame temperatures are approximately 1500 K although higher temperatures can be obtained by using preheated fuel and oxygen instead of air, but these methods are expensive, complex and inefficient although temperatures as high as 3500 K can be achieved. (Brown et al, 1968). A significant number of industrial processes require temperatures between those of flames and arcs, in the range 1500 K to 6000 K and methods of combining the two heat sources have been proposed.

Thermal ionisation occurs in flames and in theory the augmented-flame technique utilises the thermally generated electrons and ions to establish a discharge which raises the temperature of the flame. Thermal ionisation generates only $10^7 - 10^8$ electron-ion pairs per mm$^3$ but a concentration of $10^9 - 10^{10}$ per mm$^3$ is required (Fells et al, 1967) to establish a significant electrical discharge (Karlovitz, 1962) and flames must also be seeded with alkali salts to increase the degree of ionisation.

Generally as the required temperature increases, the proportion of electrical power also increases so that, at the top of the temperature range, virtually all the power is supplied by the discharge and the flame is unnecessary. The electrical power input has been reported to be 90% at a temperature of 4000 K (Lawton et al, 1969).
Different seeding compounds have been investigated (Ellington et al, 1966) but potassium salts are most often used because they are relatively cheap and readily available. An investigation into the production of a large volume flame/discharge (Johnston et al, 1976) reported that the electrical conductivity of the hot gas showed a maximum at seeding concentrations below 0.015%, for example at a seed concentration of 0.0015% the electrical conductivity of the gas passed through a maximum at approximately 3500 K (Johnston et al, 1976). The peak occurs when the seed material is completely ionised and represents a transition to a positive coefficient of electrical resistivity which will reduce the tendency of the discharge to contract. Very high degrees of turbulence, for example in a high speed gas stream, could also prevent an arc from contracting if heat was removed from the discharge at a high enough rate to limit the electrical conductivity and temperature of the discharge. (Karlovitz, 1962).

Electrically boosted burners combining 15 kW of combustion power and 10 kW (40%) of electrical power have been reported (Karlovitz, 1962) and the temperature was claimed to be increased from about 1800°C to over 3000°C with a 90% conversion efficiency although the losses due to waste gases were not included. The discharges were reported to be diffuse but were subsequently shown to be filamentary (Marynowskii et al, 1967; Davies, 1965; Fells et al, 1967). The diffuse appearance was probably a result of the persistence of luminosity associated with moving arcs (chapter 3). Temperatures up to 4500 K have reportedly been produced using potassium salts to seed the discharge produced by a combined ac plasma jet-gas burner system (Lawton et al, 1962) in which only 3 kW of electrical power was supplied. The application of augmented flames for chemical synthesis has been investigated (Marynowskii et al, 1969; Kilham et al, 1970) but the technique is unlikely to be used in many processes due to the contamination produced by the alkaline seed materials and combustion products. Interest in augmented flames has declined during the last ten years whereas the use of pure arc discharges for material processing and gas heating has increased and several arc heaters rated at over 1 MW have been developed (chapter 4).
2.5 Stability of electric arcs.

An arc discharge has a negative dynamic resistance at currents up to several hundred amperes and cannot be operated directly from a constant voltage power supply. At very high currents (kA) the arc voltage-current characteristic tends to become flat or even positive (Pfender, 1978) but currents of this magnitude are outside the scope of this work. A current limiting component must be incorporated in the supply in order to maintain a stable arc. Arcs can be stabilised by inductors in an ac line, or resistors in a dc circuit.

2.5.1 Stability requirements.

The conditions for maintenance of an arc are defined by the Kaufmann criterion (Kaufmann, 1900) which states that, if the voltage-current characteristic of the discharge is considered as a resistance, then the total circuit impedance must be positive for stable operation of an arc.

\[
\frac{dv}{dt} + Z > 0 \quad (2.23)
\]

An arc power supply and its characteristic are shown in Fig. 2.9. The arc characteristic and the power supply load-line intersect at points A and B such that

\[
V_{arc} = V_0 - IR \quad (2.24)
\]

If the arc operates at A and a disturbance moves the arc to a point C, then

\[
V_0 - IR - V_{arc} = \Delta V \text{ which is positive} \quad (2.25)
\]

and the applied voltage is greater than the sum of the arc voltage and resistance drop which will tend to increase the current and return the system to A. If the operating point is shifted to D, the voltage \(\Delta V\) becomes negative which will tend to decrease the current and again restore the system to A, which is known as the stable operating point.
Fig. 2.9  D.C. arc circuit and its voltage-current characteristic.

Equation (2.24) is also satisfied at B but any changes in current either extinguish the arc or move the operating point to A.

When the supply circuit includes inductance then for an instantaneous change in current from point A

$$ \delta V = L \frac{\delta I}{\delta t} $$  \hspace{1cm} (2.26)

so that

$$ \delta t = L \frac{\delta I}{\delta V} = \frac{L}{\delta R} $$  \hspace{1cm} (2.27)

and integrating (2.27) over the change in current gives the duration of the change in current

$$ t = L \int_{i_0}^{i_1} \frac{dI}{dV} \hspace{1cm} \text{(Cobine, 1958)} \hspace{1cm} (2.28) $$
If this time constant $t$ is longer than the time constant of the arc which is approximately 1 ms (Cobine, 1958) then the power supply will react slowly to any sudden changes in arc current, caused by fluctuations in the arc, due to the large inductance which will tend to maintain the current at a constant value and the arc will remain stable. When $t$ is less than 1 ms the supply will tend to follow fluctuations in arc current so that an oscillating arc current may flow and the arc will be more unstable. These two conditions are analogous to the response of a heavily damped, and underdamped oscillatory system and $t = 1$ ms corresponds to critical damping.

A typical arc power supply using an iron-cored inductor (a saturable reactor for example) to stabilise the arc is shown in Fig. 2.10.

![Fig. 2.10 An inductively stabilised arc power supply.](image)

The current-limiting inductor can be considered as two reactances connected in series, an iron-cored inductor and an air-cored inductor. The iron-cored inductor defines the mean operating point of the arc according to the Kaufmann criterion (equation 2.23). Its impedance is a function of the number of turns and the magnetic flux density in the iron core due to the current flowing in the winding. The air-cored inductor limits the initial (inrush) current during the instantaneous short-circuit condition when the arc is ignited. Its impedance is a function of the number of turns only, because the build-up of magnetic flux in the iron core required to produce the higher iron-cored inductance takes a finite time. The flux in the core is zero at switch-on and the only inductance in the circuit is the
air-cored inductance of the iron-cored inductor. The magnetic flux in the iron core cannot change instantaneously when the arc current changes so the air-cored inductance also governs the dynamic behaviour.

An alternative approach to arc stability has been proposed by Hare (1981) which requires that

\[
\frac{dV}{dt}_{\text{power supply}} > \frac{dV}{dt}_{\text{arc}}
\]

(2.29)

which is a transient form of the Kaufmann criterion (equation 2.23) where the term \((dV/dI)_{\text{power supply}}\) is equivalent to the stabilising impedance \(Z\).

The second criterion for stability is that

\[
\frac{dI}{dt}_{\text{power supply}} > \frac{dI}{dt}_{\text{arc}}
\]

(2.30)

which defines a power supply which responds very rapidly to changes in arc current in order to maintain the stability of the arc. This type of supply must have very low inductance and may require a higher open-circuit voltage than a supply with a large inductance which tends to maintain the current at a constant value. There appear to be two types of power supply which can be used to maintain stable arcs:

(i) A stiff supply with inductive stabilisation which tends to keep the arc current constant under transient conditions.

(ii) A flexible supply with a low inductance and higher output voltage which can follow changes in the conditions of the arc to maintain stable operation.

The position of the stable operating point on the arc characteristic (Fig. 2.9) is determined by the slope of the supply load-line, i.e. by the value of the series stabilising impedance. The maximum value is defined when the load-line becomes tangential to the arc characteristic. The slope of the load-line also determines the minimum arc current for a given supply voltage and stable operation at lower currents can only be obtained by increasing the supply voltage and stabilising impedance. The value of the stabilising impedance is usually determined empirically such that
\[ Z_{\text{STAB}} = Z_{\text{arc}} \quad \text{and} \quad V_{oc} : V_{\text{arc}} = 2 : 1 \quad (2.31) \]

although higher values may be used to stabilise welding arcs (3:1) and lower values used in arc furnaces ($\sqrt{2}$:1).

No theoretical method exists for determining the optimum value of stabilising impedance required for a stable arc. Some theoretical studies of arc stability have been carried out (Harry, 1966; Luxat et al, 1970). An instability coefficient was formulated (Harry, 1970a) in terms of the deviation of arc parameters such as voltage, current and resistance from an equilibrium value but no useful expression was derived. The same author also considered dynamic stability and used a resistor-inductor network as a model of the arc to investigate the effects of sudden changes in arc resistance. Reported results indicated that a sudden change in arc resistance produced a rapid change in arc voltage but only a slow change in arc current when the arc was inductively stabilised. The inductance maintained the flow of current and prevented the arc being extinguished. Harry (1970a) also reported that the optimum time constant of the supply circuit should be approximately 1 ms and that longer time constants decreased the stability (Harry, 1970a). It is now believed that the time-constant of an inductively stabilised arc power supply should be greater than 1 ms so that the current flow is maintained at a constant value for the duration of the transients.

Luxat et al (1970) investigated the stability requirements for ac arcs and reported that the most stable arcs were produced when the conduction angle of the arc was $\pi$ radians, which produced a continuous, symmetrical current waveform. The author also claimed that the arcs were more unstable when the power supply had a long time-constant, i.e. a large series inductance. Luxat et al (1970) reported that the optimum values of the ratio of supply voltage to arc voltage were in the range 5:1 to 8:1 which are much higher than the ratios normally used (equation 2.31).

The stability of high current arcs under the influence of self-magnetic fields has been investigated (Bowman et al, 1970). Single phase ac arcs were operated between a graphite electrode and a steel plate
at currents up to $10 \times 10^3 \text{A}$ to simulate conditions in an arc furnace. A criterion for the stability of a distorted arc column in which magnetic forces may cause instability was developed such that

$$
\log \left( \frac{\lambda}{r_0} \right) < 2 \log \left( \frac{r_0}{r_c} \right)
$$

(Bowman et al, 1970) (2.32)

where $\lambda$ is the 'wavelength' of the kink in the arc column, $r_0$ is the radius of the arc column and $r_c$ the radius of the arc root. The destabilising force is reported to be a maximum when the graphite is the anode because there is no plasma jet (section 2.4.4) to stabilise the arc column and forces similar to those existing in low-pressure magnetically-confined plasmas tend to distort and elongate the column. These forces are proportional to $r^2$ (Bowman et al, 1970) and are not likely to be significant in arcs at low currents where the stability criteria are fulfilled by the design of the power supply.

An arc has a statistical finite lifetime due to physical processes within the arc in addition to the stability conditions imposed by the interaction of the arc with its supply circuit (Copeland et al, 1945; Attia, 1973). Mean arc lifetime increases with current and gas pressure (Farrall et al, 1965; Klapas et al, 1976) and may also be affected by the electrode material.

Obvious methods of increasing the stability of an arc include increasing the supply voltage and stabilising impedance, increasing the current, and reduction of the temperature coefficient of electrical conductivity, i.e. reducing the negative slope of the arc characteristic. Several techniques have been used to carry out the latter, including seeding with alkali salts (section 2.4.6) using cored or coated electrodes (Cobine et al, 1931).

The conditions for the maintenance and stability of arcs can be summarised as follows:

(i) The Kaufmann criterion defines static stability and represents a minimum maintenance condition which must be satisfied.
(ii) Dynamically the series stabilising impedance must be large enough so that changes in arc voltage never exceed the supply voltage, for example in welding where low voltage (25 V) arcs are operated from a supply with a relatively high output voltage (100 V open-circuit).

and either:

(iii) The time constant of the power supply must be greater than 1 ms (the equilibrium time of the arc) so that the flow of current is maintained at a constant value during fluctuations in the arc.

or

(iv) The power supply must be very flexible so that it can respond rapidly to changes in the arc in order to maintain stable operation.

2.3.2 Dynamic arc characteristics.

The arc characteristics shown in Fig. 2.2 are static curves only. The dynamic characteristic of an arc (Fig. 2.11) can be determined by superimposing an ac current on the dc supply. This configuration shows the response of an arc to changes in current, simulated by the ac, and the total arc current is given by

\[ I_T = I_{dc} + I_m \sin \omega t \]  \hspace{1cm} (2.33)

The current oscillates between values \( I_a \) and \( I_b \), and at very low frequencies (less than 10 Hz) the dynamic characteristic follows the static curve \( f_1 \). As the frequency is increased \( f_2 \) the curve forms an ellipse with a higher arc voltage for increasing current than for decreasing current. This is due to ionisation in the column which lags behind the current, producing a hysteresis effect, so that a higher voltage-gradient is required to increase the ionisation to supply the higher current when the current is increased. Excess ionisation exists when the current is reduced and the current flows at a lower voltage-gradient. The slope of the dynamic characteristic becomes positive at frequencies of the order of 1 kHz \( f_3 \).
because of the increased lag in the ionisation caused by thermal inertia in the column and at the electrodes. The rate of ionisation cannot follow changes in the current at higher frequencies and a linear characteristic with a positive slope is formed ($f_4$). The slope of the characteristic becomes positive at approximately 1 kHz for a carbon arc in air which indicates a thermal time constant of the order of 1 ms (Cobine, 1958).

An ac arc can be considered as a special case of a dc arc operating with reversed polarity each half-cycle which undergoes extinction and re-ignition at current-zero. Deionisation of the arc column and cooling of the electrodes takes place at current-zero and a high voltage may be required to breakdown the gap for the next half-cycle. The anode is hotter than the cathode in a carbon arc and the new cathode will probably be hot enough at the instant of zero current to emit sufficient electrons to re-ignite the arc.

Fig. 2.11 Dynamic characteristics of a dc arc ($f_1 < f_2 < f_3 < f_4$)
The current tends to flow continuously in an inductively stabilised circuit due to the release of stored energy when the polarity is reversed. Arc voltage and current waveforms for inductive and resistive circuits are shown in Fig. 2.12. The re-ignition voltage tends to be higher in (b) (Fig. 2.12) due to the longer period of zero current.

The temperature in the column of an ac arc also oscillates due to the variation in current (Fig. 2.13). Hysteresis in the ionisation process results in a phase lag of 18 degrees between the peak current and peak temperature which also indicates that the thermal time-constant of the arc is approximately 1 ms (Von Engel et al, 1933).
Fig. 2.13  Variation of arc temperature (T) with sinusoidal current (I) at 50 Hz (after Von Engel et al, 1933).

2.5.3 Multiple arc configurations.

Multiple arcs cannot normally be operated from a common power supply. A single arc can be stabilised by inductor or resistor (Fig. 2.14(a)) and any attempt to strike a second arc in parallel with an existing one will cause the arc to be extinguished (Fig. 2.14(b)). If two arcs did co-exist momentarily, variations in the arcs due to convection etc. would cause a higher current to flow in one arc and a runaway effect due to the negative dynamic impedance of an arc would extinguish one arc.

A number of multiple discharges operating from a common supply do exist however. It is common practice to operate several glow-discharge fluorescent lamps from a single supply, which is effectively a multiple discharge system. Each lamp is separately stabilised by a series inductor which limits the discharge current and produces a back emf to initiate
the discharge. The operation of several welding supplies in a large works is similar. Each arc is operated from a separate unit but the power supplies may share a common feeder (Fig. 2.15). Each arc is operated and stabilised separately, although a common connection may exist through a large workpiece.
Multiple arcs occur in a three-phase arc furnace but separate supplies are effectively used for each arc, and the multiple arcs are connected in series (Fig. 2.16). The 120° phase-shift between the three arc currents ensures that the peak currents in the three arcs do not coincide, which reduces the magnetic forces of repulsion between the arc columns which can lead to instability at high currents.

Multiple arc systems can be classified according to the arrangement of the electrodes and the degree of interaction between the arcs. Arcs may exist between pairs of electrodes as separate or coalesced discharges, or between two electrodes of one polarity and a common electrode of the other, again either separately or coalesced, and with anti parallel electrodes, (Fig. 2.17). Configurations (c) and (d) can be operated with reversed polarity and multiple welding with negative electrodes, (Fig. 2.15) uses this connection.
Fig. 2.16. Series arcs in a three-phase arc furnace.

Fig. 2.17. Multiple arc configurations: (a) separate; (b) coalesced; (c) separate; (d) coalesced; (e) anti-parallel; (f) anti-parallel.
Separate arcs between two or more electrodes and a common workpiece have been used in a number of welding processes. A TIG (tungsten inert gas) welding system with four separate arcs to a common workpiece has been developed by SAF (Anon, 1975) to produce a large heated zone and allow increased welding speeds to be obtained. The process used a single, constant voltage, main supply and resistors to stabilise each arc but also incorporated auxiliary 150 V supplies to operate low current pilot-arcs during ignition. Separate HF units were used to strike each arc. Currents of up to 200 A per arc were reported, but no details of the value of the stabilising resistors were published. The circuit configuration is shown schematically in Fig. 2.18, and indicates that separate multiple arcs can be operated from a single supply provided each arc is individually stabilised.

Industrial use of this principle for multiple arc welding has reportedly been discontinued in favour of a system with three electrodes using separate thyristor controlled supplies for each arc (Petbow, 1980). It is understood that the new system uses electronically controlled constant-voltage supplies to stabilise the arcs and is more efficient since the power loss in the resistors is eliminated. Electronically stabilised supplies are more complex and expensive than the simple resistively stabilised systems although the efficiency may be higher.

Fig. 2.18  Separate multiple arcs operated from a common supply.
A commutated-current welding technique was developed (Brown, 1975) in which the welding current was pulsed alternately to a pair of adjacent electrodes by using rectifiers and anti-phase transformer windings (Fig. 2.19).

![Diagram of welding setup](image)

**Fig. 2.19** (a) Commutated twin electrode welder with common pilot-arc supply (after Brown, 1975), (b) Equivalent circuit.

The arcs were operated in close proximity which enabled increased welding currents and melting rates to be achieved. It was claimed that the electromagnetic interaction between high current dc arcs in close proximity adversely affected the weld bead formation process in MIG welding and necessitated the use of a pulsed system so that only one high current arc existed at a time. The main arcs were initiated each half-cycle by two continuous low-current pilot arcs which were operated from a common supply using individual stabilising resistors (Fig. 2.17(c)). The electromagnetic force of attraction between the pilot-arcs was claimed to be negligible at...
low currents (Brown, 1975) so that formation of the weld bead was not affected. Only the pilot-arcs represented a multiple arc discharge.

A submerged-arc welding process using two anodes was developed to increase deposition rates without significantly increasing the penetration depth (Hinkel et al, 1976). Multiple arcs were reportedly obtained from a single constant-voltage supply simply by connecting two anodes in parallel (Fig. 2.20(a)). No explanation of the method used to stabilise the arcs was given but Fig. 2.20(b) and (c) indicate that the arcs were probably stabilised by the resistances of the filler-rods protruding from the anode contact (Fig. 2.17(d)). The voltage drop across the electrodes was only 5 V, compared with an arc voltage of 30 V which gives a ratio of voltage drop across the arc to voltage drop across the stabilisation of 6:1 which is very high compared to the 1:1 ratio normally used, but the process operated at currents in the range 850 A to 925 A where the arc characteristic is almost horizontal, so that only a low value of stabilising resistance was required.

Fig. 2.20 Submerged-arc welding using a pair of anodes (Hinkel et al, 1976): (a) electrode configuration; (b) practical condition; (c) equivalent circuit.
Investigations into submerged-arc welding using multiple arcs operated from separate supplies have also been carried out in Sweden (Gränbeck, 1973; Almquist, 1976). Separate and coalesced arcs were used in systems with two and three arcs (Fig. 2.21).

These multiple arc systems were developed to obtain higher welding speeds. Instability was reported when two dc arcs were used due to interaction between the arc currents and the magnetic field associated with the flow of current in the workpiece, (magnetic blow), and due to electromagnetic attraction between the parallel arc columns. Combinations of ac and dc arcs were used to overcome this. When three arcs were used (Fig. 2.21(c)), the two ac arcs were operated from a delta connected three-phase transformer. The electrodes were separated by 20 mm to 70 mm in practice and the use of multiple arcs enabled increased welding speeds and heat inputs to be obtained (Almquist, 1976). Optimum welding speed and stability depended
on the inclination and separation of the electrodes which controlled the formation of the weld beads and interaction between the arcs.

Houldcroft (1977) reported that many multiple arc systems using separate supplies have been used for submerged-arc welding. The deepest penetration welds were produced using dc arcs with the electrodes positive (Fig. 2.17(c)) but electromagnetic forces between the arcs and magnetic arc blow reportedly caused instability at high currents and near to the electrical connections on the workpiece. The magnetic forces between two ac arcs depend on the phase difference between the currents. Stable arcs have been operated from a Scott connected (three-phase/two-phase) transformer which produces a 90° phase difference between the arc currents (Fig. 2.22) (Houldcroft, 1977).

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**Fig. 2.22** Submerged arc welding using two ac arcs operated from a Scott connected transformer (after Houldcroft, 1977).
Series arcs can be used to obtain high surface deposition rates with only shallow penetration (Fig. 2.23). Both ac and dc arcs can be operated and, since the arcs are anti-parallel, the electromagnetic forces tend to keep them apart.

The electrical characteristics of multiple arc systems with separate power supplies has been investigated by Philips (Ton et al, 1976). Two configurations were studied (Fig. 2.24). The first was a cascade arc between two anodes and a common cathode, (Fig. 2.17(c)), and the second an anti-parallel configuration between two electrodes of opposite polarity and a third common electrode (Fig. 2.17(f)). The cascade arc was investigated by considering the annular electrodes and power supply (1) as a Langmuir probe (chapter 3) in contact with the arc maintained by power supply (2).
Fig. 2.24  Multiple arc configurations (Ton et al, 1976),
(a) Cascade arc system,
(b) Anti-parallel system - separate supplies with a common
connection.

The anti-parallel system was regarded as either a single cathode and two
anodes, or two cathodes and one anode, depending on the magnitudes of the
currents flowing in the two circuits. The investigation was of a scientific,
not engineering, nature and no possible applications of the results were
proposed.

Several methods of controlling welding arcs electronically have been
developed as the power ratings of semiconductor devices have increased.
Power transistors have been used to control very low current (15A) welding
arcs (Esibyan et al, 1962) and a transistorised saturable reactor control
system was developed for use up to 450A (Buckland, 1964). Up to five arcs
have been operated simultaneously from a regulated constant voltage supply
using thyristors in conjunction with motor-generator welding supplies (Aldenhoff et al, 1974). Total currents up to 1000 A were used and extensive industrial trials have been reported. The authors claimed that 42 similar units were in operation in 1972, and that the system offered improved control, reduced capital/installation costs and increased supply utilisation, and required less space and maintenance than conventional equipment. Complex electronics, however, requires more protection from the transients generated by arcs and is likely to require more maintenance than simpler transformer equipment. Aldenhoff et al (1974) reported that multiple arc welding systems have been in use since the second world war, using a single constant voltage supply with tapped resistors to stabilise each arc and to control the current, but no reference was given to support this claim.

The discussion of multiple arcs has been limited to welding arcs, but several applications at higher power levels have been reported. Multiple cathodes and anodes have been used in arc heaters designed for re-entry simulation as part of the space programme (chapter 4). The use of multiple electrodes has allowed higher total currents to be used than is possible from single electrodes, and has reduced the rate of erosion of the electrodes, resulting in longer lifetimes of the electrodes and reduced contamination of the discharges. The multiple arc roots were individually stabilised by resistors in the range 0.3 Ω to 1 Ω and arc heaters rated at up to 50 MW, with total currents up to 5400 A have been developed (Vinovich et al, 1979).

A similar technique was used to stabilise multiple arc roots during a study of the distribution of current in sections of the nozzle in a plasma torch (Harry, 1968). A segmented anode was constructed as a laminated assembly of copper discs and mica insulation. The current flow through each segment was measured using ammeter shunts (Fig. 2.25). The ammeter shunts represented a multiple-arc circuit (Fig. 2.17(d)) and a stable discharge was formed between the common cathode and multiple anodes due to the stabilising effect of the shunts. The current distribution measured was not likely to be typical and may have varied between the segments because of the different arc lengths.
The multiple arcs described under welding processes, the laminated plasma torch nozzle and the early arc heaters used for re-entry simulation all operated with discharges between multiple electrodes of one polarity and one electrode of the opposite polarity, for example with three cathodes and a common anode (Boldman et al, 1962). Coalesced discharges can be produced with multiple electrodes of each polarity (Fig. 2.17(b)). Arc discharges with this configuration of the electrodes were proposed as a method of producing stable and controllable light sources for emission spectroscopy (Apolitskii, 1968). Two perpendicular arcs were operated in a stable coalesced discharge by using separate power supplies for each arc. The discharges could be operated from ac, dc or combined power supplies (Fig. 2.26). This technique has been used to operate six pairs of electrodes in close proximity to produce a large volume coalesced discharge which may be suitable for gas heating or material processing (Harry et al, 1979).
Fig. 2.26 Coalesced arcs operated from separate supplies (Apolitskii, 1968),
  (a) ac discharges, (b) dc discharges, (c) mixed discharges.

Separate dc supplies were used for each pair of electrodes and very stable discharges were produced (chapter 5).

The stabilisation requirements for the operation of multiple arcs depends on the configuration of the electrodes. Individual stabilising impedances have been used for each arc in applications where separate arcs are operated to a common electrode, as in welding, and where the arcs coalesce at a common electrode, as in re-entry simulation. Separate supplies can also be used for these arrangements. Large volume coalesced arc discharges with multiple electrodes of both polarities have only been operated using separate supplies for each arc (Harry et al, 1979), although a high powered arc heater incorporating multiple anodes and cathodes has been operated using individual stabilising resistors for each electrode (Winovich et al, 1979) (chapter 4) but the arcs coalesced into a single contracted column.
2.6 Summary.

The characteristics and properties of the important regions of the electric arc discharge have been described. The conditions for stable operation of an arc have been reviewed and the conditions under which multiple arcs have been operated have been discussed.
CHAPTER 3

REVIEW OF MEASUREMENT TECHNIQUES
APPLICABLE TO ELECTRIC ARC DISCHARGES
The principal objectives of the present work are to provide a multiple discharge system with a high degree of temporal and spatial uniformity and to investigate the conditions under which multiple discharges can be operated. A large volume coalesced discharge may be suitable for heating gaseous or particulate materials, for exciting lasers, and in discharge lamps, and hence one of the objectives is to determine the uniformity of the discharge region. Applications such as welding require separate arcs and a high current electrode requires coalesced arcs between separate cathodes and a common anode.

Only limited information concerning the internal conditions of an electric discharge can be obtained from simple macroscopic measurements of voltage and current. Detailed analysis of a discharge, particularly the temperature and temperature distribution, will be required in order to assess the suitability of the discharge for specific processes.

3.1 Summary of measuring techniques used on electric discharges.

Several measurement, or diagnostic, techniques have been developed for studying discharges, including probes, photography, microwaves and spectroscopy. Extensive reviews of the theoretical and practical aspects of these techniques have been published (Huddleston et al., 1965; Lochte-Holtgreven et al., 1969). The techniques can generally be divided into contact methods, where measurements are made within the discharge, which include probes; and non-contact methods involving remote measurements, which include photography and spectroscopy. These methods are summarised in Table 3.1, together with references for the theory of operation, advantages, disadvantages and limitations.

Only two methods were considered to be suitable for measurements on the multiple arc discharge; photography and spectroscopy. The remainder including probes and microwaves, were rejected either because the measurements would cause serious disturbances in the discharge, leading to errors, or because the theory was complex when applied to high pressure discharges.
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<td>(v) Spectroscopy</td>
<td>Several standard techniques exist</td>
<td>Theory is very complex</td>
<td>Discharge must be in L.T.E.</td>
<td>A large number of applications and results have been published in the literature</td>
<td>Baly (1927); Bouquet (1971); Dienes (1963); Huddleston et al. (1965); Herr (1968); Lochte-Holtgreven (1968); Drewin (1970); Richter (1975); Fauchais (1979)</td>
</tr>
<tr>
<td></td>
<td>Discharge temperature, volume emission coefficients and carrier density can be determined</td>
<td>Reference sources required for absolute measurements</td>
<td>Self reversal must be negligible</td>
<td>See: J.Appl.Spectroscopy High T - High P Spectroscopy etc.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Other methods include the measurement of norm temperatures (Larent, 1951), molecular band spectra (Harr, 1968); Osatani et al. (1950), line reversal techniques (Lochte-Holtgreven, 1968), line broadening (Gries, 1964) and continuum measurements (Drewin, 1970)</td>
<td>Needs high resolution dispersive devices and sensitive detectors</td>
<td>Theory modified in presence of strong electric and magnetic fields</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1 Measurement techniques applicable to arc discharges
and subject to errors. For example, microwaves require waveguides etc. and are only suitable for making measurements on low pressure discharges operating in closed vessels since waveguides cannot be easily interfaced to a free-burning arc discharge.

The application of photography and spectroscopy to the study of arcs is discussed in this review and practical details of equipment etc. are included in chapters 5 and 7.

3.2 Photographic techniques.

Photographic methods have been widely used to investigate electric discharges. Applications include the determination of the dimensions of arcs and observation of moving arcs and arc roots, for example in switchgear and arc furnaces (Suits, 1939b; King, 1957; Bagshaw et al, 1969; Strachan, 1976; Airey, 1978) and measurement of the velocity of arcs moving under the influence of magnetic fields (Mayo et al, 1962).

Single-exposure photographs are generally used to record the steady-state condition of an arc, whereas high-speed ciné photography is used to record transient or oscillatory behaviour of arcs which cannot be resolved in single exposures.

3.2.1 Single-exposure photography.

Only limited quantitative information about an arc can be obtained from single exposure photographs. Arc parameters cannot be measured accurately by this method, which is usually restricted to recording features of the arc such as dimensions and luminosity. Qualitative details such as the presence of dark bands or bright spots can be obtained. This method was used (Suits, 1939b)to measure the diameter of a high pressure arc by approximating the luminous region to the current carrying region in order to calculate the current density. Langmuir probe investigations, however, have shown that this approximation may not be valid because the outer layers of an arc contain recombining particles which emit radiation and may appear as bright as the arc itself although these layers do not conduct electricity (Siddons, 1971). Errors also result from the assumption of a uniform current density over the arc cross-section because contracted
conducting cores are formed in high current arcs in diatomic gases such as nitrogen (chapter 2). Suits, however, claimed that the radial temperature (and therefore current) gradient was small in arcs operating in polyatomic gases but this may have been due to the relatively low currents used (less than 20A) (Suits, 1939b).

The dimensions of an arc column generally appear larger than the conducting region in photographs because of the persistence of luminosity of visible radiation emitted from hot gases and recombining particles close to the arc, which is indistinguishable from the conducting region of the arc. Persistence of luminosity can be caused by vapour from arc electrodes or due to the formation of metastable excited states of atoms and molecules, such as active nitrogen, which decay to the ground state over a relatively long period. Persistences in excess of 20 ms after arc extinction has been measured (Harry et al, 1968). The material evaporated from the electrodes in the multiple carbon arc discharge will not produce a significant increase in the luminosity of the discharge due to its high boiling point and very stable atomic structure and gaseous effects are more likely to predominate. The emission spectrum of the nitrogen afterglow at atmospheric pressure has been investigated (Stanley, 1954) but the majority of experiments have been carried out in pure gases at low pressures (Golde et al, 1973) and are not relevant to the study of arc discharges in air at atmospheric pressure since the number of possible excited states is much larger. The wavelength of radiation emitted from the outer regions of an arc is inversely proportional to the energy difference between two states, i.e.

$$E_2 - E_1 = \frac{\text{constant}}{\lambda} \quad (3.1)$$

where $E_{1,2}$ are the energies of states 1 and 2 and $\lambda$ is the wavelength (nm). Only certain energy levels are allowable so the persistence of luminosity will depend on the wavelength and could be as shown in Fig. 3.1. More accurate observations of arcs can be made by photographing the arcs at wavelengths where the persistence is low, which can only be achieved using narrow-band filters. Neutral density filters reduce the effect of persistence of luminosity by only transmitting radiation from the brightest, hottest regions of a discharge (Airey, 1972). However this will
include radiation from the electrically conducting region and the layers of hot gas closest to it but the intensity of radiation from the outer layers will be reduced.

Despite these disadvantages single-exposure photography is useful as a first step investigation of electric arcs because it is simple and inexpensive. Results must be interpreted with care since rapid movements of the arc or oscillations in arc current cannot be resolved. In addition the measured intensity is integrated over the thickness of the discharge and cannot be used directly to determine spatial variations in temperature etc. Mechanical shutters are limited to exposures of longer than a millisecond. Exposures of the order of nanoseconds can be obtained, however, using non-mechanical shutters, including electro-optic devices such as the Kerr-Cell (Karolus, 1954), which rely on birefringence of chemicals, nitrobenzene for example, which is controlled by the application of high electric fields.
3.2.2 High-speed photography.

Arcs are generally in motion due to convection currents etc. and single exposures cannot record the movement unless it is very slow and high-speed ciné photography is often used to obtain a more accurate record. The films are exposed at several thousand frames per second and replayed at normal speeds.

The dimensions and velocity of arcs can be easily measured from high-speed films but the intensity distribution of a discharge can only be measured if the spectral response of the optical system, (filters, lenses and film) is calibrated against a reference source.

Streak and smear cameras use rotating mirrors or prisms to scan the image over a fixed film. Mirrors can be rotated at speeds up to $5 \times 10^5$ rpm to obtain writing speeds of up to $10^4$ m/sec. The operating principles and limitations of smear and other rotating mirror cameras have been discussed in a review of high-speed photography by Folkierski (1959). The main advantage is that faster film speeds can be obtained using a moving mirror and a fixed film because the tensile strength of the film limits the maximum speed of moving film ciné cameras.

Streak photography has been used to measure the velocity of particles emerging from a plasma torch (Lewis et al, 1971) and a camera operating at 8000 frames per second has been used in conjunction with a range of neutral-density filters to study the movement of arcs at currents of 10,000 A in an arc furnace (Bowman et al, 1969; Jordan et al, 1970). The bright electrically conducting regions and the luminous surroundings were recorded so that a complete picture of the different regions of the arc could be built up. No precautions were taken to limit observations to wavelengths where the effect of persistence of luminosity was small.

An arc rotating between coaxial electrodes, under the influence of an applied magnetic field, was reported to become diffuse at high rotational velocities (20 kHz) (Mayo et al, 1962). Harry et al (1968) measured the persistence of luminosity under similar conditions and found it to be up to 14.2 ms compared with the exposure time of approximately 0.1 µs and tests using an optical probe and search coil showed that the arc remained constricted. More recently, Harry et al (1979) reported that the introduction of neutral density filters to reduce transmission to 5% (2.9 ND)
reduced the persistence to less than 2 ms, and that narrow-band filters in the wavelength range 300 nm - 400 nm reduced the persistence to approximately 0.25 ms. When the persistence has been reduced to this level the photographs are likely to be accurate records of the discharge.

3.2.3 Schlieren and laser techniques.

Schlieren photography is an interferometric technique which utilises a bright light source to detect changes in the refractive index of gases. The technique was first used over a hundred years ago (Toepler, 1866). Disturbances in gases, including turbulence, pressure differences and temperature gradients cause changes in the refractive index of the medium which affect light passing through it. The method was difficult to apply to arc discharges, however, the development of the laser has made this possible. Laser-Schlieren methods have been used to investigate the behaviour of arcs in the high pressure gas flows in air-blast circuit-breakers (Bagshaw et al, 1969; Kogelschatz, 1972). The main disadvantage is the increased complexity involved in a technique which offers little advantage over spectroscopy. A mathematical process similar to the Abel inversion used in emission spectroscopy is also required when measurements are made through varying thickness of discharge as in a cylindrical arc.

Laser holography has been reported for recording the movement of free-burning arcs under the influence of transverse gas flows and magnetic fields (Grosse-Wilde, 1973) but interpretation of the results is difficult and the ability to record three-dimensional images appears to be the only advantage.
3.3 Spectroscopic methods.

Spectroscopic techniques are one of the most accurate methods of measuring arc parameters (temperature, carrier density etc.). The theory of spectra and spectroscopy applied to electric discharges is complex and has been reviewed extensively (Baly, 1927; Griem, 1964; Huddleston et al., 1965; Marr, 1968; Lochole-Holtgreven, 1968; Bousquet, 1971; Drawin, 1970; Richter, 1975; Fauchais et al., 1979) and a large number of studies have been carried out.

The optical spectrum of energy radiated from a hot gas or discharge is comprised of a series of lines together with a lower intensity continuum background. This is in contrast to radiation from hot solids which has the form of black (or grey) body radiation which is continuous over a very broad spectrum.

The intensity and wavelength of spectral lines result from transitions of electrons, atoms, ions and molecules between different permissible energy levels. Energy is absorbed in discrete amounts (quanta) during excitation, dissociation and ionisation processes and emitted, again as quanta, when the system returns to the ground state. The frequency and wavelength of emission is proportional to the difference in energy between two states such that

\[ E_2 - E_1 = h\nu = \frac{hc}{\lambda} (E_2 > E_1) \]  

where \( E \) is the energy (eV), \( h \) is Planck's constant \((6.626 \times 10^{-34} \text{Js})\), \( \nu \) the frequency (Hz) and \( \lambda \) the wavelength (m). The intensity of a spectral line is therefore a function of the temperature of the emitting species and measurement of the absolute and relative intensities of spectral lines forms the basis of most spectroscopic methods of temperature measurement. Lines in the same spectrum can be emitted from ions, atoms or molecules and the intensities correspond to the temperatures of these different species which complicates the theory since each group of particles is characterised by its own temperature. The theory is simplified considerably if the discharge is in complete thermodynamic equilibrium (CTE) when all the temperatures of the different particles are equal.
However, complete thermodynamic equilibrium rarely applies to laboratory discharges due to steep temperature and density gradients at the boundaries so that radiation is not described by the Planck function. An arc is generally accepted to be an LTE (local thermodynamic equilibrium) discharge where at all times and at every point the velocity distribution functions and energy distributions can be characterised by one temperature \( T \). The conditions for CTE, CLTE and LTE applying to discharges have been examined in detail in a review of spectroscopic measurements of high temperatures by Drawin (1970).

The main spectroscopic methods are described in Table 3.2 and the suitability of the simpler methods for measurements of the multiple arc discharge will be assessed and these methods discussed in more detail. The practical aspects of spectroscopy including dispersive instruments, detectors and recording instruments are discussed in chapter 7.

3.3.1 Methods based on the absolute intensity of spectral lines.

The absolute intensity of a spectral line is given by (Boumans, 1956; Lochte-Holtgreven, 1968).

\[
I_{ji} = \frac{h \, V_{ji} \, N \, g_j \, A_{ji}}{4 \, \pi \, Z(T)} \, \exp \left( \frac{-E_j}{kT} \right) \tag{3.3}
\]

where \( h \) is Planck's constant \( (6.626 \times 10^{-34} \text{Js}) \); \( V_{ji} \) the frequency of the line; \( N \) the number density, defined as the number of emitting particles, per unit volume in level \( j \); \( g_j \) the statistical weight of level \( j \), which is defined as the number of different quantum states of the particle which can give it that energy; \( A_{ji} \) the transition probability between an upper level \( j \) and a lower level \( i \); \( Z(T) \), the partition function, which determines the ratio of the number of particles in two allowable energy states, at a temperature \( T(K) \); \( E_j \) the energy of level \( j \), measured from the ground state and \( k \) is Boltzmann's constant \( (1.38 \times 10^{-23} \text{ J/K} \) or \( 8.6 \times 10^{-5} \text{ ev} \)), and \( I \) the depth of emitting source (m).

The temperature \( T \) can be determined if \( A_{ji}, N \) and \( Z(T) \) are known. The latter two and the other constants in equation (3.3) are often tabulated (CRC Handbook, 1980) but \( N \) may require calculation.
<table>
<thead>
<tr>
<th>Method</th>
<th>Theory</th>
<th>Comments</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute intensity of spectral lines.</td>
<td>$I_{\lambda} \propto \frac{1}{T}$</td>
<td>Theory is complex. Absolute method. Reference standard required. Measurement of $I_{\lambda}$ is difficult. Discharge must be optically thin.</td>
<td>Boumans (1966), Lochte-Holtgreven (1969), Drawin (1965).</td>
</tr>
<tr>
<td>Relative intensity of spectral lines.</td>
<td>$\frac{I_1}{I_2} \propto \frac{1}{T}$</td>
<td>Accuracy increased if energy difference of two lines is large. Discharge must be homogeneous and optically thin.</td>
<td>Lochte-Holtgreven (1969), Chuang (1965), Griem (1964).</td>
</tr>
<tr>
<td>Volume emission coefficients $E_j$</td>
<td>Method of Boltzmann plots uses integrated volume emission coefficients of a number of lines which, when plotted against the energy difference, produces a straight line, slope $\frac{1}{kT}$.</td>
<td>Straight line shows existence of LTE.</td>
<td>Drawin (1970).</td>
</tr>
<tr>
<td>Molecular band spectra.</td>
<td>Intensity of discharge and of discharge + blackbody source measured and the values used to determine the radiation attenuation factor which is a function of Planck's radiation law.</td>
<td>Useful for temperatures below $10^4$ K. Spectra from diatomic molecules relevant to arcs in air - CN bands.</td>
<td>Griem (1964), Lochte-Holtgreven (1968), Bartels (1949).</td>
</tr>
<tr>
<td>Line reversal techniques.</td>
<td>Doppler shift observed in spectrum of discharges with high carrier drift velocities. Degree of broadening $\propto \frac{1}{T}$. Stark broadening occurs in presence of electric fields.</td>
<td>Does not require values of transition probabilities or line profiles. Can only be applied to homogeneous LTE discharges.</td>
<td>Howatson (1976), Hoynx (1968), Griem (1964).</td>
</tr>
<tr>
<td>Broadening of spectral lines.</td>
<td>Emission coefficients of continuous radiation $E_V$ given by $\ln E_V = \text{constant} - \frac{hV}{kT}$.</td>
<td>Broadening can be detected at $\approx 5000$ K in spectra of low atomic gases atoms or ions, e.g. from low current, atmospheric pressure arcs.</td>
<td>Chang (1962), Schiller (1966), Drawin (1970).</td>
</tr>
<tr>
<td>Continuum radiation</td>
<td></td>
<td>Continuum is due to electron/ion recombination and acceleration of electrons by the electric fields of ions - Bremsstrahlung.</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.2 Summary of the main spectroscopic methods
This method appears to be relatively simple but measurement of $I_{ji}$ is difficult and large errors may be introduced if radiation is absorbed within the discharge itself, i.e. if it is not optically thin.

3.3.2 Relative intensity methods.

The ratio of the intensities of two lines of the same atomic species is given by (after Lochte-Holtgreven, 1968)

$$\frac{I_1}{I_2} = \frac{A_1 g_1 \lambda_2 Z_2 N_1}{A_2 g_2 \lambda_1 Z_1 N_2} \exp \left( \frac{-E_1 - E_2}{kT} \right)$$

(3.4)

If the two lines emanate from the same ionisation stage, then the partition functions $Z_1 = Z_2$ and number densities $N_1 = N_2$ so that

$$\frac{I_1}{I_2} = \frac{A_1 g_1 \lambda_2}{A_2 g_2 \lambda_1} \exp \left( \frac{-E_1 - E_2}{kT} \right)$$

(3.5)

and the temperature can be evaluated without a knowledge of $N$ or $Z$.

Taking logarithms, the slope of a straight line plot of $\ln\left(\frac{I_1}{I_2}\right)$ against $(E_1 - E_2)$ is proportional to $1/T$. Errors are small if $(E_1 - E_2)$ is large, but in general the energy difference is less than 2eV (Lochte-Holtgreven, 1968). Errors as large as 100% can also occur in the determination of the transition probabilities (Chuang, 1965). Larger values of $(E_1 - E_2)$ can be used if lines from different ionisation stages are considered but the solution becomes more complex since $Z_1 \neq Z_2$ under these conditions.

Certain elements can be added to discharges to act as thermometric species, producing measurable spectral lines. These elements should have high ionisation potentials so that the temperature of the discharge is not lowered appreciably by their addition, i.e. the reverse of seeding (see chapter 2). Boumans (1966) has reviewed this technique and has reported on the measurement of arc temperatures using zinc and copper as thermometric species.

Temperature can be determined from the relative intensities of lines from different elements (Lochte-Holtgreven, 1968). One component may be more highly ionised than the other such that the ratio of the intensities of two
atomic lines or one atomic and one ionic line of the two elements is strongly temperature dependent and,

\[ \frac{I_1}{I_2} = \left( \frac{\lambda_2}{\lambda_1} \right)^2 \frac{\alpha_1}{\alpha_2} \frac{f_1 f_2}{f_2 f_1} \exp \left( \frac{\Delta E}{kT} \right) \frac{f_1}{f_2} \]  

(3.6)

where \( M \) is the mixing ratio of the two elements \( \frac{N_2}{N_1} \), \( f_1,2 \) the absorption oscillator strengths, \( \Delta E \) the differences in ionisation energies and \( \alpha_1,2 \) the degrees of ionisation.

The relative intensity method is in theory one of the simpler spectroscopic methods but it is subject to errors if the discharge is not homogeneous or optically thin.

3.4 Application of spectroscopic techniques to electric arc discharges.

Almost all the published work on arc spectroscopy is concerned with single, gas or wall-stabilised arcs in tubes and plasma torches, or free-burning arcs. The theoretical and practical details of these techniques are well known and form the basis of standard methods. The application of these methods to the large volume of ionised gas produced by several arcs operating in close proximity is considered.

3.4.1 The effect of geometry on spectroscopic measurements.

Spectroscopic observations measure a value of intensity which is integrated over the thickness of the discharge rather than radiation from a point source. This can cause errors in measured radial intensity profiles of free-burning arcs and arcs from plasma torches, which are assumed to be cylindrically symmetrical, because of the different thicknesses of the discharge observed as the cross section is scanned from the side (Fig. 3.2). The true radial intensity or temperature distribution can be resolved by the Abel inversion (Hörmann, 1935). The inversion of measured values to obtain the true radial variation can be carried out manually (Berge et al., 1966). However, computer programs have been developed which are much faster and more accurate than manual calculations (Lochte-Holtgreven, 1968).
Fig. 3.2 Measurement of radiation from different thicknesses of discharge in side-on observations of a cylindrical source.

If the multiple arc discharges (Harry et al, 1979) (chapter 5) can be approximated to a disc of constant thickness, the measured intensity distribution will be integrated over a constant path length and an Abel inversion will not be required. Errors may arise from this assumption since, although the discharge may be accurately described by a disc of constant thickness, non-uniformities such as preferential conducting paths may exist within the disc (Fig. 3.3). The measured intensity profiles would indicate that both discharges were uniform although the two values need not necessarily be equal. The non-uniformity in (b) (Fig. 3.3) can only be detected if the intensity of radiation emitted from a series of points at a constant depth within the discharge is measured. This cannot even be achieved by using a lens with a very short focal length and narrow depth of focus to sample radiation from within the discharge (see chapter 7).
Photographic studies of the multiple arc discharge (Harry et al, 1979) (see chapter 5) have indicated that some discharge configurations produce diffuse, apparently uniform, volumes of ionised gas and the flat-disc approximation may be used.

Fig. 3.3 Examples of uniform and non-uniform discharges with apparently uniform intensity profiles;
(a) uniform discharge,
(b) discharge containing a high-current filament.
3.5 Summary.

The measuring techniques which have been used on electric discharges have been reviewed. Two methods, photography and spectroscopy, have been discussed in detail as these techniques respectively enable a simple record and accurate measurements of an arc discharge to be carried out. The suitability of these methods for measurements on a multiple arc discharge have been discussed, together with limitations imposed by persistence of luminosity and the geometry of the discharge zone. The other techniques available, including probes and microwaves were rejected because they disturb the discharge, causing errors, or because they are not readily adaptable to making measurements on free-burning arcs in air at atmospheric pressure.
CHAPTER 4

REVIEW OF ARC HEATERS AND APPLICATIONS
OF ELECTRIC ARC DISCHARGES FOR GAS
HEATING AND MATERIAL PROCESSING
A number of electric arc heaters have been developed, some of which are in operation today at power levels in excess of 1 MW. The factors which have influenced and limited the design of high power arc heaters for industrial processing are discussed in this review.

4.1 Use of electric arcs in high temperature processes.

Electric arc discharges are suitable for gas heating and reduction processes in which high enthalpies and temperatures above 2000 K are required. Many high temperature reactions, such as the reduction of crude or pre-reduced ore, are endothermic and require very high energy inputs and are particularly suited to arc processes.

The uncontaminated reaction environment produced by electric arcs is also an advantage in some processes, such as the manufacture of the white pigment titanium dioxide, where combustion products discolour the pigment. An electric arc process may be the only acceptable method of production in cases like this.

The use of arc heaters for processing gases, metals and ceramics etc. has been reported extensively and details of reviews and other published work are given in Appendix 1. Arc heaters can be classified in a number of different ways such as either high current/low voltage or high voltage/low current, alternatively as laboratory scale and high power, but overlaps occur between these definitions. Arc devices are considered in three categories in this review:

(i) reactors in which the arc heater is entirely within the reaction vessel as part of an integrated structure,

(ii) arc heaters based on constricted arc plasma torches which are enclosed in a furnace,

(iii) arc heaters developed for re-entry simulation as part of the aerospace programme.

The first category includes the high-voltage arc heaters used for chemical synthesis which use very long vortex-stabilised or magnetically-rotated arcs. The constricted arc torches in the second category are similar to those used for cutting and welding. The third group includes a wide variety of arc gas
heaters developed to simulate the re-entry conditions experienced by missiles and spacecraft, and some of these have been used for industrial processing. The commercial and experimental heaters in these categories are listed in Table 4.1, which includes installations operating at high powers and those relevant to this study of large volume discharges, such as multiple discharges.

A large number of processes exist which are potentially suitable for heating in discharges (Table 4.2). The general availability of plasma torches of the type used in fabrication processes has resulted in many tests being carried out, often purely for academic interest. Gaseous and particulate materials were passed through torches with varying degrees of success (Reed, 1967) and low yields, together with high capital costs have prevented further investigations. The nozzle used to constrict the arc column in torches of this type increases the heat losses from the periphery of the arc column and decreases the diameter of the arc which increases the axial voltage gradient and electrical conductivity so that equilibrium is established at a higher temperature and power output than a free-burning arc carrying an equal current (chapter 2). Plasma torches also use axial or vortex gas flows to spatially stabilise the arc column to produce a rigid heat source suitable for cutting etc. The nozzle of the torch increases the velocity of the gas stream which helps to remove molten material during cutting but may be a disadvantage when powder is to be heated. Conversely, the major objective of arc heaters designed for re-entry simulation is the production of high temperature, high velocity gas streams. The basic design of plasma torches, especially the electrodes and operating voltage, makes scaling up above 200 kW difficult although TASC, Tetronics and Freital have reported operation at power levels in excess of 1 MW (section 4.3).
<table>
<thead>
<tr>
<th>Reactors with arc electrodes inside the reaction vessel</th>
<th>Constricted arc plasma torches used for material processing</th>
<th>Arc heaters for re-entry simulation and associated devices</th>
<th>Magnetically rotated arc heaters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heater</td>
<td>Nominal power (MW)</td>
<td>Heater</td>
<td>Nominal power (MW)</td>
</tr>
<tr>
<td>Birkeland-Eyde</td>
<td>0.6</td>
<td>Linde</td>
<td>0.06</td>
</tr>
<tr>
<td>Schönherr</td>
<td>0.5</td>
<td>Arcos</td>
<td>0.6</td>
</tr>
<tr>
<td>Hüls</td>
<td>8</td>
<td>Tetronics</td>
<td>1.4</td>
</tr>
<tr>
<td>Hoechst</td>
<td>10</td>
<td>TASC</td>
<td>1 - 7.5</td>
</tr>
<tr>
<td>Knapsack-Griesheim</td>
<td>4</td>
<td>Freital</td>
<td>20</td>
</tr>
<tr>
<td>Du Pont</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AVCO</td>
<td>10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Linde</td>
<td>2.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ionarc/TAPA</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bethlehem Steel</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.1** Survey of electric arc heaters relevant to industrial processes.
<table>
<thead>
<tr>
<th>Reactants</th>
<th>Products</th>
<th>Comments</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{N}_2 + \text{O}_2 )</td>
<td>2NO</td>
<td>Process replaced when became uneconomic</td>
<td>Edstrom, 1904, Schünherr, 1909</td>
</tr>
<tr>
<td>( 2\text{CH}_4 )</td>
<td>( \text{C}_2\text{H}_2 + 3\text{H}_2 )</td>
<td>Only Hüels plant known to be still in operation</td>
<td>see section 4.2</td>
</tr>
<tr>
<td>( \text{TiCl}_4 + 4\text{Na} )</td>
<td>( \text{Ti} + 4\text{NaCl} )</td>
<td>New process route</td>
<td>Johnston et al, 1971, Bunting, 1978</td>
</tr>
<tr>
<td>( \text{TiCl}_4 + \text{O}_2 )</td>
<td>( \text{TiO}_2 + 2\text{Cl}_2 )</td>
<td>High purity pigment</td>
<td>Hare, 1981</td>
</tr>
<tr>
<td>( 2\text{FeCl}_3 + 3\text{H}_2 )</td>
<td>( 2\text{Fe} + 6\text{HCl} )</td>
<td>New process route</td>
<td>Lawton, 1975</td>
</tr>
<tr>
<td>( \text{ZrCl}_3 + 3\text{Na} )</td>
<td>( \text{Zr} + 3\text{NaCl} )</td>
<td>New process route</td>
<td>Lawton, 1975</td>
</tr>
<tr>
<td>( \text{MoS}_2 )</td>
<td>Mo + 2S</td>
<td>New process route</td>
<td>Boulos et al, 1974</td>
</tr>
<tr>
<td>( \text{Cr}_2\text{O}_3 + \text{Fe} + \text{C} )</td>
<td>Ferrochrome</td>
<td>New process route</td>
<td>Camacho, 1977\textsuperscript{a}</td>
</tr>
<tr>
<td>( \text{V}_2\text{O}_5/\text{V}_2\text{O}_3 + \text{C} + \text{Fe} )</td>
<td>Ferrovanadium</td>
<td>New process route</td>
<td>MacRae, 1979\textsuperscript{a}</td>
</tr>
<tr>
<td>Coal</td>
<td>Acetylene</td>
<td>Process never operated</td>
<td>AVCO, 1972</td>
</tr>
<tr>
<td>Coal spoil</td>
<td>Cement</td>
<td>Not economic for normal grade cement</td>
<td>Tylko, 1978</td>
</tr>
<tr>
<td>Steel scrap</td>
<td>Alloy steels</td>
<td></td>
<td>Fiedler et al, 1974</td>
</tr>
</tbody>
</table>

Table 4.2 Examples of some existing and potential plasma processes.
4.2 Arc heaters with the electrodes within the reaction vessel.

The high power arc heaters in which the arc electrodes and reaction vessel constitute an integral structure (Table 4.1) are described in detail in Table 4.3. All the systems have been operated at powers in excess of 0.5 MW and have been used for processing materials on a commercial scale.

4.2.1 Chemical synthesis in electric arc discharges.

The arc processes described in Table 4.3 are, with the exception of the Ionarc and Bethlehem Steel reactors, all high voltage heaters operating with arc lengths greater than 1 m.

The earliest commercial exploitation of arc heating for chemical synthesis was the Birkeland-Eyde nitrogen-fixation process in the manufacture of nitric acid in Norway (Edstrom, 1904). A yield of 2% nitric oxide was obtained from air passed through a long ac arc between copper electrodes. A magnetic field was used to rotate and stabilise the arc and movement of the arc roots over the surface of the electrodes reduced erosion of the electrodes and lifetimes of up to six weeks were reported (Grosse et al, 1968). The high temperature favoured the endothermic reactions involved (Timmins et al, 1967) but high energy costs and the introduction of a more economic process producing nitric acid directly by the oxidation of ammonia resulted in closure of the arc process (Phillips et al, 1960). Other arc processes for nitrogen fixation have been developed, including the Schönherr system (1909) which used a very long arc (Table 4.3), and routes via hydrogen cyanide and cyanogen (Timmins et al, 1967; Leutner, 1962) but the latter have not been used commercially (Parsons, 1970).

The Hüels, Hoechst, Knapsack-Griesheim, Du Pont and AVCO systems (Fig. 4.1(a)–(e)) were developed for the synthesis of acetylene from hydrocarbon feedstock. All the processes used long single arcs and were therefore subject to the limitations imposed by non-uniformities etc. resulting in low and variable yields. The systems were viable when introduced but, with the exception of the Hüels process, have now been superceded. The Hüels process was characterised by its exceptionally high capital costs and included provision for the use of off-peak
<table>
<thead>
<tr>
<th>Heater</th>
<th>Date</th>
<th>Nominal power (kW)</th>
<th>Voltage (kV)</th>
<th>Current (A)</th>
<th>Supply</th>
<th>Arc Length (m)</th>
<th>Mode of operation</th>
<th>Comments</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Birkeland-Eyde</td>
<td>1903</td>
<td>0.6</td>
<td>2-3</td>
<td>200-500</td>
<td>ac</td>
<td>6</td>
<td>Magne.tically rotated arc</td>
<td>Superceded by more economic process</td>
<td>Edstrom, 1904</td>
</tr>
<tr>
<td>Schönhe~</td>
<td>1909</td>
<td>0.5</td>
<td>7.2</td>
<td>100</td>
<td>dc</td>
<td>7</td>
<td>Gas vortex stabilised</td>
<td>Very long arc used</td>
<td>Schönhe~r, 1909</td>
</tr>
<tr>
<td>Hoels</td>
<td>1940</td>
<td>8</td>
<td>8</td>
<td>1000</td>
<td>dc</td>
<td>1</td>
<td>Gas vortex stabilised</td>
<td>Low yields, high capital cost. Still in operation</td>
<td>Gladisch, 1968</td>
</tr>
<tr>
<td>Hoechst</td>
<td>1940</td>
<td>5.3</td>
<td>0.77</td>
<td>4000</td>
<td>ac</td>
<td>1</td>
<td>Gas vortex stabilised</td>
<td>Superceded by more economic process</td>
<td>Edstrom, 1904</td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>1.4</td>
<td>4200</td>
<td>ac</td>
<td>1</td>
<td>1</td>
<td>Gas vortex stabilised</td>
<td>Anon, 1971</td>
<td></td>
</tr>
<tr>
<td>Knapsiek-Chriesheim</td>
<td>1963</td>
<td>4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>Vortex and axially stabilised</td>
<td>This heater is apparently the same as the Hoechst designs. Differences are not clear.</td>
<td>Anon, 1971</td>
</tr>
<tr>
<td>Du Pont</td>
<td>1963</td>
<td>10</td>
<td>3.5</td>
<td>3100</td>
<td>dc</td>
<td>0.5</td>
<td>Magnetically rotated arc</td>
<td>Closed down in 1968</td>
<td>Anon, 1968</td>
</tr>
<tr>
<td>AVCO</td>
<td>1966</td>
<td>10</td>
<td>8</td>
<td>1250</td>
<td>dc</td>
<td>-</td>
<td>Axial gas flow stabilised</td>
<td>100 kW design operated, 10 MW plant never built due to fall in demand for acetylene</td>
<td>Sadler, 1967</td>
</tr>
<tr>
<td>Linde high voltage arc heater</td>
<td>1961</td>
<td>2.5</td>
<td>6.25</td>
<td>400</td>
<td>dc</td>
<td>-</td>
<td>Magnetically rotated cathode root</td>
<td>Designed to operate up to 4 kW</td>
<td>Union Carbide, 1961</td>
</tr>
<tr>
<td>Ionarc/TAFA</td>
<td>1970</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.2</td>
<td>Axial gas flow stabilised arc in conjunction with dc plasma torch</td>
<td>Suitable for particulate feedback</td>
<td>Rainbridge, 1968</td>
</tr>
<tr>
<td>Bethlehem Steel</td>
<td>1979</td>
<td>1</td>
<td>1.75</td>
<td>480</td>
<td>dc</td>
<td>1.5</td>
<td>Gas vortex stabilised falling film reactor</td>
<td>Resistance times up to 2 minutes claimed. Scale up to 20 MW proposed.</td>
<td>Massee, 1979 (a) (b)</td>
</tr>
</tbody>
</table>

Table 4.3 High power electric arc heaters with the electrodes within the reaction vessel.
Fig. 4.1  High voltage arc heaters used for chemical synthesis:
(a) Hüels, (b) Hoechst, (c) Knapsack-Griesheim,
(d) Du Pont, (e) AVCO, (f) Linde.
electricity etc. and the very low yield was justified because East Germany has no oil supply for its plastics industry. The system has been improved and developed continually and is still in operation today (Müller et al, 1981). Electrode lifetimes of only a few hours were reported when hydrogen feedstock was used (Gladisch, 1968) but this was improved by the addition of 10% methane which shielded the electrodes. The electrodes were also shaped so that the gas vortex moved the arc roots over the surface. Cagas et al (1959) reported that the viability of the Hfels process could be increased when ac was used instead of dc. Reduced capital costs of the power supply, without the need for rectification, seems to be the main advantage of an ac system, although stability would be decreased due to reignition of the arc every half cycle.

The Du Pont process, which used a rotating discharge, was used to produce acetylene as a raw material for the manufacture of neoprene but was closed down when the manufacture of neoprene from butadiene became more economical (Ouellette et al, 1978).

A number of arc heaters have been used for laboratory experiments on the conversion of coal to acetylene (Bond et al, 1966; Kawana et al, 1967; Gannon et al, 1970). Barbier et al of AVCO (1978) reported that an 80 kW - 100 kW reactor had been developed and that a 10 MW reactor had been designed (Table 4.3) (Blaw-Knox Chemical Plants, 1971) to produce $1.37 \times 10^5$ T of acetylene per year but this has never been built due to the reduction in demand for acetylene. Research into coal gasification has increased recently and the AVCO reactor may be suitable for future use.

The Linde high voltage arc heaters (Fig. 4.1(f) (Eschenbach, 1961) are very similar to the Hfels design in one form and have been tested at up to 2.5 MW (Table 4.3) and are reported to be capable of operation at 4 MW. A magnetic field was used to rotate the cathode root over the surface of a hollow cathode and this, together with a vortex flow of air produced a higher degree of stabilisation than in the Hfels system, and reduced the rate of erosion of the electrodes. The long constricted arc column resulted in high arc voltages and relatively low currents (400A compared to 1000A in the Hfels system) which also increased the lifetime of the electrodes. Eschenbach (1961) reported that the electrode erosion rate was proportional to pressure as well as current, indicating the advantage of operating at atmospheric pressure. The Linde high voltage arc heaters
were originally developed for re-entry simulation (section 4.4.1) and operated at pressures up to 5.5 MPa to generate high stagnation enthalpies. This type of heater has been used to investigate the chemical reactions during the manufacture of acetylene (Anderson et al, 1962) and for heating oxygen to about 1800°C for the production of titanium dioxide from titanium tetrachloride (Bryson et al, 1965).

The magnetically rotated ac arc heaters developed by Westinghouse (section 4.4.5) have been used to manufacture acetylene from methane, propane and butane (Fey, 1977). Tests were carried out using single-phase heaters at powers up to 3 MW and it was reported that satisfactory yields could only be obtained at atmospheric pressure or below owing to the decomposition of acetylene into carbon at higher pressures.

4.2.2 The Ionarc and Bethlehem Steel reactors.

The Ionarc reactor utilises a three-phase ac arc between graphite electrodes. A dc plasma torch is used to initiate and stabilise the main discharge between three consumable electrodes, shown schematically in Fig. 4.2(a). The discharge, including arcs and tailflame, was reported to be 1.2 m long and 250 mm in diameter (Thorpe, 1972) but it is likely that the usable region of the discharge was much smaller due to the steep temperature gradients at the periphery of an arc column (chapter 2). The heater is suitable for processes with particulate feedstock such as spheroidisation due to the relatively large heated zone. Feedstock was injected through ports around the plasma torch and the commercial production of zirconia from zircon sand has been reported (Nilks et al, 1972). The main disadvantage of this system is the need to monitor and control the electrode feed rates as the graphite is consumed. The process is unsuitable for some processes due to contamination of the product from the electrodes.
Fig. 4.2  Schematic representations of the Ionarc consumable electrode heater and the Bethlehem Steel falling film reactor: (a) Ionarc reactor, (b) falling film reactor.

A similar three-phase ac heater has been developed by Bonet (1970) using a 30 kW dc plasma torch to stabilise an arc between three non-consumable water-cooled copper electrodes. This system overcome the disadvantage of the Ionarc reactor, because no electrode feed mechanism was required and the electrode material did not contaminate the discharge, but has only been operated at power levels up to 200 kW, possibly due to thermal overloading of the electrodes, and applications have been limited to theoretical studies (Bonet et al, 1974). A similar arrangement using three dc plasma torches with a three-phase ac supply superimposed between the nozzles has been developed by ARPOS (Schoumaker, 1976) and operated at powers in excess of 500 kW (section 4.3.4).
One of the most recent developments in high temperature technology has been the falling film reactor in which a layer of molten feedstock runs down a tube heated by an electric arc. Metallurgical reduction processes are reported to take place within the falling film and the main advantage of the process is claimed to be the long residence times obtainable. A laboratory scale device rated at 50 kW has been used to concentrate titanium ores and produce phosphorous from tri-calcium phosphate (Chase et al, 1974) but is too small for commercial operation.

A high power falling film reactor has been developed by the Bethlehem Steel Corporation (Table 4.3) for the reduction of vanadium oxide and iron ore at power levels between 100 kW and 1 MW (Gold et al, 1975; MacRae et al, 1976; MacRae, 1979(a)). The heater (Fig. 4.2(b)) is basically a long vortex stabilised arc between a tungsten cathode and a cylindrical water-cooled copper anode. Initial tests on the reduction of iron oxide were carried out at 100 kW and favourable results led to a scale up to 1 MW, with a corresponding reduction in the specific energy requirement (Gold et al, 1975). A reactor operating at a higher enthalpy was developed to produce ferrovanadium since higher temperatures were required. The 500 kW unit has reportedly demonstrated the commercial scale production of 570 T of ferrovanadium per year (MacRae et al, 1976) but at present no industrial application of the falling film reactor exists despite this and the economic potential of high cost alloy processes. Residence times of 1 to 2 minutes have been claimed (MacRae, 1979(b)) which will allow good heat transfer to the reactants. The falling film is also claimed to provide a medium for reactions between solid and liquid phases which are difficult to carry out during the short residence times (milliseconds) in the discharge itself. It is, however, likely that a significant proportion of the reduction reactions take place in the hot crucible below the falling film section, as in other arc processes, and that efficient melting of the feedstock is probably the main advantage of the process. The falling film will also thermally insulate the anode if a solid layer is formed on the cooled surface of the electrode, which will reduce electrode erosion. Continuous operation for up to 8 hours has been reported (MacRae, 1979(a)) with negligible erosion of the electrodes. Bulk steelmaking on a commercial scale will require reactors rated at approximately 50 MW which represents a very large scale up from the present 1 MW. This will involve large increases in arc current, up to 28500 A if the voltage is kept constant,
and will require the development of cathodes capable of carrying such high currents, since these are not available today, (the generally accepted current limit for tungsten cathodes is 1000 A - 2000 A although some authors have reported operation up to 8000 A (sections 4.3.5 to 4.3.7), or the use of multiple electrodes (section 4.4.2). Some work on multiple cathodes has been carried out at Bethlehem Steel (Sandall, 1974) but no details have been published. The Bethlehem Steel philosophy is that an arc heater and reaction vessel must be developed as an integrated unit rather than as separate components (MacRae, 1974) and that each chemical reaction requires a reactor specifically designed for that process (MacRae, 1976). This is in agreement with the other heaters described in this section but in contrast to most of the existing high power arc heaters used for metal melting etc. which use modified plasma torches similar to those developed for cutting and spraying (section 4.3).

Other methods of obtaining long residence times for particulate feedstocks have been investigated, including a furnace in which the walls were rotated at up to 1000 rpm to reduce convection losses from a dc arc, causing it to expand (Whyman, 1967). The furnace was used to melt refractories such as alumina, silica and zirconia but was limited to batch operation because the anode region quickly blocked with material which caused instability. Scale up of this design would be limited to increasing the length and voltage since large increases in the diameter of the furnace would not produce corresponding increases in arc diameter and the mechanics of a large rotating structure would be complex. Several other rotating furnaces have been developed and have been reviewed by Hamblyn (1977). These designs used cutting type plasma torches and were limited to maximum powers of approximately 120 kW which are too low for industrial processes.
4.3 Constricted arc plasma torches used for material processing.

Many early experiments in high temperature heating processes were carried out using dc plasma torches of the type developed for welding, cutting or spraying. These were constricted arc devices capable of generating gas streams with axial temperatures of around 20,000 K but generally limited to maximum currents of approximately 1000 A and powers of 200 kW although some designs are reportedly capable of much higher currents (section 4.3.5 to 4.3.7). The operating principles and common applications of plasma torches are described, together with details of the high power furnaces which used this type of torch (Table 4.1).

4.3.1 Operating principles of dc plasma torches.

A constricted arc plasma torch (Grosse et al, 1968) uses an arc maintained between a cathode within the torch and an anode which can be external to the torch. The cathode is normally thoriated tungsten which is water-cooled to prevent melting. The arc column is stabilised by an axial or vortex gas flow and constricted (chapter 2) by a water-cooled copper nozzle which may be connected as the anode. An arc is struck between the cathode and the nozzle or anode by breaking down the gap with a high voltage (typically 10 kV) high frequency (500 kHz) spark. The injected gas flow forces the arc through the constricting nozzle and emerges as a jet of ionised gas. The gas flow and nozzle spatially and temporally stabilise the arc on the axis of the torch and the constriction raises the temperature of the arc to approximately 20,000 K by increasing the electrical conductivity and peripheral heat losses due to convection and radiation. The arc from a plasma torch can be considered as a rigid heat source due to the spatial constraint which makes it suitable for cutting and welding. Temperature gradients of the order of $10^4$ K mm$^{-1}$ exist in the arc column.

Plasma torches can be operated in three ways (Fig. 4.3). In non-transferred operation the arc is struck between the cathode and nozzle but in the transferred mode the anode root is established on an external electrode, for example the workpiece in a cutting process. This mode of operation allows longer arcs with high voltages and higher currents to be used, developing more power for the same current than in the non-transferred
mode and increasing the efficiency since the anode root is on the workpiece. The current in the nozzle is generally limited to approximately 30 A. The lifetime of the nozzle is very short at higher currents due to overheating and erosion of the copper, although the torches developed by ARCO (section 4.3.4) can be operated at currents up to 600 A in the non-transferred mode.

![Diagram of plasma torch operation](image)

Fig. 4.3 Plasma torch operation: (a) non-transferred, (b) transferred, (c) superimposed.

In the superimposed mode, (Fig. 4.3(c)), developed primarily by ARCO (section 4.3.4), an additional ac or dc supply is connected between the nozzle and workpiece or the nozzle of another torch. Three phase arcs can be superimposed between the nozzles of three torches and powers up to 600 kW can be dissipated (section 4.3.4).

Argon, nitrogen, air, hydrogen and helium and mixtures of these gases are most often used as the working gases in plasma torches. Hydrocarbons cannot be used because they corrode the electrodes, but may be introduced downstream. Argon is normally used for starting due to its low ionisation
potential but diatomic gases produce higher enthalpy discharges due to the additional energy of dissociation. Air cannot be used in torches with tungsten cathodes because the tungsten oxidises rapidly and zirconium or hafnium cathodes are used in air cutting torches (Weatherly et al, 1965).

Plasma torches have been developed for fabrication processes including cutting, welding and spraying, and parameters such as nozzle size and gas flow rate are optimised for each process. The design and application of plasma torches has been extensively reviewed (Grosse et al, 1968; Dresvin, 1977) and will only be summarised here.

4.3.2 Applications of plasma torches.

The most common applications of plasma torches are listed in Table 4.4. The availability of plasma torches of the type used in fabrication processes resulted in extensive tests being carried out with this type of heater, some of

<table>
<thead>
<tr>
<th>Application</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma spraying refractory coatings</td>
<td>Marynowski, 1965</td>
</tr>
<tr>
<td></td>
<td>Fisher, 1972</td>
</tr>
<tr>
<td></td>
<td>Muhlberger, 1975</td>
</tr>
<tr>
<td>Cutting and welding</td>
<td>Grosse et al, 1968</td>
</tr>
<tr>
<td></td>
<td>Rykalin, 1973</td>
</tr>
<tr>
<td>Processing powders</td>
<td>Reed, 1967</td>
</tr>
<tr>
<td></td>
<td>Waldie, 1972(a) and (b)</td>
</tr>
<tr>
<td></td>
<td>Boulos et al, 1974</td>
</tr>
</tbody>
</table>

Table 4.4  Applications of plasma torches in fabrication processes.

which have been summarised by Reed, (1967). Many gaseous and particulate materials have been passed through torches with varying degrees of success (Reed, 1967). Recently advances have taken place in metal melting using plasma torches. Reclamation of valuable high melting point metals and alloys, including osmium, iridium and ruthenium has been investigated (Paton, 1973). Melting of high alloy steels is a good example of a
suitable process because of the high alloy costs and the unacceptable contamination and alloy losses produced by carbon arc furnaces.

Increased heat transfer and power input can be obtained if the material to be heated is connected as the anode of a dc plasma torch, as in transferred-arc cutting, due to the high temperature of the anode root, increased radiation from the arc column, the use of higher currents and voltages than in the non-transferred mode and resistance heating in the molten material. A cutting type torch can only be operated with arc lengths between about 25 mm and 100 mm but modifications to the insulation and nozzles of a number of torches have been made in order to operate arcs up to a metre long. The two basic requirements for the operation of long arcs are adequate supply voltage, which depends on the gas used because the arc column voltage gradient varies from 1 V mm$^{-1}$ in argon and 2 V mm$^{-1}$ in air to 10 V mm$^{-1}$ in hydrogen at 10 A (Cobine, 1958) and about half these values at high currents, and a gas flow so that the arc column is spatially constrained over its whole length, otherwise instability may occur. Low gas flow rates may be required to produce laminar flow regimes in order to maintain long arcs and this will increase the thermal loading within the torch which must be cooled more efficiently. These features have been included in some of the high power plasma torches used for materials processing (Table 4.1) which operate with arc lengths between 0.1 m (Schoumaker, 1976) and 1.4 m (Fiedler et al, 1974). The operating parameters of high power plasma torches are given in Table 4.5, where a plasma torch is defined as an arc heater which can be removed from a furnace to change electrodes etc., in contrast to the integrated structures discussed in section 4.2.
### Table 4.5  Operating parameters of high power plasma torches used for material processing.

<table>
<thead>
<tr>
<th>Plasma torch</th>
<th>Date</th>
<th>Nominal power (kW)</th>
<th>Arc voltage (V)</th>
<th>Arc current (A)</th>
<th>Supply</th>
<th>Arc length (m)</th>
<th>Principle of operation and Comments</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linde Plasmaarc</td>
<td>1964</td>
<td>0.66</td>
<td>60</td>
<td>1120</td>
<td>do</td>
<td>0.15 maximum</td>
<td>Single transferred arc do plasma torch mounted in roof of furnace.</td>
<td>Magnold, 1964</td>
</tr>
<tr>
<td></td>
<td>1971</td>
<td>1.2</td>
<td>275</td>
<td>approx. 1050</td>
<td>ac</td>
<td>approx. 0.1</td>
<td>Three phase superimposed arc between the nozzles of three torches. Developed for gas heating. Each torch dissipated 24 kW dc and a total of 200 kW ac was superimposed.</td>
<td>Schoumaker, 1972</td>
</tr>
<tr>
<td></td>
<td>1976</td>
<td>0.27</td>
<td>220</td>
<td>approx. 525</td>
<td>ac</td>
<td>approx. 0.1</td>
<td>Three separate arcs to a common pool of slag with three phase superimposed arc between the nozzles. Developed for vacuum arc melting of slag. Each torch dissipated 21 kW dc and a total of 500 kW ac was superimposed.</td>
<td>Schoumaker, 1976</td>
</tr>
<tr>
<td>Tetronics</td>
<td>1981</td>
<td>1.4</td>
<td>890</td>
<td>1500</td>
<td>do</td>
<td>up to 1</td>
<td>Processing plasma torch mounted in roof of furnace. Arc is transferred to either a ring anode in the walls of the furnace or to a molten pool. Operation of plasma torches at currents up to 3000 A reported.</td>
<td>Tylko, 1974</td>
</tr>
<tr>
<td></td>
<td>1977</td>
<td>2</td>
<td>400</td>
<td>5000</td>
<td>do</td>
<td>approx. 1</td>
<td>Transferred arc(s) from plasma torch(es) mounted in side of furnace. Copper cathode enables air and ac or dc to be used. Scale up to 7.5 kW is claimed, enabling three phase systems of 25 kW to be developed.</td>
<td>Canacho, 1977(a)</td>
</tr>
<tr>
<td>TASC</td>
<td>1981</td>
<td>0.125</td>
<td>430</td>
<td>150</td>
<td>ac</td>
<td>approx. 1</td>
<td>Small scale arc heater for laboratory research.</td>
<td>TASC product release, 1981</td>
</tr>
<tr>
<td></td>
<td>1980</td>
<td>0.125</td>
<td>430</td>
<td>150</td>
<td>ac</td>
<td>approx. 1</td>
<td>Four dc plasma torches obliquely mounted in sides of furnace. Furnace of 5T, 10T and 30T capacity reported. Specification implies torch cathode currents of 7500 A.</td>
<td>Fiedler et al, 1974</td>
</tr>
<tr>
<td>Primalt</td>
<td>1980</td>
<td>2</td>
<td>660</td>
<td>7500 x 4</td>
<td>do</td>
<td>1.4</td>
<td></td>
<td>Zhumdakov, 1976</td>
</tr>
</tbody>
</table>

TASC product release, 1981

Fiedler et al, 1974

Zhumdakov, 1976

Mayerson et al, 1976

Anon, 1976

Borodashyov et al, 1976

Table 4.5  Operating parameters of high power plasma torches used for material processing.
4.3.3 The Linde Plasmarc furnace.

The earliest example of a furnace using a plasma torch to melt steel was the Linde Plasmarc furnace (Magnolo, 1964) (Table 4.5). The principle of using one or more plasma torches instead of free burning arcs from graphite electrodes was first proposed in the same year (Lunau, 1964). The low voltage dc plasma torch was mounted in the roof of a closed hearth furnace 0.55 m in diameter, 0.14 m deep (Fig. 4.4).

![Diagram of the Linde Plasmarc furnace](image)

Fig. 4.4 Schematic cross section of the Linde 60 kW Plasmarc furnace.

The torch operated in the transferred mode using argon and the furnace was sealed to create an inert atmosphere. A water cooled metal electrode was connected to the molten material through the bottom of the furnace and reportedly showed no visible erosion after 500 hours operation, probably due to the formation of a solid skull of metal on the surface of the electrode. The lifetime of the plasma torch electrodes was also reported to be in excess of 100 hours (Magnolo, 1964), indicating the possibility
of semi-continuous operation. Melting was carried out in 150 kg batches. A magnetic stirring coil was connected in series with the bottom electrode to stir the melt during operation but this caused increased erosion of the refractory lining due to the scouring action of the molten metal. The transferred arc was reported to be very stable during melting, in contrast to conventional steel melting arc furnaces where the arcs are very mobile and which cause annoying flicker on the supply network. Stability was also increased by the relatively short (0.15 m maximum) arc used and the shallow (0.14 m) hearth so that the arc length only changed by a small amount during operation.

Published results (Magnolo, 1964) reported that steel of comparable quality to that obtained by vacuum melting was produced, indicating that furnaces of this type, operating with an inert atmosphere could be used to produce high alloy steels. Scale up to 10 T was reported, using four plasma torches during a two hour melting cycle, but no further developments have been reported.

4.3.4 The AROOS superimposed arc plasma torch system.

AROOS (Belgium) have developed high power arc heaters using vortex stabilised plasma torches (Schoumaker, 1976) similar to the Linde torch (section 4.3.3). The length of the transferred arc which can be maintained by a plasma torch depends on the supply voltage, gas type and gas flow rate (section 4.3.2) and is typically up to 0.3 m for AROOS torches at flow rates of the order of 12 l min\(^{-1}\) to 15 l min\(^{-1}\) of argon (Schoumaker, 1931). The electrodes and cooling systems of AROOS torches are designed to allow operation at powers up to 50 kW in the non-transferred mode. This feature has been utilised in two high power heating systems (Table 4.5) in which three dc plasma torches operating in the non-transferred mode are used to stabilise a three-phase superimposed arc connected between the nozzles of the torches. The torches can be operated as a gas heater (Fig. 4.5(a)) with the neutral point of the ac supply floating and three coalesced arcs or in a furnace (Fig. 4.5(b)) with the neutral point connected to the molten material with three separate arcs (Schoumaker, 1976). This configuration is similar to a conventional three-phase arc furnace but the spatially stabilised arcs are more stable and cause less interference on the supply network.
ARCOS plasma torch configurations: (a) 270 kW superimposed three phase gas heater, (b) 570 kW superimposed three phase heater for melting slag.
4.3.5 Tetronics precessing plasma torch furnace.

Tetronics have used a precessing or orbiting plasma torch in a furnace in an attempt to increase the contact time between an arc and particulate material. A dc plasma torch operating in the transferred mode was mounted in the roof of a furnace and rotated at speeds in excess of 1000 rpm so that the arc described a path shaped like a truncated cone (Tylko, 1978). The anode root was formed either on a ring electrode attached to the inside of the furnace or to a bath of molten material with an electrode inserted into the bottom of the furnace (Fig. 4.6). The discharge appeared to be expanded into a cone but the arc remains constricted although it is likely that an increased amount of material actually passes through the discharge than through a stationary arc.

Fig. 4.6 Tetronics precessing plasma torch furnace.
This system has been used to demonstrate the manufacture of cement from coal spoil (Tylko, 1978) although it is not economic for normal grades of cement. The residence time of the particles in the discharge was approximately 200 ms and it was claimed (Tylko, 1978) that the chemical reactions occurred during this time although some reactions may also have taken place in the hot tail flame or in the collecting vessel. It is likely that when metals were melted most reactions occurred in the crucible rather than in the discharge.

The transferred arc from the plasma torch was reported to be stable at lengths up to 1 metre (Monk, 1981). This is due to the combination of the very low argon flow rates used and the long body of the torch (1 m) which ensure that the stabilising gas flow is laminar so that a long arc can be maintained. Operation at currents of 1500 A have been reported in a 1.4 MVA furnace and Tetronics claim (Tylko, 1978) that the unit can be scaled up easily either by using multiple plasma torches or by scaling up a single torch. Operation at currents of 8000 A has been reported (Poster-Wheeler, 1981) and currents up to 10,000 A have been predicted. The torch utilises a single non-consumable tungsten cathode and must be very efficiently water-cooled if these claims are valid since the cooling effect of the gas will be very small. The generally accepted value of the current limit of a tungsten cathode is approximately 1000 A and operation at 8000 A represents a significant development in electrode technology.

The Tetronics system is made increasingly complex by the mechanism used to rotate the torch and the need to move the torch into the furnace to start the transferred arc initially. The power to the torch is supplied by a twelve-pulse thyristor rectifier which allows rapid control when sudden changes occur in the arc and reduces interference on the supply although the rectifiers must be protected from the electrical transients produced by arcs. The supply has a relatively high output voltage (Table 4.5) due to the long arc and hence much higher powers can be dissipated from a single torch than any other torch of this type, which generally operate at arc voltages up to 200 V.

The efficiency of the furnace is reported to be approximately 75% but this high value is probably due to the use of very thick (1 m) refractory insulation. This type of construction is against the standard practice today which is to use water cooled panels although this may result in unacceptable efficiencies in this case.
A similar system has been developed in the U.S.A. using a magnetically rotated arc between fixed electrodes instead of a moving plasma torch (Reid et al, 1981). A series of tests has been carried out to investigate the reduction of taconite (Fe₃O₄) with graphite and lignite char (a mixture of bituminous coal and peat) in a 100 kW reactor with arc rotational speeds up to 60,000 rpm. Up to 75% recovery of iron has been reported (Reid et al, 1981) but the reactor is only a laboratory tool at present.

4.3.6 TASC plasma torches.

A transferred arc plasma torch operating at up to 2 MW has been developed by TASC (Technological Application Service Corporation) (Camacho, 1977(b)). The plasma torch (Table 4.5) is described (Camacho, 1978) as a long column plasma torch which operates at high voltages and relatively low currents but a patent (US patent, 1972) indicates that the arc column is approximately 1 m in length so the corresponding arc voltage would be of the order of 400 V in argon and 800 V in air, requiring currents of 5000 A and 2500 A respectively for powers of 2 MW. A gas vortex is used to stabilise the arc and the nozzle was designed especially to eliminate double arcing, i.e. the formation of arcs between the cathode and nozzle within the torch and between the nozzle and workpiece outside the torch (US patent, 1972), which causes severe erosion of the nozzle.

Similar torches operating at powers in excess of 10 kW in the non-transferred mode have also been developed (Camacho, 1981). Both types of torch are unusual in that a copper cathode is used instead of tungsten. The arc roots are moved over the surface of the electrodes in two planes by an aerodynamic gas stream (Camacho, 1981) so that the heat from the arc roots is distributed over a relatively large area to prevent melting of the electrodes. The copper electrodes allow ac and dc to be used since the electrode will not be thermally overloaded and rapidly destroyed when connected as the anode. Tungsten cathodes have short lifetimes at currents above 1500 A, although operation at currents of several thousand amps has been reported (sections 4.3.5 and 4.3.7), or when used with ac, but lifetimes up to 800 hours have been claimed for the copper electrodes which allow continuous high power operation (Camacho, 1977(a)). The lifetime of
the electrodes depends on the gas used and increases in order with oxygen, air, nitrogen and argon. Air can be used because a protective oxide layer forms on the copper, although some oxidation does occur and the use of nitrogen instead of oxygen is claimed to increase the lifetime of the electrodes by a factor of two (Camacho, 1981). The injected gas stream also elongates and stabilises the arc column within the plasma torches in a similar manner to the system used by Westinghouse (section 4.4.5) (Fig. 4.7) although the latter uses magnetic rotation of the arc which is simpler. The arc is initiated by using a 25kV - 35 kV spark to break down the 5 mm gap between the electrodes.

![Diagram of plasma torch with water-cooled copper, hot gas, insulation, and gas injection](image)

**Fig. 4.7** TASC non-transferred plasma torch using a gas stream to rotate the arc.

The TASC plasma torches, like the Tetronics torch (section 4.3.5), are claimed to be easy to scale up. Preliminary designs of a 7.5 MW transferred-arc torch have been reported (Camacho, 1977(b)) and the use of three-phase ac systems operating at 25 MW have been proposed (Camacho, 1977(a)). Operation of torches in the non-transferred mode at up to 10 MW has also been reported (Camacho, 1981).

Applications including coal gasification, gas reforming, ignition of pulverized coal in power stations, ore reduction and recovery of precious metals have been proposed and extensive tests have been reported (Camacho, 1981) although no commercial use has been reported. A furnace
for the reduction of ferrochrome ore using a transferred-arc plasma torch is shown in Fig. 4.8. Feedstock is passed through an annular region which shields the walls of the furnace from the arc. Material is preheated by the exhaust gases as it passes down the furnace into the region of the arc. Some material passes through the discharge but it is likely that most of the melting takes place in the molten bath and the process is analogous to a carbon-arc furnace.

TASC have recently announced the marketing of plasma torches rated at powers between 125 kW and 3.5 MW for laboratory and industrial use (TASC Product Release, 1981; TASC Plasma Heating System, 1981). The torches are similar to those described earlier and incorporate water-cooled copper electrodes. Torches up to powers of 0.5 MW operate from a 480 V, three-phase ac supply but above this a 4.16 kV supply is required. Complete systems of torch, power supply and rectifiers etc. can be supplied, with a claimed delivery period of 6 months for a 0.5 MW unit. The additional complexity of the TASC torches, due to the use of copper electrodes and gas streams etc., is reflected in the cost/kW which is approximately £31, compared to £25/kW for an ARCO5 torch. The dc arc current in a torch rated at 125 kW is of the order of 400 A, which is low compared to that in the high power torches so that a tungsten cathode could be used, thereby simplifying the design.
Fig. 4.8 TASC Plasma furnace for reduction of ferrochrome ore.
4.3.7 The Freital plasma steel smelting process.

High current dc plasma torches or plasmatrons (Table 4.5) have been developed in the USSR (Zhoukov et al, 1976) and applied in East Germany (Fiedler et al, 1974; Meyerson et al, 1976; Boradachyov et al, 1980). Initially a single torch operating in the transferred mode at currents up to 6000 A was mounted in the roof of a 5 T furnace and used for melting trials. Subsequently a 10 T furnace was designed and built incorporating three plasma torches, two in the side walls and a third in the roof (Fiedler et al, 1974) but this was later modified so that all the torches were mounted in the side walls (Meyerson et al, 1976). Each torch was operated at currents up to 6000 A at arc voltages typically of 450 V so that each torch supplied almost 3 MW to the furnace.

The cathodes in the torches were tungsten, alloyed with yttrium, thorium and lanthanum (Zhoukov et al, 1976) which reduced the thermionic work function so that high current arcs could be maintained at a lower cathode temperature to prevent melting of the cathode. The service life of the cathode was reported to be increased from 5 to 60 melts, and the nozzle lifetime was increased from less than 10 to over 100 melts during these tests (Meyerson et al, 1976). Zhoukov et al (1976) reported that the lifetime of tungsten cathodes is governed by resistance heating of the metal and that at currents above approximately 1000 A the temperature inside a rod-type cathode may be higher than at the arc root, where some cooling takes place due to thermionic emission, and the tungsten may melt. Intensive cooling at the cathode can also decrease its lifetime because the arc root contracts when the cathode is overcooled resulting in a large increase in current density and cathode root temperature which causes evaporation of the tungsten and alloy elements and raises the thermionic work function (Zhoukov et al, 1976). This may not be a problem in conventional plasma torches with thoriated tungsten electrodes operating at currents below 1000 A but flat, alloyed cathodes may be necessary for operation at several thousand amps. Alternatively multiple cathodes, each carrying 1000 A, mounted in a common torch body could be used provided the multiple arcs could be operated from a common supply and that the electrodes could be mounted close together so that the diameter remained relatively small.
A vortex flow of argon was used to stabilise the long (1.4 m) transferred arcs (Table 4.5) and the furnaces operated in argon atmospheres at above atmospheric pressure. Electrical contact to the molten metal was made via a water-cooled copper electrode in the hearth of the furnace. A layer or skull of steel solidified on the surface of this electrode and ensured that erosion rates were very low. The arcs were initiated by a high voltage, high frequency spark source so that a short circuit to the charge was not required.

The magnitude of the electromagnetic forces between the arcs was dependent on the current, length and separation of the arcs (Meyerson, 1976) (chapter 2) and was balanced by the axial gas flows from the torches which tended to spatially constrain the arcs. Under certain conditions, probably at low gas flow rates and short separations, the electromagnetic forces were reported to cause instability in the arcs (Meyerson, 1976).

Recently, a 35 T furnace has been developed (Anon, 1980; Freital, 1980). Four torches mounted in the side walls are used to supply 20 kW at arc voltages of 660 V which implies arc currents of the order of 7500 A, which represents a significant (25%) increase over the previous values and is similar to the currents reported by Tetronics (section 4.3.5). Throughputs of 20 T per hour are reported, with an energy consumption of 500 kWh/T which is identical to the energy requirements of conventional steel making processes. The energy requirements indicated that efficiency increased with the size of the furnace and power input since a 6 T furnace rated at 6.6 MW had a specific energy requirement of 800 kWh/T (Freital, 1980). The sealed furnace is particularly suitable for reducing losses of alloying elements and will also reduce iron losses and eliminate carburisation caused by the graphite electrodes in conventional arc furnaces. The main disadvantage of this system is the mechanical structure. Roof linings lasted for 60-70 melts and the upper wall lining for 150-160 melts (Meyerson et al, 1976) indicating substantial down time for re-lining. Refractory wear was caused by thermal shock produced by radiation from the long arc columns (Meyerson et al, 1976) and tests reportedly showed that the lifetime of the refractories could be increased by a factor of three by varying the angle of the torches to control the arc length. These furnaces, like the Tetronics reactor (section 4.3.5) use thick refractories whereas the current trend is to use water-cooled side panels which become coated with a layer of solidified material.
Marketing of this process has been licensed to Voest-Alpine in Austria (Anon, 1980) and there are a number of suitable processes and a range of furnaces available. No commercial use exists outside East Germany where over 30000 T of high grade chromium, nickel-chromium, titanium and other alloy steels have been melted annually since 1974 (Fiedler et al, 1974).

4.4 Arc heaters used for re-entry simulation and related devices suitable for material processing.

Several high power arc heaters have been developed by NASA and other US government research establishments for re-entry simulation (Table 4.1). Work began in the 1950s as part of the Gemini and later the Apollo space programme and is continuing with the Space Shuttle and interplanetary probes. A great deal of literature on these heaters has been published and is summarised in Appendix 1.

The two main design criteria in this type of heater are the production of high enthalpy and high velocity gas flows, usually only for short periods, of the order of seconds, although in some cases up to times of half an hour (section 4.4.2). The techniques used to produce high enthalpy gas streams are relevant to this work and include the use of magnetically rotated arcs and multiple electrodes. Some features of re-entry simulators, such as magnetic rotation of arcs, have been used in heaters developed for processing materials (Table 4.1), for example the Westinghouse ac arc heaters (section 4.4.5) are based on arc heaters originally designed for use in hypersonic wind tunnels (Boatright et al, 1964), and are also discussed here.

4.4.1 Arc heaters for re-entry simulation.

The main components of an arc heater designed to simulate the conditions experienced by missiles and space vehicles during re-entry are a high current cathode, a constrictor to increase the temperature and velocity of the arc, a gas flow and an anode. Tungsten cathodes are
generally used in dc arc heaters but three phase ac heaters (Winkler et al, 1964) use water-cooled copper electrodes. Arcs can be constricted by nozzles similar to those used on plasma torches (section 4.3.1) which can be designed to produce supersonic flows, or by using long segmented constrictors (Shepard, 1972). A long arc column can shunt to the metal walls in a continuous nozzle and damage may occur and instability may be produced but a segmented structure with insulated discs between electrically isolated, water-cooled metal discs prevents the flow of current through the walls and the low voltage gradient between the metal segments reduces the possibility of electrical breakdown (Shepard et al, 1963). High enthalpies are produced by constricting the arc column, which increases the electrical conductivity, axial voltage gradient and temperature (chapter 2). This can be achieved by placing a nozzle immediately after the electrodes, but higher enthalpies can be produced if the arc column passes through the constriction, and one electrode, usually the anode, is positioned downstream of the nozzle to achieve this. The enthalpy of the arc is proportional to the length of the constricting zone, and the rate of rise of enthalpy is a maximum at the entrance of the constrictor and asymptotically tends to zero some distance inside, at which point any further increase in input power is offset by increased heat losses. This distance is proportional to the mass flow rate of the gas (Shepard et al, 1963) and varies for different applications.

Re-entry heaters operate at pressures from less than $10^4$ Pa (Winovich et al, 1979) in the space shuttle programme, to more than 30 MPa (Raezer et al, 1964) in hypersonic (Mach 7) wind tunnels.

Arc roots are generally moved over the surface of the electrodes to distribute the thermal load and reduce electrode erosion. This can be achieved by tangential gas flows (section 4.3.6) but this technique is reported to be ineffective at pressures above a few atmospheres (Raezer et al, 1964) and magnetic fields are used.

The operating parameters of the arc heaters used for re-entry simulation which are relevant to this work are listed in Table 4.6.
<table>
<thead>
<tr>
<th>Heater</th>
<th>Date</th>
<th>Nominal Power (kW)</th>
<th>Arc Voltage (kV)</th>
<th>Arc Current (A)</th>
<th>Supply</th>
<th>Arc Length (m)</th>
<th>Comments</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA (Lewis)</td>
<td>1962</td>
<td>0.5</td>
<td>up to 0.38</td>
<td>1000 to 1700</td>
<td>dc</td>
<td>0.125</td>
<td>Magnetically rotated anode root. Multiple cathodes (3)</td>
<td>Boldman et al, (1962)</td>
</tr>
<tr>
<td>NASA (Ames)</td>
<td>1963</td>
<td>0.055</td>
<td>up to 0.3</td>
<td>108 to 240</td>
<td>dc</td>
<td>0.23</td>
<td>Multiple anodes (6)</td>
<td>Shepard et al, (1963)</td>
</tr>
<tr>
<td></td>
<td>1964</td>
<td>0.35</td>
<td>0.44</td>
<td>800</td>
<td>dc</td>
<td>0.25</td>
<td>Multiple anodes (24) Basically an uprated version of the 55 kW heater described above.</td>
<td>Stine et al, (1964)</td>
</tr>
<tr>
<td></td>
<td>1979</td>
<td>60</td>
<td>11</td>
<td>5400</td>
<td>dc</td>
<td>4.12</td>
<td>Magnetically rotated arc. Multiple anodes and cathodes (6 off each)</td>
<td>Winovich et al, (1979)</td>
</tr>
</tbody>
</table>

Table 4.6 Operating parameters of re-entry simulation arc heaters with multiple electrodes.
4.4.2 Use of multiple electrodes in arc heaters designed for re-entry simulation.

Arc heaters incorporating multiple electrodes (chapter 2) have been developed to allow increased currents to be used in order to generate higher enthalpy gas streams and to reduce erosion of electrodes.

Multiple cathodes were first reported nearly 20 years ago (Boldman et al., 1962) during the development of a 1.5 MW arc heater (Table 4.6). The current limits for different shapes and diameters of thoriated tungsten electrodes are generally reported to be of the order of 1000 A (Table 4.7). Above this value excessive erosion occurs (chapter 2) which may destroy the electrode and contaminate the gas stream.

<table>
<thead>
<tr>
<th>Diameter of electrode (mm)</th>
<th>Profile</th>
<th>Current limit (A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>19</td>
<td>pointed tip</td>
<td>1000</td>
</tr>
<tr>
<td>19</td>
<td>flat end</td>
<td>1200</td>
</tr>
<tr>
<td>25</td>
<td>flat end</td>
<td>1500</td>
</tr>
</tbody>
</table>

Table 4.7 Current limits of thoriated tungsten electrodes (Boldman et al., 1962).

Tests were carried out (Boldman et al., 1962) (Fig. 4.9) with three pointed cathodes, 19 mm in diameter in conjunction with a common magnetically rotated anode, although the final design used 12.5 mm diameter electrodes. The multiple cathode roots were individually stabilised by resistances of 0.16 Ω with a common resistance of 0.075 Ω and stable operation at total currents up to 1700 A was reported (Boldman et al., 1962). The use of multiple cathodes allowed higher total currents, and therefore power, to be used.

Multiple electrodes have also been used in high power arc heaters developed by NASA at its Ames research centre in California. Shepard et al. (1963) reported that the anode root of an arc became diffuse at low pressures in supersonic flows and multiple anodes were used to promote axial symmetry of the discharge and to limit the current density at the anode roots. Six water-cooled copper anodes were used (Fig. 4.10)
Fig. 4.9 Schematic of a magnetically rotated arc heater with multiple cathodes (after Boldman et al, 1962).

Each carrying a current of only 75 A. Electrode erosion was reported to be so low at this current that magnetic rotation was not required. The anode roots were individually stabilised by 1 Ω resistors and no common resistance was included. An uprated version of this heater was developed in 1964 (Stine et al, 1964) (Table 4.6) using twenty four anodes, each capable of carrying up to 50 A, but the basic design remained unchanged.

Multiple cathodes and anodes have recently been used together, again at Ames research centre, in a 60 MW arc heater developed as part of the Space Shuttle programme (Winovich et al, 1979). The heater incorporates six anodes and six cathodes, each carrying currents between 250 A and 1000 A, up to a total maximum current of 5400 A (Table 4.6).
The electrodes each consist of six water-cooled copper rings with insulators between them. The anode and cathode are identical and the construction is shown in Fig. 4.11. The arc roots are stabilised by 0.3 Ω resistors connected to each electrode, and moved over the surface of the electrodes by magnetic fields produced by a coil inside each electrode, connected in series with the arc. This reduces erosion of the electrodes and contamination of the discharge and it is reported that the erosion rate is up to two orders of magnitude lower than from free-burning arcs on water-cooled electrodes (Winovich et al, 1979). An interesting feature of this heater is that the ratio of open-circuit voltage to arc voltage (Table 4.8) is less than 2:1 which is the value normally used to produce stable arcs and to restore stable operation during fluctuations.

Fig. 4.10  Constricted arc heater with multiple anodes (after Shepard et al, 1963).
in arc voltage. This may be due to the high currents used (i.e. above 1000 A) so that the voltage–current characteristic of the arc is almost flat, requiring less stabilisation than at lower currents (chapter 2).

Table 4.8  Supply characteristics of the NASA 60 MW arc heater.

<table>
<thead>
<tr>
<th>Current (kA)</th>
<th>Voltage (kV)</th>
<th>Ratio of open-circuit to arc voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Open-circuit</td>
<td>arc</td>
</tr>
<tr>
<td>16.2</td>
<td>5.5</td>
<td>3.7</td>
</tr>
<tr>
<td>8.1</td>
<td>11</td>
<td>7.4</td>
</tr>
<tr>
<td>5.4</td>
<td>16.5</td>
<td>11.1</td>
</tr>
<tr>
<td>2.7</td>
<td>33</td>
<td>22.2</td>
</tr>
</tbody>
</table>

1.48 : 1
Investigations into multiple electrodes have also been reported by McDonnell-Douglas (Painter et al, 1979) (Table 4.6) who claim that at pressures of 10 MPa arc roots apparently oscillate between electrodes at high frequencies and do not form separate multiple roots. These results are not consistent with the generally reported behaviour of multiple arcs and have not been substantiated, although oscillating arc roots may be a high pressure phenomena which is not relevant to arcs operating at atmospheric pressure.

The main disadvantage of arc heaters used for re-entry simulation is that they can only be operated at high powers for short times due to the high currents used and are therefore not suitable for processing material. Typical operating times (Table 4.9) are limited to minutes or seconds at powers above 10 MW and continuous operation is impossible, although the NASA 60 MW heater (Winovich et al, 1979) can be operated for up to 30 minutes but, at a level of 110 kW, the time is reduced to 10 s indicating that it is vastly overdesigned for operation at 60 MW.

<table>
<thead>
<tr>
<th>Heater</th>
<th>Nominal power (MW)</th>
<th>Duty</th>
<th>Comments</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA (Lewis)</td>
<td>0.5</td>
<td>continuous</td>
<td>relatively low power</td>
<td>Boldman et al (1962)</td>
</tr>
<tr>
<td>NASA (Ames)</td>
<td>0.055</td>
<td>continuous</td>
<td>low power</td>
<td>Shepard et al (1963)</td>
</tr>
<tr>
<td>John Hopkins University</td>
<td>10</td>
<td>2 minutes</td>
<td></td>
<td>Raezer et al (1964)</td>
</tr>
<tr>
<td>NASA (Ames)</td>
<td>60</td>
<td>30 minutes on/30 minutes off</td>
<td>over designed at 60 MW</td>
<td>Winovich et al (1979)</td>
</tr>
<tr>
<td></td>
<td>110</td>
<td>10 s</td>
<td></td>
<td></td>
</tr>
<tr>
<td>McDonnell-Douglas</td>
<td>13</td>
<td>8 s</td>
<td></td>
<td>Painter et al (1979)</td>
</tr>
</tbody>
</table>

Table 4.9 Operating times for high power arc heaters used for re-entry simulation.
Power loss in the stabilising resistors is also a disadvantage. The calculated losses in the heaters developed by NASA are shown in Table 4.10. Over half of the 370 kW dissipated by the stabilisation in the heater with multiple cathodes (Boldman et al, 1962), and the heater with multiple anodes (Stine et al, 1964) is due to the common resistance in the supply circuit. In the latter case more power was dissipated in the stabilisation than in the arc (Table 4.10). This common resistance was probably not necessary for stable operation since later heaters showed that stable multiple arcs could be maintained by individual stabilisation for each arc root. The common resistor was probably included to adjust the arc voltage during the development of the heaters. At 60 MW (Winovich et al, 1979) the power loss in the stabilisation was only 4.8% of the output power but 2.9 MW represents a large quantity of heat to be dissipated, particularly during tests lasting for 30 minutes.

4.4.3 Magnetically rotated arc heaters for material processing.

Magnetic rotation of arcs has been used in some re-entry simulators (section 4.4.2) to move the arc roots over the surface of the electrodes which prevents overheating and reduces electrode erosion and contamination of the discharge. This principle has been used in arc heaters designed for materials processing (Table 4.11) and other advantages have been claimed including the formation of a diffuse discharge (Mayo et al, 1962) and uniform heating of gas streams (Lawton, 1967).
<table>
<thead>
<tr>
<th>Heater</th>
<th>Nominal power (MW)</th>
<th>Number of electrodes</th>
<th>Stabilising resistance (Ω)</th>
<th>Typical total current (A)</th>
<th>Power dissipated in the stabilisation (MW)</th>
<th>% of useful power</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA (Lewis)</td>
<td>0.5</td>
<td>1 anode 3 cathodes</td>
<td>0.16 individual 0.075 common</td>
<td>1700</td>
<td>0.37</td>
<td>74</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NASA (Ames)</td>
<td>0.055</td>
<td>1 cathode 6 anodes</td>
<td>1 individual</td>
<td>240</td>
<td>0.0096</td>
<td>17.5</td>
</tr>
<tr>
<td></td>
<td>0.35</td>
<td>1 cathode 24 anodes</td>
<td>2 individual 0.5 common</td>
<td>800</td>
<td>0.37</td>
<td>105</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>6 anodes 6 cathodes</td>
<td>0.3 individual</td>
<td>5400</td>
<td>2.9</td>
<td>4.8</td>
</tr>
</tbody>
</table>

Table 4.10  Power dissipated in the stabilising resistors in multiple arc heaters.
<table>
<thead>
<tr>
<th>Heater</th>
<th>Date</th>
<th>Nominal power (kW)</th>
<th>Arc voltage (V)</th>
<th>Arc current (A)</th>
<th>Supply</th>
<th>Arc length (s)</th>
<th>Comments</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>NASA (Langley)</td>
<td>1962</td>
<td>1.2</td>
<td>400</td>
<td>2600 to 3800</td>
<td>dc</td>
<td>8</td>
<td>Arc characteristic reported to be positive. Formation of diffuse discharge claimed at high currents and magnetic fields. Later disproved by Harry (1968).</td>
<td>Mayo et al., (1962)</td>
</tr>
<tr>
<td>J. E. Harry</td>
<td>1968</td>
<td>0.1</td>
<td></td>
<td></td>
<td>ao</td>
<td></td>
<td>Arc remained constricted at all times. Apparent diffuse discharge caused by persistence of luminosity.</td>
<td>Harry et al., (1968)</td>
</tr>
<tr>
<td>ECRC Capenhurst</td>
<td>1972</td>
<td>0.03</td>
<td>40</td>
<td>300</td>
<td>dc</td>
<td>15</td>
<td>Uniform heating of gas stream claimed. Used to extract titanium from titanium tetrachloride.</td>
<td>Chen et al., (1969)</td>
</tr>
<tr>
<td></td>
<td>from 1966</td>
<td>1.5</td>
<td>700</td>
<td>10,000</td>
<td>dc or single phase ac</td>
<td>75</td>
<td>Three heaters can be combined to produce a three-phase heater rated at 15 kW.</td>
<td>Maniero et al., (1966)</td>
</tr>
<tr>
<td></td>
<td>1973</td>
<td>1</td>
<td></td>
<td></td>
<td>three phase ac</td>
<td>300</td>
<td>Different design incorporating vertical electrodes. Suitable for processing particulate materials.</td>
<td>Pey et al., (1977)</td>
</tr>
</tbody>
</table>

Table 4.11 Magnetically rotated arc heaters suitable for gas heating or material processing.
4.4.4 Magnetically rotated arc heaters with coaxial electrodes.

A magnetically rotated dc arc heater developed by NASA (Fig. 4.12) (Mayo et al, 1962) for aerodynamic testing was reported to produce an arc with a positive dynamic characteristic and a diffuse discharge. The water cooled field coil was connected in series with the arc current and produced magnetic flux densities up to 2.55 T. No external stabilisation was used but the field coil in series with the arc may have stabilised the arc. The positive arc characteristics may have been due to the effects of convection and viscous drag on the arc column. As the current was increased, the arc rotated faster and convection currents elongated the arc column causing an increase in arc voltage, giving an apparently positive arc characteristic. Back emf induced in the field coil by the rotating arc was reported to have contributed to the increased arc voltage when the current was increased (Mayo et al, 1962) but the voltage induced in the arc is estimated to be of the order of only 20% maximum, which is negligible.

![Schematic of magnetically rotated arc heater](after Mayo et al, 1962).
The discharge was photographed with a high speed camera operating at 7800 frames per second, giving an exposure time of 43µs, and with a low speed framing camera operating at 64 frames per second, in conjunction with a Kerr-Cell shutter (chapter 3) giving an exposure of 0.1µs, and no distinct arc could be detected (Mayo et al, 1962). This apparently indicated that either the arc was rotating completely within the exposure time of the cameras or that a transition to a diffuse discharge had occurred. Rotational speeds in excess of 6 x 10^8 rpm would be required in order for the arc to appear diffuse at exposures of 0.1µs and it was also claimed that the emf induced in the field coil by the arc would be several orders of magnitude higher than the observed voltage if the arc did rotate at such speeds, (Mayo et al, 1962). Calculations based on the measured arc voltage indicated that the maximum rotational speed was approximately 10^5 rps (Mayo et al, 1962) and the observed results could only be explained by the formation of a diffuse discharge. These operating conditions were duplicated (Harry et al, 1968) during the development of an ac plasma torch (Table 4.11) and high speed photography again showed that an apparently diffuse discharge was formed. An optical probe and a search coil close to the discharge showed that the arc remained constricted at rotational speeds up to 1.68 x 10^6 rpm and no transition occurred (Harry et al, 1968). The apparently diffuse discharge was a result of the persistence of luminosity (chapter 3) in the wake of the rotating arc. Measurements (Harry et al, 1968) indicated that radiation from a 60 A arc in air persisted for more than 10 ms.

The ac plasma torch developed by Harry (1970b) used a magnetic field to rotate an arc between two water-cooled, coaxial copper electrodes. The arc was reignited every half cycle by a 1 MHz, high voltage spark to maintain continuous operation. The efficiency of the torch was reported to be in excess of 60% (Harry, 1968; Roots et al, 1969) and the design is suitable for heating gases, including air (section 4.3.6).

A considerable amount of theoretical work on heat transfer from magnetically rotated arcs has been carried out at the Electricity Council Research Centre, Capenhurst (Lawton, 1967; Chen et al, 1968; Humphreys et al, 1972). An arc rotating between coaxial electrodes is reported to take up an involute shape such that the power density in the annular region between the electrodes is approximately uniform.
(Lawton, 1975), whereas the power density due to a rotating spoke is inversely proportional to the radius. Results claim that, if the rotational speed is such that the arc completes one revolution in the time that the gas flow takes to travel a distance equal to the thickness of the arc, then the gas will be uniformly heated (Chen et al, 1969). At lower rotational speeds a spiral of hot gas will be produced, which is undesirable. This model of the rotating arc assumed that the arc could be considered as a solid heat source, like a hot wire, but gas flows tend to bypass arcs (Johnston et al, 1976) which can result in non-uniform heating. In a typical heater of this type, with a 10 mm separation between the electrodes, approximately 30% of the arc column is likely to be dominated by the arc roots and transition regions (chapter 2) which are cooler than the arc column so that non-uniform heating occurs. The turbulence and rotation of the hot gas produced by the rotating arc will, however, tend to increase the uniformity of the heated gas (Lawton, 1975) and the high degree of mixing and heat transfer may be useful for chemical processing. This type of arc heater has been used at power levels of approximately 20 kW (Table 4.11) to heat titanium tetrachloride to react with sodium vapour at 2000°C to produce molten titanium (Johnston et al, 1971; Bunting, 1978).

\[
\text{TiCl}_4 + 4\text{Na} \rightarrow \text{Ti} + 4\text{NaCl} \quad (4.1)
\]

Extraction of metals via the chloride compounds using arc heaters operating at temperatures of approximately 2000°C offers a new product route which is advantageous because the boiling points of the chlorides are generally lower than the metals and the chloride salt products are formed as gases and can be removed easily and do not contaminate the metal. Several reactions have been investigated (Table 4.2) but no commercial exploitation has occurred.
4.4.5 Westinghouse magnetically rotated arc heaters.

The basic single-phase ac arc heater developed by Westinghouse is shown schematically in Fig. 4.13. The design is based on a 10 MW short duration dc arc heater supplied to NASA by Westinghouse for use in a hypersonic wind tunnel (Boatright et al., 1964) and comprises a magnetically rotated arc between water-cooled annular electrodes.

Several models have been introduced since the 1960s and can now be operated continuously at powers up to 3.5 MW, using ac or dc, with electrode lifetimes of 170 hours at currents in excess of 2000 A (Fey et al., 1979). A high voltage (4 kV) is used to break down the 1 mm gap between the electrodes although the operating voltage is only about 700 V (Table 4.11). The arc is rotated at speeds up to $60 \times 10^3$ rpm by the interaction between the arc current and a dc magnetic field produced by an external field coil (Fey, 1976). The arc column is elongated by its self magnetic field and by gas injected between the electrodes. This type of heater has been used for the production of acetylene from methane,
propane and butane (Fey, 1977). Yields of up to 18.2% were obtained from butane feedstock and up to 5.5% ethylene was also produced. No commercial application exists due to the reduction in demand for acetylene (section 4.2.1).

Two configurations of heater suitable for operation from a three-phase supply have been developed. The first, rated at 1 MW, incorporated arcs rotating at up to $60 \times 10^3$ rpm between three water-cooled copper electrodes (Fey et al, 1977) (Fig. 4.14) and has been used to investigate the spheroidisation of magnetite.

![Fig. 4.14 Schematic of 1 MW arc heater used for magnetite spheroidisation (after Fey et al, 1977).]

Over 90% of the material was heated but agglomeration and sintering of the products reduced the yield of acceptable product to only 20% (Fey et al, 1977).
The second, rated at up to 10 MW (Fey, 1976) consisted of three single-phase heaters, of the type shown in Fig. 4.13, arranged so that the hot gas streams coalesce in a common plenum chamber (Fig. 4.15). This configuration is suitable for processing particulate material due to the high power input and common plenum chamber and a system for the extraction of ferrochrome from pre-reduced ore has been designed (Fey, 1976) but no commercial application is known.

![ARC HEATERS](image)

Fig. 4.15 10 MW three-phase arc heater suitable for processing particulate material. (Fey, 1976)

Six single-phase heaters (Fig. 4.13) with a total rating of 8 MW have recently been installed in SKF Steels Plasmared process in Sweden. Coal, natural gas and liquid propane gas are heated to approximately 4000°C by the arc heaters and used for the direct reduction of iron oxide to iron in a shaft furnace (Anon, 1980; Fey et al, 1981). The arc heaters replaced
a resistance heated catalytic coke reformer which used expensive metallurgical coke as fuel. The higher gas temperatures produced by the arc heaters has reportedly increased annual production from $2.5 \times 10^3$ T to $70 \times 10^3$ T (Fey et al, 1981). Electrode lifetimes of 200 hours have also been reported and scale up to 2.3 MW for each heater is in progress (Fey et al, 1981).

SKF Steel have also reportedly carried out pilot plant level tests using arc heaters placed in the tuyères of a blast furnace (Anon, 1980; Fey et al, 1981). This Plasmamelt process consists of a shaft furnace filled with coke, and a mixture of pre-reduced ore and coal particles is passed through an arc heater into the furnace. The hot coke acts as a reduction site and filter, allowing molten iron to collect in the bottom of the shaft. Tests have been carried out using an arc heater rated at 1 MW and the energy consumption is reported to be 1120 kWh/T of iron (Fey et al, 1981) which is double that of a conventional blast furnace, but this is probably due to the small scale of the plant. The coke consumption was reported to be only 50 kg per tonne of iron (Fey et al, 1981) which is very low since the coke is only used to carburize the molten iron because the heat input is supplied by the arc. A plant rated at 9 MW, using three 3 MW arc heaters, believed to be as a three-phase unit, with a capacity of $50 \times 10^3$ T per year is being developed (Fey et al, 1981).

In a similar application, a 3.5 MW arc heater is being installed in a blast furnace producing 500 T of iron per day at Cockerill Steel in Belgium to investigate plasma superheating of the gas injected at the tuyères (Fey et al, 1981).

Westinghouse arc heaters operate at efficiencies typically in the range 60% to 85% (Fey et al, 1981). The main disadvantage is the requirement for a separate power supply to energise the field coils when an ac arc is used although a low voltage dc supply can be used and generally powers up to only 10 kW are required (Fey et al, 1970).
4.5 Summary.

The operating conditions, advantages and disadvantages of existing high power arc heaters have been discussed.

The high voltage, long column arc heaters, designed with the electrodes as part of the reactor vessel, used for chemical synthesis (section 4.2.1) have, with the exception of the HtMels system, been closed down. This is either because cheaper alternative processes and materials have become available or because the processes were not economic to operate. The continued existence of the HtMels system has been assured by the massive capital cost of the project and the lack of naturally occurring oil in East Germany.

The Ionarc and Bethlehem Steel falling film reactors, together with a number of reactors incorporating constricted arc plasma torches (section 4.3), have been used to carry out material processing such as ore refining and scrap melting on a commercial scale and a number of arc heating systems of this type are available but industry has shown little interest. Several innovations have been used, including the ARCOS three-phase superimposed arc (section 4.3.4), the Tetronics precessing plasma torch (section 4.3.5), and the use of copper electrodes in the TASC plasma torch (section 4.3.6). The Tetronics, TASC and Freital systems all operate plasma torches at currents of several thousand amps. The TASC torch uses copper electrodes, with a gas stream to move the arc root over the surface, but the Tetronics and Freital torches both incorporate tungsten cathodes carrying currents of the order of 8000 A, apparently obtained simply by scaling up or by use of additional alloying elements in the tungsten to lower the thermionic work function (section 4.3.7). The generally accepted current limit for thoriated tungsten electrodes is in the range 1000 A - 2000 A and these developments represent a significant improvement. A simpler alternative would be to use multiple electrodes in a common plenum in a single torch operating from a single supply. In this way torches could be operated at 10,000 A without the need for special electrode materials or cooling arrangements.

High power arc heaters rated at up to 60 MW have been developed for re-entry simulation (section 4.4.1) but are not suitable for material
processing in their existing form due to the very high gas velocities and short operating times. These heaters are of interest because of the high currents used and because multiple electrodes have been used to reduce erosion of the electrodes and contamination of the discharge and to allow currents up to approximately 6000 A to be used to produce the enthalpies required to simulate re-entry conditions for the space shuttle and for probes sent to the outer planets. This technique offers an alternative approach to that adopted by Tetronics etc. and higher currents still can be obtained simply by using more electrodes. The multiple electrodes used to date have been stabilised by individual resistors, which dissipate and waste power (Table 4.10) and a method of using inductive stabilisation would be extremely useful.

Magnetically rotated arc heaters (sections 4.4.3 - 4.4.5) have been developed as an offshoot of re-entry type heaters and operate at high efficiencies with long electrode lifetimes and can be used to heat gases and particulate materials, such as iron ore.

Future developments, including the bulk melting of iron and steel, will require arc heaters operating continuously at powers of 50 MW and, if the heaters are to remain relatively small, i.e. low voltage, currents of the order of 30,000 A will be required. It is doubtful whether this can be achieved simply by scaling up and the use of multiple electrodes offers a possible solution.
Addendum

Since the review of plasma devices was written, a number of important developments have been reported and these are described here.

A number of commercial developments of considerable significance to the design of high current multiple arc devices have taken place. These include the operation of plasma torches manufactured by Tetronics Ltd. at currents up to 10 kA (Heanley, 1983) for which short term operation at 14 kA has been claimed, and operation of plasma torches at 4.5 kA by Daido Steel in Japan which have been used to supply additional heat to, and a protective atmosphere of argon over, a molten layer of slag during refining operations in combined plasma/induction melting furnaces (Bhat, 1981). Freital are also reported to be developing a 100T capacity plasma furnace, for melting prereduced iron and ferro alloys, which incorporates six dc plasma torches, operating from separate power supplies, each carrying currents up to 10 kA (Bhat, 1981). These commercially available plasma torches show the feasibility of operation with tungsten cathodes carrying currents of the order of 10 kA with acceptable cathode lifetimes which is directly relevant to the design and operation of a compact non-consumable multiple electrode assembly (Chapter 8) at total currents up to 30 kA.

Rotech Inc. have developed furnaces for melting titanium incorporating a dc plasma torch based on the Linde design but operating with the polarity of the supply reversed using a central copper anode within the torch (Rotech, 1983). This may be relevant to the design of a high current (400A per arc for example) radial discharge reactor (Chapter 5) requiring water-cooled copper anodes instead of graphite. A non-consumable arc electrode for melting titanium in a water-cooled skull furnace has also been reported (Rotech, 1983); the electrode is rotated so that the arc root is in constant motion over its surface to prevent erosion of the surface of the electrode. No details of the power ratings of either system have been published, however.

Other recent developments include SKF Steels design and use of arc heaters rated at up to 10 MW based on the Westinghouse magnetically rotated arc heaters in the Plasmared and Plasmamelt processes (SKF Steel, 1983), and the use of a computer program to design and simulate the operation of re-entry type constricted arc heaters by the Aerotherm Division of the
Acurex Corp. Arc heaters rated at up to 24 MW, operating at up to thirty times atmospheric pressure, have been supplied to NASA, and a similar heater rated at 80 kW has reportedly been supplied to Ontario Hydro for experimental plasma processes (Liu et al, 1983; Acurex, 1983). Detailed reviews of plasma torches and their applications have been published by Labrot et al (1981), Bhat (1981) and Barcza et al (1981), the latter proposing the utilisation of plasma heating as an alternative to submerged arc smelting furnaces and therefore relevant to the development of a high current non-consumable multiple electrode assembly (Chapter 8).
CHAPTER 5

PRELIMINARY INVESTIGATIONS OF MULTIPLE ARC DISCHARGES
A horizontal multiple arc discharge system was developed at the University (Harry et al, 1979; Hobson, 1980) as part of an investigation into the coupling of rf energy into an arc discharge to produce a uniform volume of ionised gas. The geometry of the arc system was not suitable for induction coupling but some investigations of the discharge have been reported (Hobson, 1980).

A series of tests has been carried out to extend these results by determining the electrical, geometrical and physical characteristics of the multiple arc discharge prior to the experimental and theoretical examination of the conditions required for the stable operation of multiple arcs carried out in chapter 6.

5.1 The multiple arc system.

The horizontal discharge system using six pairs of 6 mm diameter carbon electrodes was developed at the University (Harry et al, 1979). The electrodes were mounted on a circular base which allowed simultaneous radial movement of the electrodes (Fig. 5.1). Each pair of electrodes was connected to a separate dc supply so that a stable coalesced multiple arc discharge was produced (chapter 2). Three different electrode configurations were reported (Harry et al, 1979) (Fig. 5.2(a)-(c)). The discharges were reported to be stable, showing no tendency to contract into a single arc. The uniformity of the discharge was determined by single-exposure photography, in conjunction with neutral density filters, and by high-speed ciné-photography, together with bandpass filters, which were used because of the wavelength-dependence of the persistence of luminosity which may have caused errors in the single exposures (chapter 3). The discharge produced by configuration Fig. 5.2(c) was reported to be most uniform when observed with a single exposure but it was considered that the diffuse appearance of the discharge may have been a result of the rapid movement of filamentary arcs.
Fig. 5.1  The horizontal multiple arc system.

Fig. 5.2  Multiple arc electrode configurations (Harry et al, 1979).
and the persistence of luminosity (Harry et al., 1968; Harry, 1971), and also radiation from the incandescent electrodes. The persistence of luminosity in the multiple arc discharge was measured using a high-speed camera and the reported results are shown in Table 5.1. The results indicated that persistence of luminosity is lowest at the ultraviolet end of the visible spectrum and could be reduced to very short times by observing the discharge at wavelengths between 300 nm and 480 nm although the persistence was reduced by a factor of 10 by simply attenuating the radiation input to the camera using a neutral density filter with 5% transmission so that only the brightest parts of the discharge were seen.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Wavelength</th>
<th>Persistence</th>
</tr>
</thead>
<tbody>
<tr>
<td>high speed film only</td>
<td>-</td>
<td>15-20 ms</td>
</tr>
<tr>
<td>high speed film + ND 1.3</td>
<td>-</td>
<td>2 ms</td>
</tr>
<tr>
<td>high speed film + Ilford filter no.828</td>
<td>300-400 nm</td>
<td>0.25 ms</td>
</tr>
<tr>
<td>high speed film + Ilford filter no.806</td>
<td>420-480 nm</td>
<td>0.25 ms</td>
</tr>
<tr>
<td>high speed film + Ilford filter no.807</td>
<td>510-560 nm</td>
<td>1 ms</td>
</tr>
<tr>
<td>high speed film + Ilford filter no.808</td>
<td>560-640 nm</td>
<td>1 ms</td>
</tr>
</tbody>
</table>

Table 5.1 Measured values of persistence of luminosity in the multiple arc discharge (after Hobson, 1980).

Configurations (a) and (c) in Fig. 5.2 were reported to produce large volumes of apparently uniformly ionised gas. Bright areas were observed in the regions close to $A^+F^-$ and $A^-F^+$ in Fig. 5.2(a). The non-uniformities were explained in terms of the difference in path length and the effects of alternative paths provided by the ionised gas from arcs between other electrodes so that preferential conducting paths were formed between $A^+F^-$ and $A^-F^+$ in configuration Fig. 5.2(a).

The formation of short peripheral arcs between alternate pairs of electrodes in configuration (b) of Fig. 5.2 was claimed to be due to a similar effect so that a well defined conducting path was produced between the electrodes around the periphery of the discharge zone (Hobson, 1980). The flow of current between and through adjacent supplies was not investigated or reported.
The experiments carried out at the University (Harry et al, 1979; Hobson, 1980) indicated that a horizontal multiple arc discharge may produce a large volume of uniformly ionised gas which could have applications in material processing or gas heating and the principles may be applied in other areas such as welding and lighting (chapter 2). Further investigations are required to expand on these initial results and extend the understanding of multiple arc discharges.

5.2 Multiple electrode configurations.

A series of tests was carried out to determine the possible geometrical arrangements of six pairs of electrodes, and five new configurations were found. All the possible arrangements are shown in Fig. 5.3(a) to (h), in which (a), (b) and (c) are identical to those shown in Fig. 5.2(a) to (c). Configurations (d) to (h) were discovered during these tests. Each arrangement of the electrodes is self-consistent in that the spacing of the electrodes of each supply relative to each other is the same for all six supplies, for example, diametrically opposed in (a) or perpendicular in (c). Different configurations can be produced by the same spacing of the electrodes, for example in both (b) and (c) the anode and cathode of each supply are at right angles to each other but the resultant configurations are totally different. The electrode configurations shown in Fig. 5.3 can be divided into three types:

(i) those with all the electrodes of the same polarity grouped together. ((a), (c) and (e)).

(ii) those with alternate electrodes of opposite polarity ((b), (d) and (h)).

(iii) hybrids of the other two types ((f) and (g)).

The nature of the discharges produced by the new configurations can be predicted to some extent by considering the results of previous work (Harry et al, 1979). Configuration (e) is similar to (a) and (c) and should produce a fairly uniform, large volume, discharge, arrangements (d) and (h) are similar to (b) and should produce six short arcs around the periphery of the central region, and the hybrid configurations should produce some ionised gas in the central region but
Fig. 5.3 Multiple arc discharge electrode configurations.
this may be non-uniform due to the electromagnetic forces of repulsion between anti-parallel currents within the discharge (Fig. 5.4).

It is interesting to note that a clockwise circulation of current within the discharge would occur if the anti-parallel flows of current in arrangement (f) (Fig. 5.4) coalesce close to $C^+F^-$ and $A^-D^+$. This may occur at short separations of the electrodes when the effects of convection are small and jets from the arc roots (chapter 2) force the arcs to coalesce. Electromagnetic repulsion would then tend to force the discharge to take up an annular path around the central region. This indicates that a dc current circulating in ionised gas will tend to increase its diameter unless limited by electrodes or a containing vessel. The effect will depend on the magnitude of the current and the diameter of the discharge.

Fig. 5.4  Repulsion between anti-parallel current flows in configurations (f) and (g).
Experiments were carried out to verify the predicted behaviour of the discharges produced by the additional configurations. In these tests the discharges were initiated by shorting the electrodes together on the minimum pitch-circle diameter and separating them simultaneously to produce the multiple arc discharges. The discharges were operated at currents between 10A and 20A per arc with the electrodes on pitch circle diameters between 20 mm and 40 mm. Bright, flame-like discharges were formed by all the configurations and arc roots were visible on all the electrodes. Convection currents distorted the discharges into irregular cones which indicated that some errors may be introduced by approximating the discharge zone to a flat disc (Fig. 5.5).
5.2.1 Experimental results.

The discharges were observed through a series of neutral-density filters to reduce the intensity of transmitted light to 0.0003% so that only the brightest, and therefore hottest, regions of the discharge could be seen. This would also reduce the persistence of luminosity to less than 2 ms (Table 5.1). Observations of the three configurations due to Harry et al (1979) (Fig. 5.2) were included for comparison and completeness.

Electrode configurations (a), (c), (e) and (f) produced large volumes of ionised gas in the central region between the electrodes; configurations (b) and (d) produced six short arcs between adjacent electrodes of alternate polarity, and configurations (g) and (h) produced non-uniform discharges with some ionised gas visible in the central region.

Considering the four large volume discharges, (a) was brightest in the regions adjacent to A\text{+}F\text{−} and A\text{−}F\text{+}, (c) produced an apparently uniform discharge, (e) was brightest in the regions adjacent to 3\text{+}A\text{+}E\text{−}F\text{−} and 3\text{−}A\text{−}E\text{+}F\text{+}, and (f) was characterised by a dark band across the central region between F\text{−}E\text{−}D\text{−} and C\text{−}E\text{−}A\text{−}.

The results for configurations (a), (b) and (c) were in agreement with those of the original investigations (Harry et al, 1979). No further investigations of configurations (f), (g) and (h) were carried out because the non-uniform discharges were considered to be unsuitable for processing materials where uniform heating of feedstock is the most important requirement. The discharges produced by arrangements (a), (c) and (e) may have sufficient temporal uniformity for material processing or gas heating whereas those produced by (b) and (d) may be useful in understanding the behaviour of multiple discharges and the interaction of power supplies and could be relevant to applications requiring separate discharges, such as welding.
5.2.2 Discussion of results.

The results of the tests carried in the previous section can be explained by considering the possible current flow paths for the six separate supplies. The direct path of current for each supply, assuming that the arcs remain as separate filaments, for simplicity, are shown in Fig. 5.6.

Fig. 5.6 Direct current flow paths for each supply and possible high voltage-gradient regions.
Possible current flow between electrodes of opposite polarity from different supplies are also shown. Current entering the discharge from any anode will follow the lowest impedance path available which could be through neighbouring supply circuits via separate, short arcs, as in (b) and (d); or via a common coalesced discharge in the central region between the electrodes. In the latter case, the path taken cannot be rigorously defined since the common discharge is comprised of several coalesced arcs. Clearly defined conducting paths existed in configurations (b) and (d) where six separate arcs were formed around the periphery of the central region.

Under open-circuit conditions, the potential difference between electrodes of opposite polarity from different supplies, $A^+$ and $F^-$ for example, will be zero because the circuits are isolated from each other and no complete circuit can exist. When a coalesced discharge was formed, however, a point common to all the supplies existed which allowed currents to flow between supplies (if this was the path of lowest resistance) via the discharge which completed the circuits. The current flowing from $A^+$ to $F^-$ and $F^+$ to $A^-$ in configuration (a) can be considered as two separate, short, higher current arcs because a complete preferential circuit was formed between power supplies $A$ and $F$ (Fig. 5.7). The arcs coalesce with the remainder of the discharge to a limited extent but are brighter due to the higher current flow in the shorter arcs. Stable operation of the arcs is maintained by the use of separate supplies. The current entering a coalesced discharge at an anode must equal that leaving the discharge at the cathode of the same supply, although the current need not be equal in all the supplies, as observed in the $A$ and $F$ supplies in configuration (a).

A low-impedance preferential path could be established between the electrodes $A^+$ and $C^-$ in configuration (c) but the subsequent path between $C^+$ and $A^-$ required to complete the circuit is much longer (Fig. 5.6(c)) and is unlikely to be formed since the overall path length and impedance would be greater than the direct route. This configuration produced the discharge which appeared to be most uniform and which may be considered as a disc of ionised gas to a first approximation. The separate power supplies act as sources and sinks of current. The uniformity of the coalesced discharge may be enhanced by electromagnetic forces of attraction between the parallel currents flowing on opposite sides of the discharge (Fig. 5.6(c)).
Several regions of higher current may exist in configuration (e) because preferential paths could be formed between $A^+$ and $E^-$ or $F^+$ and $B^-$ but the paths $E^+A^-$ and $B^+F^-$ necessary to complete the circuits are relatively long (but shorter than those considered in arrangement (c)) and only minor variations in current are expected. Experimental observations, however, indicated that the discharge was brighter in these areas.

Six separate arcs, approximately 5 mm long, were formed between adjacent electrodes of opposite polarity around the periphery of configurations (b) and (d). These arcs were the result of the formation of complete circuits through the separate power supplies when the electrodes were shorted together to initiate the discharges. A single arc cannot be
Fig. 5.8 Alternative routes for current from the 'A' supply through adjacent supplies in configuration (b).

NB 'forbidden' indicates that a path has already been used.
maintained between electrodes of opposite polarity from separate supplies and a minimum number of arcs are needed to complete the circuits and maintain a discharge. This number depends on the number of supplies used and the electrode configuration. Several alternative paths exist in arrangements (b) and (d) and the possible paths for one supply of configuration (b) are shown in Fig. 5.8. The shortest path for the A supply requires three arcs between $A^+B^-$, $B^+C^-$ and $C^+A^-$, although other, longer paths may exist but are unlikely in practice because discharges follow the lowest impedance path available. The shortest path for each of the six supplies requires three arcs but supplies A, C and E have identical shortest paths and supplies B, D and F also have identical but different shortest paths due to the symmetry of the system (Fig. 5.9). The resultant discharge (Fig. 5.9) has only six short arcs which provide complete circuits through all the power supplies.

Fig. 5.9 Shortest paths for current flow through adjacent supplies and resultant discharge for configuration (b).
A similar explanation can be applied to configuration (d) but only two arcs were required to establish complete circuits between adjacent supplies since the electrodes were arranged so that $A^+$ was adjacent to $D^-$ and $D^+$ adjacent to $A^-$ etc. (Fig. 5.10). The overall result will again be a system with six arcs. Electromagnetic forces will also tend to repel the arcs in configurations (b) and (d) due to the anti-parallel flow of current on opposite sides of the discharge so that very little ionised gas will be formed in the central region. These results are in agreement with the experimental observations.

Fig. 5.10 Shortest paths for current flow between adjacent supplies for configuration (d).
5.3 Measurements and analysis of the multiple arc discharges.

Single-exposure photography and a conducting-paper analogue technique are used to record and model the discharges produced by the different electrode configurations in order to determine the internal structure of the ionised gas as far as possible prior to quantitative spectral measurements (chapter 7).

5.3.1 Single exposure photography.

The advantages and disadvantages of photographic techniques have already been discussed (chapter 3). Single-exposure photography can be carried out very easily but the results must be interpreted with care due to the effects of persistence of luminosity (chapter 3). Despite this disadvantage the technique is useful to record macroscopic features of large volume discharges such as the presence of dark bands and to determine whether or not a coalesced discharge is formed.

The discharges produced by the five electrode configurations (Fig. 5.3(a)-(e)) were photographed from below using a 35 mm SLR camera and Ilford FP4 black and white print film. The arc currents were typically 10A per arc, with arc voltages between 50V and 70V at electrode separations of 20 mm to 30 mm. Neutral-density filters were placed between the discharges and the camera lens to reduce the intensity of light from the arcs so that only the brightest parts of the discharges were recorded (Airey, 1972). The results (Fig.5.11) showed that configurations (a), (c) and (e) produced large volumes of ionised gas in the central region and configurations (b) and (d) produced six short arcs between alternate pairs of electrodes around the periphery of the central zone.

The neutral-density filters will attenuate light uniformly over the visible spectrum and reduce the persistence of luminosity to less than 2 ms (Hobson, 1980) (Table 5.1) so that only the hottest parts of the discharges are visible. The filters cannot distinguish between radiation from the discharges and radiation from incandescent electrodes (particularly the anodes of arcs which are hotter than the cathodes (chapter 2)), or emission from the afterglow of excited species, such as active nitrogen,
Fig. 5.11 Photographs of multiple arc discharges at f8, with 2 ms exposure using 1.61 + 1.3 neutral-density filters to reduce transmission to 0.12%, (results correspond to the electrode configurations (a) to (e) in Fig. 5.3).
which have equilibrium times greater than 2 ms. These sources add to the total intensity of a discharge. Radiation from the anodes will tend to detract from the apparent uniformity of the discharges produced by configurations (a), (c) and (e) where all the anodes are grouped together (Fig. 5.3) but an afterglow may be emitted over a larger area of the discharge and will tend to enhance the apparent uniformity. The emission from active nitrogen at atmospheric pressure has been studied (Stanley, 1954; Noxon, 1962) but the spectral distribution is reported to be dependent on the concentration of oxygen and moisture. The effects of these two processes on the multiple arc discharges are difficult to quantify but the photographs have shown the general nature of the discharges produced by different arrangements of the electrodes.

5.3.2 Use of a conducting-paper analogue technique to model multiple arc discharges.

A simple resistance analogue of the multiple arc discharge region was used to investigate the distribution of voltage in the discharge zone with different arrangements of the electrodes. The discharge zone between the electrodes was assumed to be a circular disc of uniform resistivity and thickness. Five stabilised dc power supplies and a sixth incorporated in a field plotting instrument were used to represent the separate supplies for each pair of electrodes. The supplies were connected to a circular sheet of Teledeltos conducting paper 230 mm in diameter representing the discharge region. All electrical connections to the paper were embedded in high conductivity silver paint (DAG 915) to eliminate contact resistances which would affect the distribution of equipotentials in the paper. The output voltages of the six supplies were made equal and the equipotential distributions of configurations (a) to (e) (Fig. 5.3) were plotted between 0% at the cathodes and 100% at the anodes. Field plots were produced using an automatic paper marker in the field plotter. The results were photo-reduced and a composite result is shown in Fig. 5.12.

The distribution of the equipotentials in configurations (a), (c) and (e) indicated that the general direction of current flow was across the central region between the anodes and cathodes so that large volume
Fig. 5.12 Field plots produced by electrode configurations (a) to (e) (Fig. 5.3) using conducting paper to represent the discharge region.
coalesced discharges would be produced. The equipotentials were almost parallel in the central regions, indicating a high degree of uniformity, but in configuration (a) the concentration of equipotentials close to $A^+F^-$ and $F^-A^-$ (Fig. 5.12(a)) showed that higher currents were likely to flow between the two supplies and discharges would appear brighter in these regions (section 5.2.1). The field plot of configuration (c) was symmetrical about the 50% equipotential and the equipotentials were parallel over a greater area than in (a) and (e) which indicated that this arrangement produced the most uniform flow of current and was likely to produce a uniform volume of ionised gas.

Equipotentials were concentrated between the electrodes round the periphery of the conducting zone in configurations (b) and (d) (Fig. 5.12), indicating that high currents would flow between adjacent electrodes of opposite polarity. This would produce six separate arcs around the edge of the discharge region. The field plots (Fig. 5.12(b) and (d)) also indicated that some current flowed across the central region, but the potential gradient in this area was only about 2% of the total voltage applied and in practice the ionised gas would contract into separate arcs in the regions of high voltage gradient between alternate pairs of electrodes. The electromagnetic forces of repulsion between anti-parallel currents would also tend to produce separate arcs.

The conducting-paper analogue represents an idealised and simplified model of the multiple arc discharges but the results are in good agreement with experimental observations (sections 5.2.1 and 5.3.1). The actual discharges were not flat discs of ionised gas due to convection currents and electromagnetic forces which distort the arcs and reduce the uniformity in the plane of the electrodes. The analogue method may not accurately represent the discharges produced by configurations (b) and (d) (Fig. 5.3) since the model assumed that a conducting medium existed throughout the discharge zone whereas in practice there was no ionised gas in the central region and arcs were only established around the periphery. The analogue may, however, represent the conditions in these configurations at short separations of the electrodes (2 mm) immediately after the arcs are initiated when the arc columns coalesce, and the effects of convection are negligible. The discharge may then extend throughout the region between the electrodes and potential distributions identical to Fig. 5.12(b) and (d) will exist until separate arcs are formed when the electrodes are drawn apart.
5.4 Summary of results and conclusions.

The results of the initial series of tests on multiple arc discharges can be summarised as follows:

(i) Five additional electrode configurations have been found and investigated together with the original three due to Harry et al (1979). Stable discharges were maintained at electrode separations up to 30 mm, at dc currents of the order of 10 A per arc, using separate power supplies for each pair of electrodes.

(ii) The discharges produced by all the configurations have been studied and the five considered to be potentially useful for process heating have been investigated by single-exposure photography, using neutral density filters to reduce the persistence of luminosity.

(iii) Large volumes of apparently fairly uniformly ionised gas were produced by configurations (a), (c) and (e) (Fig. 5.3). The other arrangements either produced peripheral discharges comprised of six separate arcs ((b) and (d)), or non-uniform coalesced discharges ((f), (g) and (h)).

(iv) The large volume discharges (a), (c) and (e) (Fig. 5.3) appeared to be diffuse, with no detectable filamentary arcs, and may be suitable for processing materials or gas heating but further investigations are required to determine the temporal uniformity of the discharges.

(v) The existence of separate arcs in configurations (b) and (d) and the non-uniformity of the coalesced discharges produced by arrangements (f), (g) and (h) show that preferential conducting paths can exist in both types of discharge. The arrangement of the electrodes determines whether a coalesced discharge is formed but convection currents and electromagnetic forces between currents will affect the uniformity. Electromagnetic forces, for example, act in opposite directions in configurations (c) and (f) and only (c) appears to be homogeneous (Fig. 5.4 and Fig. 5.6).
(vi) The formation of separate multiple arcs in arrangements (b) and (d) (Fig. 5.3) has been explained by considering the flow of current through adjacent supplies between electrodes of opposite polarity. A minimum of up to three short arcs were required to provide complete circuits. The behaviour of this type of discharge may be relevant to applications using separate arcs, such as welding.

(vii) Field plots of the discharge regions were made using conducting paper to represent the ionised gas. Results were in agreement with experimental observations and indicated that configurations (a), (c) and (e) (Fig. 5.3) would produce large volumes of ionised gas, (c) being the most uniform, and that (b) and (d) would produce six short arcs around the periphery of the central region.

A higher powered version of the horizontal multiple arc system has recently been designed at the University (1984) and installed in the Metallurgy Department at Cambridge University, by Plasma Systems Ltd., for carrying out chemical and metallurgical reductions in a fluidised bed. The power supply has a rated power output of 50 kW and incorporates a single main transformer, with six separate three-phase secondary windings, saturable reactors designed to limit and control the arc current in the range 10A to 50A dc, and three-phase bridge rectifiers. The electrode movement mechanism is mounted in a sealed reactor cabinet for safety, with the discharge region contained within a refractory tube, into which gas may be introduced. The electrodes are moved together manually at present although automatic control with feedback may be introduced in the future. Other features include water-cooled electrode holders, with the water flow interlocked to the power supply, 10 mm diameter graphite electrodes and magnetic stabilisation of the discharge against the effects of convection. Stable coalesced discharges have been operated at diameters up to 150 mm in argon and showed no tendency to contract into a single high-current filament.
CHAPTER 6

INVESTIGATION OF THE CONDITIONS FOR SIMULTANEOUS OPERATION OF MULTIPLE ELECTRIC ARCS FROM A COMMON SUPPLY
The conditions under which two electric arcs can be operated from a single dc supply are investigated. The conditions for stabilising separate and coalesced arcs are analysed as an unbalanced bridge circuit and solved by computer program. The effects of electromagnetic forces between parallel arcs is also discussed.

6.1 Operation of separate parallel arcs from a common power supply.

The basic supply circuit for a dc arc is shown in Fig. 6.1.

![Diagram](image)

**Fig. 6.1** Basic arc power supplies and their characteristics;
- (a) supply circuits,
- (b) characteristics of the arc and its supply.

The value of current limiting impedance is generally chosen to be approximately equal to the resistance of the arc and the circuit approximates to a constant current supply. Inductance tends to improve stability due to the effect of stored energy although the overall time
constant of the circuit governs the stability of the system under transient conditions (chapter 2), and must be greater than 1 ms.

Initiation of a second arc in parallel with an existing arc, with a shared stabilising impedance, causes instability since the increased current due to the second arc reduces the voltage across the first arc so that insufficient voltage may be available to maintain two arcs at the higher total current and one may be extinguished, restoring the system to stable operation. Shorting the electrodes of the second arc together represents the worst case and is most likely to cause the first arc to be extinguished because the short circuit presents a lower impedance path to the supply. The negative dynamic resistance of an arc also prevents the operation of parallel arcs under these conditions. If two arcs do co-exist, then a small increase in current in arc 1 ($\delta I_1$) would cause a reduction in the common arc voltage and a decrease in current in arc 2 which would cause further increases in $I_1$ due to the negative dynamic resistance of the arc, until arc 2 was extinguished and a single arc carried all the current.

Two separate arcs can be maintained by use of separately rectified dc supplies (Fig. 6.2), (chapter 2).

Fig. 6.2 Separate parallel arcs operated from individually rectified supplies.
This circuit can be simplified to an equivalent circuit consisting of two dc arcs with individual stabilising resistances $R$, and a common resistance $R_0$ corresponding to the common ac supply impedance (Fig. 6.3).

When only arc 1 is operated the open-circuit voltage of arc 2 is less than $V_s$ due to the current $I_1$ flowing through the common resistance $R_0$ such that

$$V_{o/c}(arc \ 2) = V_s - I_1R_0$$  \hspace{1cm} (6.1)

The ignition of the second arc (Fig. 6.3) decreases the common voltage between A and B even further due to the increased current flow through $R_0$. The worst case occurs when arc 2 is a short circuit. With a single arc, the arc voltage is given by

$$V_{al} = V_s - I_1(R_0 + R)$$  \hspace{1cm} (6.2)

which corresponds to a load-line with a slope equal to $-(R_0 + R)$ (Fig. 6.4),

---

**Fig. 6.3** Equivalent circuit of two arcs operating from separate supplies.
but with two arcs, since the total arc current \( (I_1' + I_2) \) flows through \( R_0 \), then

\[
V_{al} = V_s - I_1'(R_0 + R) = I_2(R_0)
\]

which represents a parallel shift of the load-line where the open-circuit voltage is reduced as given by an equation similar to (6.1) in terms of \( V_{oc}(arc \ 1)' \), and the slope remains constant (Fig. 6.4). The currents \( I_1 \) and \( I_1' \) will not be equal because the voltage between A and B is reduced when two arcs are operated. The magnitude of \( R_0 \) determines how much the stable operating point is shifted (equation 6.1) and the limiting value occurs when the load-line becomes tangential to the arc characteristic.

![Diagram of load-line and arc characteristic](image)

**Fig. 6.4** Effect of parallel arcs on the stable operating point when the power supply includes a common resistance.

If the common resistance \( R_0 \) is large the stable operating point of the arcs may be shifted to a current below that required to maintain the arcs or there may be insufficient voltage available from the supply to maintain
both arcs and one will be extinguished. At low arc currents, small values of $R_o$ (→ 0) are required so that the operation of multiple arcs does not produce large variations in the arc voltages which can result in unstable operation. When $R_o$ is zero, the ignition of the second arc (Fig. 6.3) will not reduce the voltage applied to the first arc and, provided the stabilising resistances of each arc are equal and the arcs are of the same length (i.e. equal resistance), the total current drawn from the supply will be twice the initial value since the effective resistance will be halved and two arcs can be maintained. If $R$ is large enough to stabilise each arc, then any number of separate parallel arcs may be operated provided the current capability of the supply is not exceeded.

6.1.1 Coalesced arc discharges.

Coalesced arcs can be considered as a special case of parallel arcs. Two arcs with separate stabilising resistances but no common resistance (i.e. $R_o$ → 0(Fig. 6.3)) which are brought together to coalesce can be represented by an equivalent circuit (Fig. 6.5) in which $R$ is the stabilising resistance, $r_a$ and $r_c$ represent the regions of the arc column from the anode and cathode respectively and $r_{dd'}$ represents the conducting path formed where the arcs coalesce.

If the arc column represented by $r_{c2}$ increases in resistance, due to an increase in length caused by convection currents or interaction with its self-magnetic field, then the current in this part of the arc will decrease by $\delta I_2$, causing the voltage at $d'$ to increase by $\delta V$. In a single arc any increase in column voltage tends to restore the current to its original value but, in this case, the current flow through $r_{dd'}$ and $r_{c1}$ is increased by $\delta I_2$ and, due to the negative dynamic resistance of the arc, the current flow in $r_{dd'}$ and $r_{c1}$ increases until the cathode root of arc 2 is extinguished, producing a three-root discharge (Harry et al, 1979). Similarly an increase in $r_{c1}$ will result in the cathode root of arc 1 being extinguished. Variations in $r_{a1}$ and $r_{a2}$ tend to be restored to stable operating conditions because the stabilising resistors limit the flow of increased currents, unless $V_s$ is increased, and stabilise the anode roots. The total resistance of the circuit will only change by a small amount when the arcs are coalesced if $r_{dd'}$ is small. The stabilising resistors divide
Fig. 6.5 Equivalent circuit of coalescing arcs with individual stabilising resistors.

The total current approximately equally between the two parallel branches of the circuit and limit the current in each arc since the voltages applied to each arc and its stabilisation are equal.

6.2 Experimental investigation of the operating characteristics of multiple arcs.

A series of tests was carried out using two vertical dc carbon arcs in air at atmospheric pressure with resistors for stabilisation to determine how the magnitude and position of the resistors affected the behaviour of coalesced arcs. Vertical arcs were used because they are more stable than horizontal arcs, in which convection currents elongate the arc column, and could therefore be maintained over greater electrode separations for a given supply voltage. The results are, however, also applicable to
horizontal arcs. The carbon electrodes were mounted at an angle on a moveable support (Fig. 6.6) to allow easy access to the arcs, and avoid restriction due to the electrical connections to the electrodes.

The experiments corresponded to the use of separate supplies for each arc and used configurations similar to that shown in Fig. 6.3. The arcs could be moved together to coalesce the columns or operated as separate parallel arcs. Three circuit configurations were investigated using different stabilisation arrangements:

(i) Resistors on the cathode side of each arc.
(ii) Resistors on the anode side of each arc.
(iii) Resistors on both sides of each arc.

Three conditions of operation were also examined: a single arc, two separate parallel arcs, and coalesced parallel arcs. Tests were carried out with both cathodes at the top, with both polarities reversed (to
determine the effect of convection currents), and with a single polarity reversed (to determine the effect of having adjacent electrodes of opposite polarity).

6.2.1 Parallel arcs with separate stabilising resistors.

Tests showed that single and separate parallel arcs could be maintained from a single supply using individual arc stabilising resistors in the range from 56 Ω to less than 1 Ω connected in the cathode leads of the two arcs (Fig. 6.7). Currents of 5A - 20A were used and stable arcs were maintained at electrode separations up to approximately 50 mm. Operation with the cathodes at the bottom of the discharge produced the most stable arcs.

Supply voltages in excess of 400 V dc were required to maintain arcs with high values of stabilising resistance with arc voltages of 50 V - 70 V at electrode separations up to approximately 40 mm but shorter (15 mm) arcs could be maintained from supply voltages of 80 V - 120 V using stabilising resistances of less than 2.25 Ω and, even down to less than 1 Ω, per arc.

![Fig. 6.7 Parallel arcs with individual stabilisation on the cathode side.](image-url)
The ratio of open circuit voltage to arc voltage varied between greater than 4:1 ($R = 56 \, \Omega$) and less than 1.5:1 ($R$ less than 2.25 $\Omega$), which is lower than the generally accepted value of 2:1 required for stability.

When the electrodes were moved together horizontally to coalesce the arc columns one of the anode roots was extinguished and a three-root discharge comprised of two cathodes and a single anode was established (Fig. 6.8(a)). The transition to this discharge took place instantaneously at a horizontal separation of approximately 10 mm for 15 mm long arcs when electromagnetic forces attracted the arcs together.

![Three-root coalesced discharges;](image)

(a) stabilisation on the cathode side only,  
(b) stabilisation on the anode side only.

When very short arcs (less than 5 mm) were coalesced, an unstable system was formed and fluctuating currents flowed in both anode circuits. The total current drawn from the supply remained constant, indicating that the anode root oscillated between the electrodes, producing a transient four-root discharge.
Separate parallel arcs were only reformed when the two pairs of electrodes were separated if the non-conducting anode was heated to incandescence close to the discharge.

Similar results were obtained when the stabilising resistors were connected to the anode sides of the arcs. Coalesced discharges with three arc roots were again produced but these consisted of two anode roots and a single cathode root (Fig. 6.8(b)). Transient four-root discharges were again produced between arcs less than 5 mm long.

The formation of transient four-root discharges when two short arcs, stabilised on one side only, were coalesced (section 6.2.1) may have been due to oscillation of the arc root between the two electrodes on the opposite side to the stabilising resistors, since the total current flowing remained steady. This phenomenon could be due to some thermionic emission occurring at each electrode in the case of cathodes heated to incandescence by the close proximity of the arc column or simply a random phenomenon caused by the availability of alternative conducting paths. Similar results have been reported for arcs operating at pressures of the order of 10 MPa (Painter et al, 1979) in arc heaters used for re-entry simulation (Chapter 4).

The tests on parallel arcs were carried out at currents up to 30 A per arc with values of stabilising resistance down to 1 Ω but higher currents caused excessive direct resistance heating within the electrodes resulting in high rates of erosion and short lifetimes of the electrodes.

6.2.2 Parallel arcs with distributed stabilising resistors.

Tests on arcs with single individual stabilising resistors (section 6.2.1) indicated that the operation of single or separate parallel arcs from a common supply was not affected by the position of the resistors. Coalesced arcs, however, were affected and discharges with three arc roots were formed when arcs stabilised on one side only were coalesced. These results indicated that stable coalesced discharges might be produced by using stabilising resistors on both sides of each arc so that the electrodes on each side were isolated from each other and a series of tests was carried out to investigate this circuit configuration (Fig. 6.9).
Stable operation of single, parallel and coalesced discharges with four arc roots was maintained using total stabilising resistances between 56 Ω and approximately 2 Ω per arc. The coalesced discharges were more stable and quieter than separate arcs and could be maintained at greater separations of the electrodes because they were less distorted by convection currents, possibly due to the electromagnetic forces between the arc columns. The coalesced arcs were most stable with the cathodes at the bottom since convection currents aid the flow of electrons away from the cathodes in this configuration.

Fig. 6.9  Parallel arcs with distributed stabilising resistors.
The coalesced discharges produced larger volumes of ionised gas than single arcs or coalesced discharges with only three arc roots (Fig. 6.10).

Fig. 6.10 Large volume of ionised gas produced by a coalesced discharge with four arc roots.

The stability of the parallel arc power supply was increased when a common series inductance of 40 mH was connected in the dc side of the circuit although stable discharges could be maintained without it. The time constant of the circuit \( \frac{L}{R} \) varied between 1.2 ms (at \( R = 56 \, \Omega \) per arc) and greater than 13 ms (at \( R = 2.25 \, \Omega \) per arc) and was greater than the 1 ms required for stability during transients at all times (Chapter 2).

The polarity of one pair of electrodes was reversed, and horizontal arcs were formed when the lateral separation between the electrodes became less than the vertical separation allowing the formation of preferential paths (Fig. 6.11).
Conducting paths from electrodes 1 to 3 and 2 to 4 were produced by coalescence of the arc columns but this only occurred when the arcs were close together because the electromagnetic forces tended to repel the arcs and only convection currents could move the arcs together. The discharge appeared to be homogeneous when the horizontal and vertical separations between the electrodes were equal but distinct horizontal arcs were formed if the upper pair of electrodes was raised. Similar results were obtained with two arcs operating from separate supplies (Fig. 6.12) but this test showed a major difference between the use of common and separate supplies for multiple arcs because two arcs must exist in order to complete the circuits between separate supplies and maintain the discharge, whereas one or two arcs could be operated from a common supply. The discharges established between separate supplies (Fig. 6.12) were series arcs rather than parallel arcs.
Fig. 6.12  Operation of coalesced arcs from separate supplies with adjacent electrodes of opposite polarity showing the two paths required to complete the series circuits between the supplies.
6.2.3 Operation of a multiple discharge system from a common supply.

The multiple arc system using six pairs of electrodes arranged in a circle (chapter 5) was operated from a single power supply by applying the techniques for stabilising multiple arcs developed earlier (section 6.2.2). Two supply configurations were investigated; distributed inductive stabilisation of six dc supplies connected in parallel to a single transformer (Fig. 6.13(a)), and distributed stabilising resistors on the dc side of a single supply (Fig. 6.13(b)). Both arrangements enabled stable multiple discharges, identical to those produced by totally separate supplies, to be maintained.

The use of common supplies (Fig. 6.13) reduced the number of different arrangements of the electrodes to four (Fig. 6.14) because the six anodes and cathodes were no longer unique and current could flow from any anode to any cathode via a coalesced discharge due to the common transformer winding (Fig. 6.13(a)) or the single rectifier (Fig. 6.13(b)). Single arcs could also exist between any pair of electrodes of opposite polarity, despite the use of separate rectifiers (Fig. 6.15) which is in contrast to the system with isolated supplies (chapter 5) where up to three paths through the supplies were required to complete the circuits when current flowed between adjacent anodes and cathodes. This difference affected the uniformity of the large volumes of ionised gas produced by configuration (a) Fig. 6.14 (similar to (a), (c) and (e) Fig. 5.3, chapter 5) because high currents flowed between the adjacent anodes and cathodes irrespective of whether the electrodes were A⁺C⁻ or A⁺C⁺ since the spacing of the electrodes from each rectifier did not affect the path length in the same way as if separate supplies were used. This effect could be reduced by increasing the impedance in these supplies so that equal currents flowed in each pair of electrodes.
Fig. 6.13  Stabilisation configurations used to operate six multiple coalesced arcs; (a) distributed inductors, (b) distributed resistors.
Fig. 6.14 Possible electrode arrangements when a common power supply is used (Fig. 5.3, chapter 5).
Fig. 6.15  Formation of an arc between the anode and cathode of separate rectifiers connected to a common transformer; (a) positive half-cycle, (b) negative half-cycle.
6.3 Analysis of the interaction between parallel arcs.

The experimental results described in section 6.2 indicated that the behaviour of coalesced arcs operating from a common supply was affected by the position of the stabilising impedance in the supply circuits of each arc (Table 6.1). An analysis of the equivalent circuits of coalescing arcs was carried out to determine the conditions for stable arc operation. The magnitude of the electromagnetic forces between parallel arc columns has also been determined since these forces can cause arcs in close proximity to coalesce.

<table>
<thead>
<tr>
<th>Position of stabilising resistors</th>
<th>Number of cathode roots</th>
<th>Number of anode roots</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cathode side</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Anode side</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Both sides</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 6.1 Effect of stabilisation position on the arc roots in two coalescing arcs operated from a single supply.

6.3.1 Equivalent circuit analysis of coalescing arcs.

The equivalent circuit of two coalescing arcs with stabilising resistors on both sides of each arc can be arranged in the form of a Wheatstone bridge which will only be balanced when the conditions in both arcs are identical (Fig. 6.16). In the equivalent circuit $\frac{3}{2}$ represents the stabilising resistors, $r_{a_x}$ and $r_{c_x}$ the parts of the arc close to the anode and cathode respectively, and $r_{1-2}$ the region of coalescence between the two arcs.
Fig. 6.16 Representation of coalescing arcs by a Wheatstone bridge.

For the unbalanced circuit, four equations with four unknowns were obtained from the equivalent circuit to give:

\[ I_1 \frac{R}{2} + I_1 r_{a1} + I_1' r_{c1} + I_1' \frac{R}{2} = V \]  \hspace{1cm} (6.4)

\[ I_2 \frac{R}{2} + I_2 r_{a2} + I_2' r_{c2} + I_2' \frac{R}{2} = V \]  \hspace{1cm} (6.5)

\[ I_2 \frac{R}{2} + I_2 r_{a2} + (I_2 - I_2') r_{1-2} + I_1' r_{c1} + I_1' \frac{R}{2} = V \]  \hspace{1cm} (6.6)

\[ I_1 + (I_2 - I_2') = I_1' \]  \hspace{1cm} (6.7)
which were simplified and rearranged for easier solution into the equations:

\[
\begin{align*}
AI_1 + BI_1' + 0 + 0 &= V \quad (6.8) \\
0 + 0 + CI_2 + DI_2' &= V \quad (6.9) \\
0 + BI_1' + (C + E)I_2 - EI_2' &= V \quad (6.10) \\
I_1 - I_1' + I_2 - I_2' &= 0 \quad (6.11)
\end{align*}
\]

where \( A = (R/2 + r_{a1}) \), \( B = (R/2 + r_{c1}) \), \( C = (R/2 + r_{a2}) \), \( D = (R/2 + r_{c2}) \) and \( E = (r_{1-2}) \). These equations were all of the same form and were solved using the method of determinants and Cramer's rule (Bajpai et al., 1973) to obtain general solutions for \( I_1 \), \( I_1' \), \( I_2 \) and \( I_2' \) in terms of the circuit components. The calculations in the solution are shown in Appendix 2 and involved the expansion of fourth order determinants, although this was relatively simple due to the number of zero terms in the equations.

The general solutions are given by:

\[
\begin{align*}
I_1 &= \frac{V(BC + CE + CD + DE)}{(AC(B+D) + AD(B+E) + BC(D+E) + 3DE)} \quad (6.12) \\
I_1' &= \frac{V(AD + CE + CD + DE)}{(AC(B+D) + AD(B+E) + BC(D+E) + 3DE)} \quad (6.13) \\
I_2 &= \frac{V(AB + AE + BE + BC)}{(AC(B+D) + AD(B+E) + BC(D+E) + 3DE)} \quad (6.14) \\
I_2' &= \frac{V(AB + AE + BE + BC)}{(AC(B+D) + AD(B+E) + BC(D+E) + 3DE)} \quad (6.15)
\end{align*}
\]

where the denominator is the same in each case. These equations were also applicable to coalescing arcs with stabilising resistors on the cathode or anode side only but, in these configurations, the terms \( A \), \( B \), \( C \) and \( D \) were different, for example \( A = r_{a1} \) when the stabilisation was on the cathode side, and \( A = (R + r_{a1}) \) when the stabilisation was on the anode side.
Equations (6.12) to (6.15) were solved by Fortran IV computer programs run on a Prime 400 digital computer. The voltage drop across the arc column represented by \( r_{c2} \) was also calculated as the value of \( r_{c2} \) varied over the range from 0.1 to 10 times its nominal value. This determined the effects of a change in one part of an arc, due to convection currents for example, on its stability when two arcs were brought together to coalesce.

An electric arc can be modelled by a linear resistance but this is not strictly accurate due to the arc's negative dynamic resistance characteristic. Initially, for simplicity, however, the arcs were represented by linear resistors and the computer program calculated the variation of voltage across \( r_{c2} \) for different positions of the stabilising resistors. Data for the programs, including values for \( r_{a1}, r_{a2}, r_{c1} \) and \( r_{c2} \) was calculated from actual measurements on coalesced arcs with total stabilising resistances between 4 \( \Omega \) and 56 \( \Omega \), operating at currents in the range 6A to 14A from supply voltages between 110V and 400V. The resistance \( r_{1-2} \), which represented the region of coalescence, was fixed at 1 \( \Omega \) to simplify the calculations, however this value was commensurate with measured values of the resistance of arcs.

The linear model showed that the voltage drop across \( r_{c2} \), as its resistance increased, was a maximum when all the stabilising resistance was connected on the cathode sides of the arcs, adjacent to \( r_{c2} \) (Table 6.2(a), Fig. 6.17).

The analysis was extended to incorporate a function to calculate the voltage drop across \( r_{c2} \) so that it varied non-linearly with current, thereby approximating more closely to the characteristics of an arc discharge. An exponential equation of the form

\[
V = I e^{1/I} \cdot R
\]  

(6.16)

was used to represent \( r_{c2} \). The remaining parts of the arcs were again represented by linear resistors since any changes in current in the rest of the circuit were assumed to be small compared to the change in the current flowing through \( r_{c2} \). The values of voltage drop across \( r_{c2} \) based on the exponential function (Table 6.2(b)) indicated that, for large values of stabilising resistance (56 \( \Omega \)), the voltage developed was highest when
the stabilisation was distributed on both sides of the arcs, whereas for low values of stabilisation (4 $\Omega$), the voltage was highest when all the resistance was connected on the cathode side of the arcs (Fig. 6.18). This disagreement with the results obtained using the linear model (Table 6.2(a)) was due to the different values of $r_{c2}$ used (Table 6.3) in each circuit configuration. Small differences in $r_{c2}$ were magnified by the functions used to calculate the voltage drops.

<table>
<thead>
<tr>
<th>Stabilisation $R$ ($\Omega$)</th>
<th>Supply $V$ ($V$)</th>
<th>Voltage drop across $r_{c2}$ ($V$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Distributed resistors</td>
<td>Resistors on cathode side</td>
</tr>
<tr>
<td></td>
<td>0.1$\text{nom}$</td>
<td>nom</td>
</tr>
<tr>
<td>56</td>
<td>400</td>
<td>3.9</td>
</tr>
<tr>
<td>4</td>
<td>110</td>
<td>4.3</td>
</tr>
</tbody>
</table>

Table 6.2 Effect of the position of the stabilising resistance on the voltage developed across $r_{c2}$:
(a) linear model, (b) exponential model.

Table 6.3 Experimentally determined values of $r_{c2}$.
Fig. 6.17(a) Voltage–current characteristics for $r_{co2}$ under different stabilisation conditions.

Linear model, $R = 56 \, \Omega$, supply voltage = 400 V.
Fig. 6.17(b) Voltage-current characteristics for $R_{C2}$ under different stabilisation conditions.

Linear model, $R = 4 \, \Omega$, supply voltage = 110V.
Fig. 6.18(a) Voltage–current characteristics for \( r_{o2} \) under different stabilisation conditions.

Exponential model, \( R = 56 \, \Omega \), supply voltage = 400V.
1 $R/2$ on both sides
2 $R$ on anode side only
3 $R$ on cathode side only
4 Ayrton equation

Fig. 6.18(b) Voltage-current characteristics for $\rho_{c2}$ under different stabilisation conditions.
Exponential model, $R = 4 \, \Omega$, supply voltage = 110V.
The important result, however, is that a section of two coalescing arcs was stable either:

1. when all the stabilisation was connected adjacent to it,
2. when the stabilisation was distributed on both sides of each arc.

The static behaviour of the arc $r_{c2}$ was also determined using the Ayrton equation (Ayrton, 1902).

$$V_{arc} = A + Bx + \frac{C + Dx}{I}$$ \hspace{1cm} (6.17)

where $A$, $B$, $C$ and $D$ are constants, $x$ is the arc length (mm) (5 mm - assuming that the arcs coalesced at the centre), and $I$ the arc current (A). Inserting the constants for an arc in air at atmospheric pressure between carbon electrodes (Cobine, 1958), the equation reduced to:

$$V_{arc} = 48.9 + \frac{69.1}{I}$$ \hspace{1cm} (6.18)

which was solved by computer program (Appendix 3) for currents up to 30 A where the characteristic was almost horizontal. The static voltage/current characteristics were superimposed on the dynamic response curves for $r_{c2}$ (Fig. 6.17 and Fig. 6.18) so that the behaviour of coalesced arcs operating under different conditions could be compared.
6.3.2 Discussion of results.

The analysis of parallel coalescing arcs showed that the voltages developed across one section of the arcs ($r_{c2}$), when its resistance increased by a factor of up to ten, were significantly higher when the arcs were stabilised by resistors connected on the cathode side only, or distributed on both sides of each arc, than when all the stabilisation was connected on the anode side of each arc. The high voltages may either tend to restore the arc $r_{c2}$ to its original operating point, or allow stable operation under the new conditions (i.e. a longer arc). An arc is more likely to be extinguished if a lower voltage is developed across it for an equal increase in resistance which corresponds to coalescing arcs individually stabilised on one side only, which are known to be unstable, forming three-root coalesced discharges (section 6.2.1). The voltage developed across a section of two coalescing arcs, as its resistance increases, may be a maximum when all the stabilising resistance is adjacent to it (section 6.3.1) but this configuration is undesirable in practical circuits since one of the arc columns on the opposite side of the coalesced region, remote from the stabilisation, will be extinguished. Stable coalesced arcs with multiple anode and cathode roots can only be maintained if each arc is stabilised on both sides. This results in the production of slightly lower voltages across any section of the arcs when the resistance of the arc increases than if all the stabilisation was adjacent to that section but enables stable coalesced discharges to be maintained. When arcs with stabilisation on both sides are coalesced, each section of the arc is stabilised by the resistor closest to it (Fig. 6.19).

The dynamic response of $r_{c2}$ (linear model) only intersected the static voltage-current characteristic determined using the Ayrton equation, for all values of stabilisation used ($4 \ \Omega$ to $56 \ \Omega$), when the resistors were connected on the cathode sides of the arcs only, immediately adjacent to $r_{c1}$ and $r_{c2}$ (Fig. 6.17). The curves for distributed stabilisation intersected the static curve for high values of stabilisation ($56 \ \Omega$) but not for low values ($4 \ \Omega$). The dynamic response (exponential model), however, intersected the static characteristic when the stabilising resistors were either connected on the cathode side only, as in the linear model, or on both sides of the arcs, irrespective of the value of resistance.
Intersection between the dynamic and static characteristics of $r_{c2}$ coincide with stable operation since tests (sections 6.2.1 and 6.2.2) showed that a particular section of two coalescing arcs was only stable when resistance was connected adjacent to that section or distributed on both sides of each arc. The arc column represented by $r_{c2}$ is likely to remain stable when its resistance is suddenly increased if the voltage developed across it exceeds the static requirement for that length of arc (5 mm in the tests carried out). The static arc characteristic represents the minimum conditions required for stable operation.

Both the linear and exponential models showed that the voltage developed across $r_{c2}$ was insufficient for stable operation when all the stabilisation was connected on the anode sides of each arc. Under these conditions, $r_{c2}$ did not meet the minimum conditions for stability, indicating that a resistor only stabilises the part of an arc closest to it.
Resistance on both sides of a pair of parallel coalesced arcs provides isolation between the four arc roots so that no single preferential path can be formed, and also limits the flow of current on both sides of the supply circuit, preventing the flow of increased currents through the arcs.

The variations of currents flowing in the branches of the bridge circuit (Fig. 6.16) are shown in Fig. 6.20. Points denoted A correspond to the condition when the resistances of, and currents flowing through, all sections of the arcs are equal. Over the range of values of $r_{c2}$ considered, the changes in $I_1, I_1'$ and $I_2$ were less than the variation in $I_2'$, indicating that the use of linear resistances for $r_{a1}, r_{a2}$ and $r_{c1}$ would not cause serious errors in the analysis of coalescing arcs.

Fig. 6.20(a) Variation of circuit currents using distributed stabilisation (a)
Fig. 6.20(b) Variation of circuit currents using distributed stabilisation (b)

R = 4 Ω
supply voltage = 110V
6.4 Electromagnetic forces between arcs.

Electromagnetic forces exist between arcs in close proximity in the same way that forces act between other current carrying conductors. The effects will be significant at much lower currents for arcs due to the low inertia and higher mobility of the ionised gas in an arc compared to rigid metal conductors. The magnitude of the forces of attraction and repulsion between arcs is relevant to the design of devices such as a coaxial multiple cathode carrying hundreds of amps, where contraction of the arcs may be desirable, and multiple arc heaters producing large volumes of ionised gas, where it is not desirable.

The force per unit length between two parallel conductors carrying dc is given by (chapter 2)

\[ F = \frac{\mu_0 I_1 I_2}{2 \pi r} = \frac{\mu_0 I^2}{2 \pi r} \quad \text{when} \quad I_1 = I_2 \quad (6.19) \]

where \( F \) is the force per unit length (N/m), \( I \) the current in each conductor (A), \( \mu_0 = 4 \pi \times 10^{-7} \) (H/m) and \( r \) the separation between the conductors (m). The forces between two parallel arcs have been calculated for separations between 0.25 mm and 20 mm at currents up to 100 A (Fig. 6.21). Results show that the force of attraction increases rapidly at electrode separations less than 10 mm, since it is inversely proportional to the distance between the conductors. The force also increases rapidly with current due to the square law term in equation (6.19). The extreme values not shown in Fig. 6.21 are listed in Table 6.4 and indicate that very strong forces exist between arcs at high currents.
Fig. 6.21 Variation of the force between parallel arcs with arc current and distance between the arcs.
<table>
<thead>
<tr>
<th>Separation (mm)</th>
<th>Current (A)</th>
<th>Force (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>10</td>
<td>$2 \times 10^{-3}$</td>
</tr>
<tr>
<td>10</td>
<td>100</td>
<td>$200 \times 10^{-3}$</td>
</tr>
<tr>
<td>1</td>
<td>10</td>
<td>$20 \times 10^{-3}$</td>
</tr>
<tr>
<td>1</td>
<td>100</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 6.4 Forces between parallel arcs.

Increasing force with decreased separation will cause parallel arcs to be accelerated together once the force has become sufficient to overcome the (relatively low) inertia of the arc columns. Electromagnetic forces can cause arcs to be extinguished if the output voltage of the power supply is insufficient to maintain stable operation at the higher voltages required when the columns are elongated. This technique has been used in circuit-breakers to increase the speed of interruption (Reece, 1975).

The effects of electromagnetic forces between arcs were not significant in the multiple arc discharge system (chapter 5) operating at currents of the order of 10 A per arc, but were detectable during the tests on two parallel coalescing arcs (section 6.2). Two vertical arcs, 15 mm in length, carrying currents of approximately 10 A, were attracted together so that the columns coalesced when the arcs were approximately 10 mm apart. This required a force of only $2 \times 10^{-3}$ N/m (Fig. 6.21) which indicates that parallel arcs closer together, or at higher currents, will readily coalesce, although the force required to deflect the arcs will depend on the arc length. The electrode fall and transition regions of arcs less than 5 mm in length represent a significant fraction of the arc and the relative stiffness of these regions, together with plasma jets (chapter 2), increase the rigidity of the arc so that higher forces may be required to coalesce the arcs than in the case of long arcs where the arc column is more mobile.

The diffuse appearance of some of the large volume coalesced discharges generated by the multiple arc system (chapter 5) may be either:
(a) due to the rapid movement of filamentary arcs within the discharge, which is unlikely since the discharges did not contract into a single filament,

or

(b) because the discharge zone was a homogeneous volume of ionised gas with the electrodes simply acting as sources and sinks of electrons. The coalescence of a number of arcs to produce a diffuse discharge causes a reduction in the temperature gradient and heat losses at the periphery of the arcs which reduces the tendency to contract.

The horizontal multiple arc discharge system has not been operated at currents above about 20 A per arc and the possibility of contraction into a single filament exists at high currents.
6.5 Summary of results and conclusions.

Two or more separate arcs can be operated in parallel from a common supply either by using separate isolated circuits for each arc (Fig. 6.2) or by individually stabilising each arc (Fig. 6.3). A common impedance in the supply reduces stability in the latter case since the stable operating point (chapter 2) moves to lower currents when two arcs are operated (Fig. 6.4) and insufficient voltage may be available to maintain more than one arc. The common impedance should be as low as possible in practice.

Theoretical considerations (section 6.1.1) have shown that when two arcs operating from the same supply, with individual stabilising resistors on one side only of each arc, are moved together to coalesce, one of the arc roots on the opposite side of the arcs to the stabilisation will be extinguished, producing a discharge with only three arc roots.

A series of tests has been carried out to investigate the operating characteristics of a pair of parallel free-burning arcs in air at atmospheric pressure at currents up to 30 A per arc (section 6.2) and results showed that:

(i) separate parallel arcs could be operated from a common power supply provided each arc was individually stabilised.

(ii) coalescing the arcs in (i) caused one of the arc roots to be extinguished when the stabilising resistors were connected on one side only, producing a discharge with three arc roots.

(iii) stable coalesced arc discharges (4 roots) could only be maintained when the stabilising resistors were distributed on both sides of each arc so that the electrodes were all isolated from each other. Coalesced discharges were very stable and produced larger volumes of ionised gas than separate arcs.

(iv) transient four-root discharges were produced when short arcs (less than 5 mm) with individual stabilising resistors on one side only were coalesced.

(v) stable operation of parallel arcs was maintained using stabilising resistors between 56 Ω and 2.25 Ω per arc, corresponding to values
of the ratio of open-circuit voltage to arc voltage between 4:1 and 1.5:1 respectively, the latter value being lower than the generally accepted value required for stability (2:1).

These results have been extended and applied to the horizontal multiple arc discharge system which is described in Chapter 5. The system has been operated from:

(i) six separate dc supplies, with distributed inductive stabilisation, connected in parallel to a single transformer winding (Fig. 6.13(a));

and (ii) a single rectifier with distributed stabilising resistors connected to each pair of electrodes (Fig. 6.13(b));

in addition to the original mode of operation using completely isolated supplies for each pair of electrodes. Stable coalesced multiple arc discharges were produced using both additional methods of operation.

The interaction between parallel coalescing arcs has been analysed (section 6.3) by considering two coalescing arcs as an unbalanced Wheatstone bridge, which was solved using determinants and computer programs. Calculated results showed that the voltage developed across a given section of one arc was high when the stabilising resistor was adjacent to that part of the arc, or distributed on both sides of the arcs, but lower when all the resistance was on the opposite side of the coalescing region (Table 6.2). These results indicated that for a given change in arc length, and therefore voltage and resistance, the voltage available to maintain that section of the arc under the new operating conditions, or restore it to its original condition, was most likely to be produced when the stabilising resistor was adjacent to the arc or distributed on both sides. The voltage developed across a section of an arc on the opposite side to the stabilising resistors was below the static requirement for that length of arc (as determined by the Ayrton equation) (Figs. 6.17 and 6.18) indicating the need for stabilising resistors on both sides of each arc, which is in agreement with experimental results described earlier (section 6.2). Linear and exponential models were used to represent the section of the arcs under consideration and comparison between analysis and experimental results showed that an exponential model most accurately represented the characteristics of the arc.
Distributed stabilising resistors (or inductors on the ac side (Fig. 6.13(a))) provide isolation between all the arc roots when parallel arcs operating from a common power supply are coalesced so that no preferential conducting path can be established.

The magnitude of the electromagnetic forces between parallel arcs in close proximity have been calculated for currents between 10A and 100A at separations between 1 mm and 18 mm (Fig. 6.21) and the results indicate that the force increases with the square of the current, and inversely with the separation between the arcs, which will tend to accelerate the arcs together so that they coalesce. The significance of this effect depends on the length of the arc and external factors such as gas flows. Experimental results showed that two arcs carrying 10A each were attracted together over a distance of 15 mm, requiring a force of $2 \times 10^{-3}$ N/m (Fig. 6.21), whereas no contraction has been observed in the coalesced discharges produced by the horizontal multiple arc system (chapter 5) operating at currents up to 20A per pair of electrodes, although the force between parallel current-carrying filaments within the discharges would be sufficient to attract the arcs together, indicating that these discharges were diffuse.

The principles of operating separate or coalesced multiple electric discharges from a common supply can be applied to a number of areas including the operation of multiple plasma torches from a supply incorporating a single transformer, thereby reducing capital costs, and in low pressure glow discharges, used for laser excitation for example, and high pressure discharge lamps where increased lifetime of the electrodes and efficiency may result. The use of resistors to stabilise multiple arc discharges is undesirable at high currents due to the power losses involved but the principle of operation is unchanged by the use of inductors on the ac side of dc supplies.
CHAPTER 7

INVESTIGATION OF THE INTENSITY DISTRIBUTION OF LARGE VOLUME MULTIPLE ARC DISCHARGES
One of the most important factors affecting the suitability of large volumes of ionised gas, produced by coalesced multiple arc discharges, for processing materials and heating gases is the uniformity of the discharge and a high degree of temporal and spatial uniformity is necessary in order to achieve the high throughputs, high efficiencies and high yields required in industrial processes. A series of tests has been carried out using a spectroscopic method of measurement, based on a scanning monochromator, to determine the intensity distribution produced by horizontal multiple arc discharges carrying individual arc currents up to 20A.

7.1 Spectroscopic determination of the uniformity of multiple arc discharges.

The principles of various different methods used to make measurements on arcs, including probes, photography and spectroscopy, have been described already (chapter 3). The advantages and disadvantages of photographic and spectroscopic methods, such as non-perturbation of the discharge and persistence of luminosity respectively have also been discussed.

Previous photographic results (Harry et al, 1979a) and results of recent photographic tests together with an electrical analogue (chapter 5) indicated that multiple arc discharges with all the anodes and cathodes grouped together (chapter 5, Fig. 5.3(a), (c) and (e)) produced large volumes of ionised gas which apparently filled the central region between the electrodes uniformly, whereas discharges with adjacent electrodes of opposite polarity (Fig. 5.1(b) and (d)) produced a number of short, separate arcs around the periphery of the central region, with little or no ionised gas between the electrodes.

A spectroscopic method was chosen to make measurements on the discharges since it would not disturb the arcs, and measurement of the intensities of lines in the emission spectra of arcs potentially offers an accurate means of determining temperature or temperature distribution.
Temperature is a function of the absolute and relative intensities of spectral lines in optically thin plasmas. A large volume of ionised gas at atmospheric pressure can be assumed to be in local thermodynamic equilibrium (LTE) (Drawin, 1970) which simplifies the theory, although the calculation of the temperature of an arc is still complex and subject to errors (chapter 3). The uniformity, or intensity distribution, however, can be easily determined by measuring the spatial variation of the intensity of spectral lines emitted from the discharge.

The components of a measuring system for determining the intensity distribution of an arc discharge can be considered to be:

(i) the light source to be measured
(ii) an optically dispersive element – a prism or diffraction grating
(iii) a detector
(iv) recording and/or analysing systems.

Measurements at a specific wavelength could also be carried out using a narrow-band interference filter instead of dispersing the light into a spectrum although the latter method offers more flexibility since the whole spectrum can be examined and the intensity of several spectral lines can be measured by one system.

7.1.1 Scanning monochromator for measuring the intensity of spectral lines.

The intensity of radiation emitted from the multiple arc discharges was measured using a scanning monochromator system (Appendix 4) which enabled complete spectra in the range 300 nm to 1100 nm to be displayed on an oscilloscope. Ancillary equipment also enabled the relative intensity at any wavelength in this range to be measured and recorded. The oscilloscope display was useful since the whole spectrum could be examined and lines suitable for measurement could be identified.

Light from the source to be measured is directed into the monochromator via a flexible fibre-optic light-guide and dispersed into a spectrum by a diffraction grating mounted in an Ebert optical configuration (Fig. 7.1). Light from the output slit of the monochromator is directed onto a silicon detector, the output of which is amplified, displayed on an
Fig. 7.1 Schematic of optical system for measuring the relative intensities of spectral lines (after Angus, 1980).
oscilloscope and recorded on a chart recorder. A complete spectrum is produced by rotating the diffraction grating using an accurately controlled dc motor. The display of the spectrum is renewed every 60 ms to 100 ms, depending on the speed of the grating, so that fluctuations in the discharge during this interval are recorded. An accurate wavelength scale is generated by a shaft encoder attached to the rotating diffraction grating and is also displayed on the oscilloscope so that wavelength can be measured easily. Wavelength can be measured to an accuracy of ±0.5 nm between 400 nm and 700 nm, and to ±1 nm for the remainder of the spectrum between 300 nm and 1100 nm, by using a moveable cursor pulse generated as part of the wavelength scale. The relative intensity of spectral lines is measured using the wavelength marker pulse in conjunction with a sample and hold circuit, and recorded by a moving-coil meter (with a damped movement-time constant approximately 1s) or plotted by a chart recorder. Absolute intensity can be determined by comparison of results with a standard light source such as a tungsten ribbon lamp.

7.1.2 Bandwidth and spatial resolution.

The optical bandwidth of the monochromator could be set at 2 nm, 5 nm, 10 nm or 20 nm by selecting different width input and output slits and should be as small as possible consistent with adequate sensitivity. A large bandwidth does not allow closely spaced lines to be resolved, but may be acceptable for observations at wide intervals across the spectrum.

The optical input to the monochromator consisted of a tubular collimator 100 mm long, with an aperture 1.6 mm in diameter, and a flexible fibre-optic light guide (2.5 mm active diameter). A collimated input is necessary to obtain good spatial resolution, otherwise light from the whole of the discharge zone could enter the monochromator, irrespective of the position of the light guide relative to the discharge (Fig. 7.2). The transmission of off-axis rays from the source is reduced by using a long collimator since approximately 40% of the energy is absorbed at each reflection from the walls of the tube. Tests carried out with this configuration showed that light observed by the optical system was emitted.
Collimated light input.

from a conical volume of discharge with a cross-sectional area of approximately \(3 \text{ mm}^2\) (measured at the surface of the discharge).

Measured values of intensity correspond to a value which is integrated over the thickness of the discharge and not to the intensity at points within the discharge. No non-contact method is known to have been used for sampling radiation from isolated volumes within a plasma. Even lenses with very short focal lengths, and narrow depths of focus, transmit light from relatively large regions along the principal axis either side of the focal points.
7.1.3 Spatial scanning of the discharge zone.

The monochromator system (section 7.1.1) measures the intensity of radiation emitted by a relatively small fraction of the total volume of a discharge (Fig. 7.2) and a spatial scanning system was required to determine the intensity distribution over the whole discharge region. The collimator and light-guide was scanned across the discharge using a screw-driven linear traverse (Fig. 7.3). Slow-speed control was achieved by separately controlling the armature and field windings of the dc drive motor.

![Discharge schematic with linear traverse](image)

**Fig. 7.3** Schematic of linear traverse for scanning the discharge.
7.2  Determination of the uniformity of multiple arc discharges.

A series of tests was carried out, initially observing complete spectra to identify suitable lines for determining the intensity distributions of multiple arc discharges. The uniformity was subsequently determined by physically scanning the discharges at the selected wavelength.

7.2.1 Observations of complete spectra.

Complete spectra produced by different electrode configurations (chapter 5, Fig. 5.3) were generated by the scanning monochromator and displayed on an oscilloscope. The basic requirements of these general observations were:

(i) to locate and identify a spectral line (or lines) of suitable intensity in the spectra emitted by all the different discharge configurations,

(ii) to assess the test to test repeatability/consistency of the spectrum emitted by each electrode arrangement.

The line(s) observed in (i) should occur at a wavelength where the persistence of luminosity is low, since this phenomena increases the apparent uniformity of discharges at certain wavelengths (chapter 3).

Two examples of each spectrum emitted by two different multiple arc discharges are shown in Fig. 7.4. The spectral line at a wavelength of 418 nm was common to the spectra emitted by all the discharges and occurred at a wavelength where the persistence of luminosity has been measured to be less than 0.25 ms (Hobson, 1980). This line corresponds to the molecular band spectra emitted by cyanogen (CN) which are characteristic of carbon arcs in air and a simplified energy level diagram is shown in Fig. 7.5 (after Smit, 1950). A number of other lines was available but the cyanogen band was chosen because other measurements have been carried out at this wavelength (Boumans, 1966). The temperature of carbon arcs can be calculated from the measured intensities of CN bands (Boumans, 1966) but the method is reported to be laborious, offering no advantages over methods based on atomic and ionic lines.
Fig. 7.4  Spectra emitted by multiple arc discharges; (i) and (ii)–configuration (b), (iii) and (iv)–configuration (c). Bandwidth 20 nm. Discharge current 10A/arc.
Simplified energy level diagram for cyanogen (after Smit, 1950).

The repeatability of the spectra emitted during different tests (Fig. 7.4) indicated temporal stability within the discharges so that measurements of intensity were likely to be accurate representations of the conditions within the discharges.
7.2.2 Measurement of the intensity distribution.

The collimator and light guide (Fig. 7.2) were traversed beneath the electrodes at a rate of approximately 0.6 mm/s to determine spatial variations in the intensity of radiation emitted by different discharge configurations at a wavelength of 418 nm and the output of the monochromator system was recorded using a chart recorder.

The results can be divided into two general types, like the electrode arrangements and photographic results (chapter 5):-

(i) electrode configurations with the anodes and cathodes grouped together on opposite sides of the discharge (Fig. 5.3(a),(c) and (e)) produced discharges with a high degree of uniformity at currents up to 10A per arc. The uniformity decreased as the current was increased to 15A-20A per arc due to increased distortion by convection currents;

(ii) electrode configurations with alternate electrodes of opposite polarity (Fig. 5.3(b) and (d)) produced non-uniform discharges in which the intensity was highest close to the electrodes, at the periphery of the discharge region, and relatively low in the central region. The uniformity of these discharges increased when the current was increased to 15A-20A per arc since more ionised gas was produced by the arcs at the higher currents and tended to fill more of the central region. The discharges were never as uniform as those described in (i).

The two different characteristic intensity distributions are shown schematically in Fig. 7.6 and typical experimental results are shown in Fig. 7.7, together with the radial intensity distribution due to a single arc operating under the same conditions for comparison.

The effect of distortion by convection currents (arrangements (a), (c) and (e)) was reduced by using a magnetic field to spatially stabilise the discharge in the plane of the electrodes (Fig. 7.8). Results (Fig. 7.9) showed that a discharge of this type (symmetrical) could be stabilised in the plane of the electrodes, or even completely inverted and distorted beneath the electrodes at higher field strengths.
Fig. 7.6 Schematic of characteristic intensity distributions:
(i) configurations (a), (c) and (e),
(ii) configurations (b) and (d).

Fig. 7.8 DC magnetic field used to spatially stabilise multiple arc discharges.
Fig. 7.7 Measured intensity distributions of multiple and single arc discharges: (i) configuration (b), (ii) configuration (c), (iii) single arc (10A).
Fig. 7.9 Effect of transverse magnetic field on a multiple arc discharge:
(a) no field - distorted, (b) field current = 8.8A - stabilised,
(c) field current = 20A - distorted and inverted.
Photographic exposure 2 ms at f8 in conjunction with ND 1.61 + 0.98.
A series of tests was carried out using a calibrated Hall probe to measure the magnetic flux density acting on the discharge. The variation of flux density with distance from a polepiece at different field currents is shown in Fig. 7.10 and results indicated that the field strength in the discharge region was less than $1 \times 10^{-3} \text{T}$ (10 gauss), corresponding to a force/unit length given by

$$F/l = BI \sin \theta = 0.06 \text{ N/m} \tag{7.1}$$

![Graph showing variation of magnetic flux density with distance from a polepiece at different field currents.](image)

Fig. 7.10 Variation of magnetic flux density with distance from a polepiece at different field currents.
7.3 Discussion of results.

The intensity distributions of the discharges produced by configurations (a), (c) and (e) (Fig. 5.3) at currents of approximately 10A per arc (Fig. 7.6) showed a much higher degree of uniformity than those produced by configurations (b) and (d) (Fig. 7.6) or by a single free-burning arc (Fig. 7.7). The uniformity typically varied by 17.7% ((a), (c) and (e)) and 90% ((b) and (d)) and a single arc exhibited a characteristic Gaussian intensity distribution.

The effects of persistence of luminosity and fluctuations occurring in the arcs during the finite time taken to scan the discharge zone will result in some inaccuracies in the measured intensity distributions but these errors are estimated to be small since the persistence of luminosity is of the order of 0.25 ms at a wavelength of 418 nm, which is short compared to the equilibrium time of an arc (1 ms, chapter 2) and comparisons of complete emission spectra (Fig. 7.4) indicated a high degree of repeatability between tests. The Gaussian distribution for a single arc (Fig. 7.7) is consistent with results of previous work and shows that a single arc is not suitable for use in processes requiring uniform heating. The spectroscopic measuring technique could be refined to incorporate optical components with higher resolving power (narrower bandwidth) but the results obtained with the existing system are in agreement with the results of photographic observations and an electrical analogue (chapter 5) and are adequate for the present series of tests.

Configurations (a), (c) and (e) may be suitable for processing materials or heating gases due to the high degree of uniformity, although this decreased at currents in excess of 10A per arc due to increased convection currents but could be restored using a transverse dc magnetic field. Configuration (c) remained most uniform as the discharge current was increased above 10A per arc. The force acting on the discharge due to the external magnetic field used to overcome the effects of convection was less than 0.06 N/m, which was a factor of three higher than the force which caused two parallel arcs, 1 mm apart, each carrying currents of 10A, to coalesce (chapter 6, Fig. 6.21). These results indicated that the force per unit length between arcs at high currents (100A for example) would be
greater than that which has already been shown to produce significant movement of arcs at lower currents (via an external magnetic field) and may cause the large volume discharges to contract into single, narrow filaments. The magnitude of this effect is difficult to predict at this stage since the intensity distributions of some discharges, carrying 10A per arc, show a high degree of temporal uniformity (Fig. 7.7(ii)) with no detectable current carrying filaments although the possibility of a transition to a single discharge at high currents cannot be discounted.
7.4 Summary of results and conclusions.

The intensity distributions produced by various different configurations of the electrodes in a horizontal multiple arc discharge system were investigated using a scanning monochromator system in conjunction with a linear traverse used to spatially scan the discharges. Measurements were carried out at a wavelength of 418 nm on discharges carrying currents of approximately 10A per pair of electrodes (section 7.2) and results indicated that two different characteristic discharges were produced:

(i) discharges with all the anodes and all the cathodes grouped together (arrangements (a), (c) and (e) (chapter 5, Fig. 5.3)) produced uniform discharges (Fig. 7.6(i)) in which the intensity typically varied by 17.7% across the discharge (Fig. 7.7(ii));

(ii) discharges with alternate electrodes of opposite polarity (arrangements (b) and (d) (chapter 5, Fig. 5.3)) produced non-uniform discharges, in which the intensity typically varied by 90% across the discharge (Fig. 7.7(i)), owing to the formation of a number of separate arcs around the periphery of the central region between the electrodes.

The uniformity of the large volume discharges described in (i) decreased when the current was increased to 15A–20A per pair of electrodes due to increased distortion caused by convection currents. Stabilisation of the discharges in the plane of the electrodes against the effects of convection was demonstrated using an external magnetic field applied across the discharge zone (Fig. 7.9). The field strength acting on the discharge was $1 \times 10^{-3}$ T corresponding to a force/unit length of 0.06 N/m.

The results of these tests indicate that electrode configurations (a), (c) and (e) (chapter 5, Fig. 5.3) produce uniform discharges which may be suitable for processing materials or heating gases, the high degree of uniformity ensuring uniform heating of feedstock and the large volume of ionised gas enabling high throughputs, high yields and high efficiencies to be obtained compared with using a single arc which is characterised by steep temperature gradients (Fig. 7.7(iii)).
Investigations have only been carried out using discharges operating at currents up to 20A per arc, with total power inputs of the order of 7 kW and scale-up to power levels in excess of 100 kW, as required for pilot-plant investigations, using currents up to 400A per arc, may result in contraction of the discharge to a single high-current filament due to the magnetic forces between parallel arcs (chapter 6) although results at low currents indicate that the discharges are diffuse, with no detectable filamentary arcs. Further work is required to investigate the operation of horizontal multiple arc discharges at high powers and to develop a plasma reactor incorporating fixed, non-consumable electrodes with remote (i.e. non-contact) initiation of the arcs.

CHAPTER 8

APPLICATIONS OF MULTIPLE ELECTRIC ARC DISCHARGES
Multiple electric discharges may be applied in several areas which use single discharges at present—sparks, glow discharges and arcs. The application of multiple discharge techniques to a number of processes, including CO₂ lasers (Saleh, 1981), glow discharge lamps (Taylor, 1982), spark plugs (Duncan, 1982), plasma torches and electrodes for arc furnaces, has been investigated at the University. Tests described here have been carried out, as part of this study of multiple arc discharges, in two areas:

(i) multiple plasma torches for use in a plasma furnace,
(ii) high-current multiple electrodes for arc furnaces.

The work on plasma torches was supported by industry and the results described here are the embodiment of an extensive research programme but, due to the commercial interest and in order to retain confidentiality, certain technical details and specifications have been omitted. However, the principles involved are unaffected and show how multiple plasma torches can be operated from a common power supply.

8.1 Design and operation of a reactor incorporating multiple plasma torches.

The principle of operating multiple arcs from a common power supply using individual resistors to stabilise the arcs (chapter 6) has been used to operate three plasma torches simultaneously in a plasma furnace. The torches dissipated a total power of approximately 50 kW in the transferred mode. The reactor was developed at the University as part of a programme to design a plasma system for extractive metallurgy. The initial requirement was for a small-scale furnace to be designed, built and used to evaluate the feasibility of a plasma–arc melting process for the extraction of metals from powdered feedstock at temperatures above 1400°C.

Melting was carried out using three dc plasma torches operating in the transferred mode with long arcs between thoriated tungsten cathodes in the torches and a conducting refractory crucible, supported beneath the furnace, connected as a common anode. The plasma torches were mounted in the roof of the furnace so that maximum power could be dissipated.
(longest arcs) when the crucible was empty, at the beginning of a melting cycle. As feedstock was subsequently introduced and melted in the crucible the length of the arcs, and power input, would be gradually reduced.

The furnace was required to operate for a melting period of forty minutes to process material at a rate of approximately 50 kg/hr. Power requirements were calculated to be of the order of 60 kW and three commercially available plasma torches were used. Each torch would dissipate a power in excess of 20 kW.

8.1.1 Parameters affecting the stable operation of multiple plasma torches.

Some of the principal operating parameters which affected the design of the furnace are listed in Table 8.1. Several parameters, including furnace atmosphere, supply voltage, arc length and size of the crucible were interdependent so that it was not possible to change one variable without affecting the others. A series of tests was carried out to investigate these parameters (Table 8.1) and to demonstrate the simultaneous operation of three plasma torches from a common supply. Subsequent stages included operation in a furnace environment and the design and construction of a power supply to operate multiple plasma torches.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of the crucible</td>
<td>Determined by feed rate required.</td>
</tr>
<tr>
<td>Maximum arc length</td>
<td>Dependent on atmosphere, supply voltage, gas flow, and size of crucible.</td>
</tr>
<tr>
<td>Furnace atmosphere</td>
<td>Determines the arc voltage.</td>
</tr>
<tr>
<td>Supply voltage</td>
<td>Limits maximum length of arc.</td>
</tr>
<tr>
<td>Method of stabilising the arcs</td>
<td>Inductors or resistors.</td>
</tr>
<tr>
<td>Multiple hf ignition</td>
<td>Simultaneous ignition of three torches required.</td>
</tr>
<tr>
<td>Transfer of arcs to crucible</td>
<td>Long non-transferred arcs required.</td>
</tr>
<tr>
<td>Geometry of torches within the furnace</td>
<td>Symmetry required.</td>
</tr>
</tbody>
</table>

Table 8.1 Parameters affecting the operation of multiple plasma torches.
8.1.1.1 Size of crucible, arc length, furnace atmosphere and supply voltage.

The furnace was designed to operate with a fixed refractory roof supporting three plasma torches above a refractory crucible (Fig. 8.1). Maximum arc length would occur at the beginning of a melting cycle and the coalesced anode root produced by the three torches would be sited on the bottom of the empty crucible.

The capacity of the crucible was pre-determined by the feed rate required. An average-size crucible between two possible extremes of the same capacity; wide and shallow or narrow and deep, was used. Heating would only occur over a small proportion of the surface in a shallow bath, and heat losses from the surface would be higher than from a narrow crucible. Higher arc and supply voltages would, however, be required if a deep crucible was used.

Fig. 8.1 Schematic of plasma furnace.
The voltage gradient in an arc column depends on the working atmosphere and current (chapter 2) and varies by a factor of about two between monatomic and diatomic gases. An argon atmosphere was chosen for the furnace in order to achieve the maximum arc length from a commercially available plasma power supply with an open-circuit voltage of approximately 400 V dc, assuming that approximately half this voltage would be dropped across the stabilising impedance during operation. The maximum length of transferred arc was of the order of 300 mm, which determined the size of the crucible. If insufficient power input was obtained in an argon atmosphere, a change to nitrogen could be considered although a higher supply voltage would be required if the arc length remained constant.

8.1.1.2 Stabilisation of multiple arcs.

Investigations of multiple, free-burning, arcs in air (chapter 6) showed that stable parallel arcs can be maintained from a single supply provided each arc is separately stabilised. Multiple arcs to a common electrode can be operated with either separate or coalesced arc roots on the common electrode, depending on the distance between the arcs (Fig. 8.2).

![Diagram](image)

**Fig. 8.2** Multiple arcs with a common electrode, (a) separate, (b) coalesced.
Conventional power supplies for plasma torches utilise transformers with a high leakage-reactance, which forms part of the stabilising impedance. This reactance constitutes a common impedance $Z_0$ (Fig. 8.2) when multiple plasma torches are connected to a supply of this type. Large common impedances decrease the stability of multiple arcs (chapter 2) and cause increased voltage drops in the supply as the number of torches is increased, which reduces the maximum available arc voltage. Common impedances must therefore be minimised in the design of power supplies for multiple plasma torches.

Multiple arcs can be stabilised by resistors (Fig. 8.2) or by inductors prior to rectification of the ac supply. The use of resistors to stabilise arcs is a simple but inefficient method since approximately 50% of the power output from the supply is dissipated in the stabilisation as heat, which is wasted. This method of operation was, however, justified during the initial stages of this work because the available power supply could not be easily modified to provide three inductively-stabilised dc outputs. When the electrical characteristics of the arcs have been determined a multiple-output supply using inductors for stabilisation can be designed.

The high-current transferred arcs were individually stabilised by resistors of less than 1Ω, and during non-transferred operation the currents flowing through the nozzles of the torches, or pilot-arc currents, were limited to approximately 20A per torch by 14Ω resistors to prevent excessive erosion of the nozzles.

8.1.1.3 Ignition circuits for multiple arcs.

Plasma torches are normally ignited by breaking down the gap between the cathode and the nozzle with a high frequency (up to 4 MHz), high voltage (up to 10 kV) spark. Series and parallel connected hf units can be used, but parallel connected generators must be isolated from the main dc supply to prevent the flow of high currents which may damage the hf unit.

Two problems existed in the development of an hf generator for the simultaneous ignition of multiple plasma torches. Firstly, isolation of the hf and dc supplies, to prevent the flow of dc into the high-frequency supply
and to prevent damage to the rectifiers in the dc supply caused by the high-voltage spark; and secondly to obtain multiple spark discharges from a single supply. A spark is an electrical discharge and supply circuits similar to those used to operate multiple arcs from a common supply (chapter 6) may be used. Resistors (or inductors) (Fig. 8.3(a)) can be used to individually stabilise each discharge, and to satisfy the isolation criterion. Tests were carried out using resistors to stabilise multiple spark discharges and results showed that the resistance required to isolate the hf unit from the dc supply (1 kΩ) caused such a high hf voltage drop that breakdown in the torches could not be achieved.

Capacitors can be used to prevent the flow of dc but tend to create constant-voltage conditions, which generally cause instability in electric discharges due to the negative dynamic resistance of the discharge. The high-frequency spark, however, is only a transient discharge and capacitors can be used as series stabilising impedances (Fig. 8.3(b)) which transmit the hf signal with little attenuation and isolate the spark generator from the dc supply.

![Diagram of stabilisation of multiple hf ignition](image)

**Fig. 8.3** Stabilisation of multiple hf ignition, (a) resistive, (b) capacitive.
A series of tests was carried out using capacitors to stabilise spark discharges and simultaneous breakdown was obtained in three plasma torches using 400 pF capacitors connected on both sides of the discharge. The cathodes and nozzles of the three plasma torches were therefore mutually isolated, which prevented interaction between the arcs via the hf circuit.

8.1.1.4 Establishment of transferred arcs.

A reliable method of establishing long transferred arcs between the plasma torches and crucible in the plasma furnace was required. Once a stable non-transferred arc has been initiated in a plasma torch a transferred arc can be produced by providing a low impedance path between the arc and an external anode - the crucible in a plasma furnace for example. The pilot arc impinges on the workpiece in plasma cutting processes to breakdown the gap, which may be up to 25 mm, but transferred arcs approximately 300 mm long were required in the plasma furnace. Several methods of producing long transferred arcs have been investigated (Table 8.2).

<table>
<thead>
<tr>
<th>Method of transferring arc</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long non-transferred arc</td>
<td>Requires laminar gas flow.</td>
</tr>
<tr>
<td></td>
<td>Limited by design of torch.</td>
</tr>
<tr>
<td>Auxiliary vertical arc</td>
<td>A long, stable, free-burning arc is difficult to maintain.</td>
</tr>
<tr>
<td>Thin conductor inserted into nozzle</td>
<td>No access to the plasma torches in the furnace once the crucible is in place.</td>
</tr>
<tr>
<td>Consumable metal starting electrode placed in crucible</td>
<td>Arc must transfer to the electrode and elongate as the electrode melts.</td>
</tr>
</tbody>
</table>

Table 8.2 Methods of producing long transferred arcs.

Tests were carried out to investigate all these methods and results showed that a consumable metal starting electrode was the most successful and reliable method of establishing transferred arcs. The other methods were rejected either because they did not give repeatable results or were not suitable for use in the plasma furnace.
8.1.2 Preliminary investigations.

A series of tests was carried out to investigate the behaviour of a long transferred arc in an argon atmosphere, and the operation of multiple plasma torches from a common power supply. The long transferred arc was operated in a sealed enclosure to simulate the conditions in a plasma furnace. The multiple plasma torches were mounted symmetrically in the roof of a circular furnace, 120° apart, angled downwards at approximately 60° to the vertical so that a single coalesced arc root would be produced on the crucible. This was expected to increase the stability of the arcs since the electromagnetic attraction between the parallel arcs (chapter 6) would reduce the tendency of the arc roots to wander randomly.

8.1.2.1 Maintenance of a long transferred arc in an argon atmosphere.

The conditions for stable operation of long transferred arcs were investigated in a series of tests using a single plasma torch enclosed in a glass tube 160 mm in diameter containing a metal anode (Fig. 8.4). This arrangement enabled an argon atmosphere to be obtained to simulate conditions in the plasma furnace. Non-transferred arcs broke down to the anode over distances up to 75 mm at argon flow rates of 10-20 l/min. This was an improvement over the lengths obtained in air but was insufficient to break down the required distance to the bottom of an empty crucible (300 mm). Longer non-transferred arcs can be produced using laminar gas flows (Harry, 1968) although laminar flow only occurs in argon at flow rates below 5 l/min. Tests were carried out using laminar flow for increasing values of the separation between the nozzle of the plasma torch and the anode (Fig. 8.4(a)). The arcs were ignited at high gas flow rates (15 l/min) which were subsequently reduced to approximately 5 l/min to establish transferred arcs. The arcs remained stable when the gas flow was increased, but turbulent flows in excess of 15 l/min caused instability and long arcs were extinguished. Breakdown was achieved at separations up to 105 mm by this method which was in agreement with published information (Table 8.3) although this was insufficient to break down the required separation of up to 300 mm.
Fig. 8.4 Test chamber for transferred arcs,
(a) non-transferred arc only,
(b) with consumable auxiliary electrode.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Flow rate (l/min)</th>
<th>Maximum non transferred arc length (mm)</th>
<th>Transferred arc length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>He</td>
<td>laminar 15</td>
<td>200 - 250</td>
<td>N/A</td>
</tr>
<tr>
<td>Ar</td>
<td>turbulent 12-15</td>
<td>30 - 40</td>
<td>approx 300 (400V supply)</td>
</tr>
<tr>
<td>Ar</td>
<td>laminar 5</td>
<td>100</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Table 8.3 Maximum lengths of arcs obtainable in different gases (Schoumaker, 1981).
Longer transferred arcs were obtained using a vertical auxiliary electrode (Fig. 8.4(b)). Arcs transferred to this electrode (provided the distance between the nozzle and electrode was less than 105 mm) which melted and extended the column until an arc root was established on the anode. The maximum length of transferred arc produced was 230 mm. The test chamber was not perfectly sealed and the effect of air poisoning could not be quantified although it is likely that the maximum attainable arc length was decreased due to the increase in the axial voltage gradient of the arc column.

8.1.2.2 Simultaneous operation of multiple plasma torches in air and argon.

A series of tests was carried out to demonstrate the simultaneous ignition and operation of three plasma torches from a common supply. The supply circuit incorporated individual stabilising resistors for each arc and multiple hf supplies (Fig. 8.5).

![Diagram of power supply circuit for multiple plasma torches.](image)

**Fig. 8.5** Power supply circuit for multiple plasma torches.
Multiple spark breakdowns were observed in three plasma torches using a capacitively stabilised hf supply (Fig. 8.5, section 8.1.1.3).

Three plasma torches were operated simultaneously in air in the non-transferred and transferred modes using individual stabilising resistances of approximately 0.5Ω and 1Ω respectively, and argon flow rates of 15 l/min. Instability occurred when $R_3$ (Fig. 8.5) was reduced to approximately 0.25Ω (non-transferred mode) or 0.5Ω (transferred mode) and only one or two torches could be operated simultaneously since the higher currents flowing (30A per arc in the transferred mode) produced a high voltage drop across the common impedance in the power supply ($Z_C$, Fig. 8.5) and insufficient voltage was available to maintain three arcs.

Three separate transferred arcs were maintained at a total current of 200A, and for a total power output of 22 kW approximately 8.5 kW was developed in the arcs, the balance being dissipated as heat in the stabilising resistors.

The behaviour of multiple transferred arcs operating in argon was investigated under conditions representing a plasma furnace by mounting three plasma torches in a simple rigid structure above a conducting crucible. The transferred arcs were established using an auxiliary electrode (section 8.1.2.1) but unstable and unrepeatable operation was obtained. Throughout the tests the presence of even small quantities of air, due to faulty seals etc., could not be ignored and tended to increase the arc voltage and cause instability. The total power dissipated by two transferred arcs was greater than 30 kW per torch, due to the effect of air, indicating a power requirement in excess of 90 kW for three torches. The output of the plasma power supply used for these tests (Fig. 8.5) was limited to 70 kW, which prevented the simultaneous operation of more than two torches under these conditions. This series of tests indicated that the design requirements may be satisfied provided a pure argon atmosphere could be maintained in the furnace so that the total power dissipated was less than 70 kW.
8.1.3 Furnace incorporating multiple plasma torches.

The power supply, plasma torches and ancillary equipment (stabilisation etc.) were installed with the refractory-lined plasma furnace (Fig. 8.1) in order to evaluate the furnace design and to carry out melting tests.

8.1.3.1 Maintenance of transferred arcs in the furnace.

The furnace was purged with argon for approximately 30 s to remove air before the arcs were ignited. Transferred arcs were established between the plasma torches and a 200 mm long starting electrode (section 8.1.2.1) as soon as the pilot-arcs ignited. An anode root was formed on the crucible when the auxiliary electrode melted but was unstable initially and the total arc current fluctuated over the range 200A–400A due to random movement of the anode root over the surface of the crucible. The coalesced anode root eventually stabilised at a point on the side of the crucible, where preferential arcing occurred, probably due to the emission of positive ions from the hot crucible. The stability of the anode root was increased initially by

(i) increasing the angle of the plasma torches to the vertical by approximately 15° to an angle of 75°,

(ii) raising the base of the crucible relative to the plasma torches by 50 mm using a graphite disc.

Adjustment of the angle of the torches increased the stability of the arcs, although the anode root remained on the side of the crucible, but a stable coalesced anode root was established on the graphite disc placed in the bottom of the crucible. These results indicated that stable operation could be maintained with the arcs coalesced on the base of the crucible and not above it (section 8.1.3.3).

The total power output of the supply was approximately 80 kW, of which 27 kW was dissipated in the arcs, the remaining 53 kW being dissipated in the stabilising resistors.

Interaction between an arc and its self-magnetic field, and between the magnetic fields produced by two arcs may affect the behaviour and stability of arcs in a conducting crucible (chapter 6 and section 8.1.3.3)
8.1.3.2 Initial melting tests.

The behaviour of the furnace and arcs under operating conditions was investigated using calcium oxide-iron oxide-silica slag \((\text{CaO}.\text{FeO}.\text{SiO}_2)\), with a melting point of approximately 1100°C, as feedstock. The arc voltage increased when material was introduced owing to the increase in electrical resistivity in the arc column as unheated material passed through it (Table 8.4). The transferred arcs remained stable, but off-centre, throughout the tests and the crucible was heated uniformly. All the feedstock was melted and the temperature of the melt was estimated to be approximately 1250°C.

<table>
<thead>
<tr>
<th>Process</th>
<th>Duration (min)</th>
<th>Feed rate (kg/min)</th>
<th>Supply Voltage (V)</th>
<th>Total Current (A)</th>
<th>Total Power (kW)</th>
<th>Furnace Power (kW)</th>
<th>Gas Flow (1/min)</th>
<th>( R_S ) (( \Omega ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start</td>
<td>4</td>
<td>-</td>
<td>175</td>
<td>400</td>
<td>70</td>
<td>43.3</td>
<td>6</td>
<td>0.5</td>
</tr>
<tr>
<td>Preheat</td>
<td>4</td>
<td>-</td>
<td>160</td>
<td>380</td>
<td>60.6</td>
<td>36.7</td>
<td>11</td>
<td>0.5</td>
</tr>
<tr>
<td>Feed</td>
<td>8</td>
<td>0.5</td>
<td>210-220</td>
<td>300</td>
<td>66</td>
<td>51</td>
<td>11</td>
<td>0.5</td>
</tr>
<tr>
<td>Soak</td>
<td>8-9</td>
<td>-</td>
<td>160</td>
<td>300</td>
<td>48</td>
<td>33</td>
<td>11</td>
<td>0.5</td>
</tr>
<tr>
<td>End</td>
<td>-</td>
<td>-</td>
<td>170</td>
<td>340</td>
<td>57.8</td>
<td>38.5</td>
<td>11</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Table 8.4 Variation of electrical parameters during a melting cycle.

These tests showed that a furnace incorporating multiple plasma torches can be used for melting at temperatures in excess of 1100°C. The power input to the arcs was 46 kW typically and 24 kW was dissipated in the stabilising resistors.
8.1.3.3 Discussion of results.

The instability of the anode root on the crucible may be attributed to two main factors – geometrical asymmetry and an unstable multiple arc configuration. The resultant gas flow produced by three plasma torches arranged symmetrically in a furnace will be directed downwards towards a common point if the gas flows in the torches are equal since the horizontal components of velocity cancel out. This will tend to establish an anode root at the centre of the base of the crucible. An asymmetrical arrangement of the torches and/or differences in gas flow, however, will produce a resultant horizontal component of gas velocity and the anode root will tend to be established on the side of the crucible, opposite the torch with the highest gas flow. This occurred in practice (section 8.1.3.1) and stability was increased when the torches were arranged symmetrically.

An unstable multiple arc discharge is formed if the arc columns coalesce above the base of the crucible (Fig. 8.6(a)). The equivalent circuit of this configuration is shown in Fig. 8.6(b) where $R_S$ represents the stabilising resistors and $r_a$ and $r_c$ represent the arcs adjacent to the anodes and cathodes respectively. The worst-case condition tends to establish three anode roots on the crucible, with three separate arcs $r_a$ from the point (c) where the arcs coalesce. The three arcs represented by $r_a$ will be unstable since they are connected to a common anode – the crucible – and are not individually stabilised (chapter 6). Electromagnetic forces will also attract the arc columns $r_a$ together. This force will have a greater effect on these arcs than the force of similar magnitude existing between the arcs represented by $r_c$ since the relatively high gas flows from the torches spatially stabilise the arcs $r_c$. The net result is a tendency to form a single arc between the point of coalescence $C$ and the base of the crucible. This single arc, however, will be distorted by gas flows due to convection etc. and if the distance $x$ is less than $y$ (Fig. 8.6(a)) the arc will take the shortest, most stable, path to the side of the crucible. This condition is undesirable in practice since non-uniform heating of the crucible and feedstock will occur. The criterion for stable operation with an arc root on the base of the crucible is that $y \ll x$, and ideally the coalesced point $C$ should be on the crucible.
Fig. 8.6 Unstable coalescing arcs.

(a) conditions in the furnace, (b) equivalent circuit.

This theory is in agreement with the experimental results, where stable operation was initially achieved by raising the base of the crucible so that the arcs actually coalesced on it. Stable operation into an unmodified crucible was subsequently obtained when the angle of the torches was increased further.

An alternative approach, used by Freital in East Germany (chapter 4), also in a furnace operating with an argon atmosphere, is to operate with separate multiple arcs, for example to 4 or more anode roots on the surface of the bath. The arc columns do not intersect in this configuration and the degree of interaction between the arcs is likely to be less than between coalesced arcs although the force on the arcs due to the magnetic field produced by currents flowing in the bath may be higher in the case of separate arcs.
Generally, coalesced arcs were preferred since:

(i) the overall stability was increased by allowing the arcs to coalesce and controlling the interaction by using a symmetrical arrangement of the torches, balanced gas flow rates etc.,

(ii) concentrating the power input at a single point creates a region of high energy intensity which causes more rapid melting than a large number of arc roots (carrying the same total current) distributed over a larger area although it is possible that the large volumes of ionised gas produced by multiple arc columns may increase the efficiency.
8.1.3.4 Summary of results.

The initial series of tests has shown that a furnace incorporating multiple plasma torches can be operated from a single power supply and used to melt particulate material. The important results can be summarised as follows:

(i) Three dc plasma torches have been operated simultaneously from a common supply. Stable non-transferred and separate multiple transferred arcs (common anode) were maintained in air using individual stabilising resistances of less than 1 Ω connected in series with each cathode.

(ii) Multiple simultaneous hf breakdown was obtained in three plasma torches using a single, parallel-connected, ignition unit. The multiple hf discharges were stabilised on both sides of the supply by capacitors, which also prevented dc from the main power supply from flowing through the ignition unit.

(iii) Transferred arcs were established between the plasma torches and the crucible in the furnace using a 200 mm consumable metal auxiliary starting electrode. Stable operation with the anode root on the base of the crucible was only possible when the separation between the point of coalescence and the base of the crucible was less than the distance to any other part of the crucible. Symmetrical alignment of the torches was also required so that a single point of coalescence was produced in order to establish a single anode root on the crucible.

(iv) Stable coalesced transferred arcs were maintained on the base of the crucible with arc lengths of the order of 280 mm in a pure argon atmosphere. The arcs were individually stabilised by resistances of approximately 0.5 Ω and power inputs to the furnace of up to 50 kW were obtained. Unstable operation occurred with resistances below 0.5 Ω due to the effect of a common impedance in the power supply.
(v) The model of three coalescing arcs (Section 8.1.3.3) is in good agreement with the results and analysis obtained in Chapter 6.

(vi) The plasma furnace has been used to melt slag at temperatures of 1100°C at a rate of 0.5 kg/min with a power input of approximately 50 kW.

(vii) The furnace has been in operation in industry for approximately 3 years and has been uprated to a power output of 100 kW. The arcs are now individually stabilised by inductors, with saturable reactors for current control over the range 100A – 180A.
8.2 High current multiple electrodes for use in arc furnaces

The basic design, and principle of operation, of high power ac direct arc furnaces has remained essentially unchanged for almost a century. Arc furnace technology has improved over the years, however, resulting in an increase in the capacity and power density of furnaces and today three phase ac arc furnaces with capacities up to 400T, rated at 163 MVA, have been developed for the production of bulk steel from scrap and pre-reduced iron ore (Schwabe, 1976). Graphite electrodes of up to 0.61 m in diameter are used to carry the high currents, typically in excess of 30 kA, necessary to obtain sufficient power input for melting since the arcs are short (50 mm - 125 mm) with correspondingly low arc voltages.

Electric smelting processes, using arc and submerged arc furnaces, are used to produce various materials, including pig iron, ferro-chrome and ferro-manganese and non-ferrous metals such as nickel and copper (Robiette, 1955). These furnaces utilise both self-baking or Söderberg and graphite electrodes, up to 2 m in diameter, in linear and trefoil configurations, carrying currents up to 100 kA. In the case of submerged arc furnaces there are considerable differences of opinion between authors as to whether an arc actually exists or whether melting is carried out by resistance heating (Robiette, 1955; Baicher et al, 1968; Otani et al, 1968). In some cases both arc and resistance heating have been reported (Robiette, 1955). However, it is likely that the dominant process will be determined by the particular metallurgical process being carried out.

The electrodes are consumed due to spalling, oxidation, mechanical fracture and erosion at the arc root in melting and smelting furnaces and the cost of the electrodes represents a significant proportion of the cost of the final product. The cost of graphite is approximately £7 per tonne of steel produced in the UK with an annual total cost of £28M, and worldwide the annual figure is of the order of £500M.

A number of techniques for reducing electrode consumption have been proposed, including new electrode designs and dc operation of arc furnaces. These techniques are described together with the potential advantages and disadvantages of using multiple electrodes in ac and dc arc furnaces.
8.2.1 Multiple consumable electrodes for use in ac arc melting and smelting furnaces.

High power ac arc furnaces are subject to a number of operating problems, some of which are summarised in Table 8.5. Reduced oxidation of the electrodes has been obtained by spraying the graphite with a protective refractory coating (Valchev, 1972). A composite electrode, comprised of a water-cooled body with a consumable graphite tip, has also been developed (Zöllner et al, 1982) and graphite savings of up to 35% have been reported.

Alternatively the graphite electrodes used in ac arc furnaces may be replaced by arrays of multiple electrodes, using individual stabilisation of each electrode, to reduce the individual thermal loading and electrode erosion. A secondary, but important, advantage would be more uniform heating of the bath. The effect of using multiple electrodes on the amount of graphite required, the resistance of the electrodes, and the operating conditions are considered.

8.2.1.1 Variation of graphite requirements, resistance and inductance of the electrodes due to the use of multiple electrodes.

The flow of current in the electrodes of ac arc furnaces is not distributed uniformly over the whole cross-section of the electrodes due to skin and proximity effects (Dunski, 1962; Bühmann et al, 1963). For example the skin depth in graphite is 0.166 m and electrodes carrying currents in excess of 30 kA are typically 0.61 m in diameter. Single large electrodes could be replaced by arrays of smaller electrodes of equivalent total cross-sectional area to produce a more uniform distribution of current within each electrode, making more efficient use of the conductor. A simplified analysis of this technique indicates potential material savings of up to 20% (Appendix 5).

The resistance and inductance of arc furnace electrodes cause power losses and voltage drops which may be significant at high currents; however, the use of multiple electrodes would only have a marginal effect on the overall resistance since equivalent current-carrying capacity requires an equal total resistance for the multiple electrodes. The ac resistance of n multiple electrodes, diameter d, connected in parallel to replace a single larger electrode, diameter D, is given by:
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Typical Value</th>
<th>Disadvantages</th>
<th>Proposed Solutions</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactance of the supply</td>
<td>2 m Ω - 4 m Ω</td>
<td>Must be minimised in order to obtain high arc currents</td>
<td>Symmetrical arrangement of conductors and busbars</td>
<td>Schwabe, 1976</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Six-electrode arc furnace</td>
<td>Bazeley et al, 1968</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>DC arc furnace</td>
<td>Harry, 1979</td>
</tr>
<tr>
<td>Cost of graphite electrodes</td>
<td>£2200 per section</td>
<td>Graphite is consumed due to spalling, oxidation, erosion at the arc roots and</td>
<td>Refractory coated electrodes</td>
<td>Valchev, 1972</td>
</tr>
<tr>
<td></td>
<td>2.4 m l x 0.6 m D</td>
<td>mechanical fracture</td>
<td>Composite copper/graphite electrode</td>
<td>Zühlner et al, 1976</td>
</tr>
<tr>
<td></td>
<td>(UCAR, 1981)</td>
<td></td>
<td>DC arc furnace</td>
<td>Zühlner et al, 1982</td>
</tr>
<tr>
<td></td>
<td>£7 per tonne of steel produced</td>
<td></td>
<td>Inert furnace atmosphere</td>
<td>Harry, 1979</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Multiple consumable electrodes</td>
<td>Harry et al, 1983</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Multiple non-consumable electrodes</td>
<td>&quot; &quot; &quot;</td>
</tr>
<tr>
<td>Damage to the refractories</td>
<td></td>
<td>Plasma jets (Chap.2)</td>
<td>Use of short arcs (50mm-100mm)</td>
<td>Schwabe, 1976</td>
</tr>
<tr>
<td></td>
<td></td>
<td>damage furnace walls.</td>
<td>Water-cooled side panels</td>
<td>Parkin et al, 1979</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Electrodes mounted towards the centre of the furnace, resulting in poor</td>
<td>Water-cooled roof</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>energy distribution</td>
<td>DC arc furnace</td>
<td></td>
</tr>
<tr>
<td>Flicker</td>
<td>0.25% in the range 1 Hz - 10 Hz</td>
<td>Nuisance to other consumers connected to the supply network</td>
<td>Connect furnaces to the point of common coupling at as</td>
<td>Kirkby et al, 1974</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>high a voltage as possible</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Harmonic filters</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>DC arc furnace</td>
<td>Harry, 1979</td>
</tr>
</tbody>
</table>

Table 6.5: Operating problems associated with high power arc furnaces
\[ R_{ac}(n) = \frac{1}{n} \frac{4\varrho}{\pi d^2} \left(1 + \frac{1}{783} \left(\frac{d}{\delta}\right)^4\right) \Omega/m \quad \text{(after Hammond, 1979)} \] (8.1)

where \( \delta \) is the skin depth (m), \( \varrho \) is the resistivity (5.44 \times 10^{-6} \Omega\cdot m for graphite (Samsonov, 1968)) and \( d \) is determined as shown in Appendix 5.

The value of \( (d/\delta) \) will be less than 3 for the case of replacement of a 0.6 m graphite electrode by multiple electrodes of a smaller diameter, so that the second bracketed term in (8.1) can be neglected, giving:

\[ R_{ac}(n) = \frac{1}{n} \frac{4\varrho}{\pi d^2} = \frac{1}{n} R_{dc} \] (8.2)

which is approximately 90% of the exact value of \( R_{ac}(n) \).

The self inductance of graphite electrodes is also a function of \( (D/\delta) \) such that for \( D >> 2\delta \) the reactance is approximately equal to the ac resistance, and for \( D \leq 2\delta \) the uniform distribution of current across the conductor fixes the inductance at a (lower) constant value. The specific inductance of a homogeneous, non-magnetic conductor such as graphite, due to internal flux linkage produced by current flowing through it, assuming a uniform current density is given by:

\[ L_i = \frac{\mu_0}{2\pi} \int_0^R x^3 \, dx = \frac{\mu_0}{8\pi} = 5.0 \times 10^{-3} \text{ H/m} \] (8.3)

(after Carter, 1962)

The inductance of a graphite electrode 0.6 m in diameter, where \( D/\delta = 3.6 \), lies between the two extremes, however, the use of arrays of multiple electrodes of smaller individual diameters connected in parallel, and individually stabilised, will reduce the overall inductance of the electrodes. For individual electrode diameters of less than approximately 0.33 m, the reactance of each component will become constant at \( 5.0 \times 10^{-3} \text{ H/m} \) so that the overall inductance will be inversely proportional to the number of electrodes. The additional impedances (resistors or inductors) required to stabilise the separate electrodes in each array are likely to increase the overall impedance of the furnace supply above that for single electrodes, thereby outweighing the advantage gained by using multiple electrodes.
8.2.1.2 Problems and limitations associated with the use of multiple electrodes in ac arc melting and smelting furnaces.

Replacement of the individual graphite electrodes used in ac arc furnaces etc by arrays of multiple electrodes has a number of practical disadvantages. Separate raising and lowering mechanisms would be required for each electrode, rather than ganged movements for each group of multiple electrodes, since in the latter case breakage of an electrode would reduce the total arc current. Independent movement of all the electrodes would increase the complexity of the cables and connections and would require more, or larger, holes in the roof of the furnace, resulting in increased heat losses, increased oxidation of the electrodes and weakening of the roof lining.

A number of changes would also be required in furnace operating procedure due to the increased time required to replace worn or damaged electrodes. Melting efficiency is likely to be increased owing to the greater number of arc roots distributed over the surface of the melt, and flicker would be reduced since it is unlikely that all the arcs supplied from a particular phase would be extinguished, or short-circuit, simultaneously, except at current-zero. Variations in the impedances of individual electrodes would reduce the possibility of simultaneous current zero in each phase.

Generally steps are taken to minimise the inductance of the power supply, transformer, busbars and connecting cables, in high power arc furnaces. However, the use of multiple electrodes may require additional series inductances to stabilise the arcs since the individual arc currents would be much lower than in conventional furnaces. The total additional inductance of the system would be comparable with that of a standard furnace, however, because the multiple electrodes would be connected in parallel.

The distance between the electrodes, and hence diameter of the bath, is determined by the separation required to prevent instability due to electromagnetic interaction between the arcs. The magnitude and variation of the current flow, and the forces between the arcs, in a three-phase arc furnace are complex due to the phase difference between the electrodes. Both attractive and repulsive forces may exist because the arcs are connected in series via the bath and two or three arcs may exist simultaneously.
Bath diameters up to 9 m are used in large smelting furnaces incorporating Söderberg electrodes. In a system with a multiple electrode array connected to each phase the parallel arcs within each array will be attracted together. These arrays of separately stabilised electrodes carry the equivalent current of a single electrode, however the physical size and effect of the currents in the multiple electrodes are different so that the repulsive forces between the anti-parallel currents flowing in the other phases are likely to be reduced as a function of \( \frac{1}{n \text{PHASE}} \). This has potential advantages in both arc and submerged arc furnaces, enabling the electrodes to be positioned closer to the side walls in the former case, since spatial stability would be improved, or closer together in the latter case resulting in a smaller diameter bath and increased power density.

Theoretically it is possible to propose multiple electrode arrays with a large number of electrodes per phase in which the forces of attraction between the parallel arcs may be arranged so that some of the arcs within each array would tend to remain separate (Fig. 8.7). Practically, however, more than three electrodes per phase would result in a very complex furnace structure and separate arcs can only be obtained by means of large separations between the electrodes and/or reduced arc currents.

![Diagram](image-url)

**Fig. 8.7:** Forces acting within an array of multiple free-burning arcs connected to one phase of an ac arc furnace,

(a) three electrodes - resultant forces cause the parallel arcs to coalesce,

(b) large number of electrodes - possible balanced forces maintaining separate arcs.
The electromagnetic force of attraction between two parallel arcs is given by:

\[ F = \frac{\mu_0 L_1 I_2}{2 \pi r} \text{ N/m} \]  

(8.4)

and calculations and tests (Chapter 6) have shown that two vertical free-burning arcs, 10 mm apart, each carrying only 10A, coalesce due to a force of 0.002 N/m. In an ac multiple electrode system with three electrodes per phase, each carrying peak currents in excess of 10 kA, the electromagnetic force between the arcs at an arbitrary (practical) separation of 0.5 m would be of the order of 40 N/m, a factor of $20 \times 10^3$ higher. Attraction between the arc columns would tend to increase the arc length and arc voltage, possibly beyond that which could be maintained by the supply, resulting in instability and random extinction of the arcs. However, the stability of arcs increases with current and the effects of plasma jets at the electrodes (Chapter 2) may enable stable operation to be obtained.

In general the use of multiple electrodes in large ac arc furnaces offers theoretical rather than practical advantages over the present system owing to the difficulty of modifying existing furnaces.

3.2.2 Multiple consumable electrodes for use in dc arc furnaces.

Reductions in the price of high power semiconductor rectifiers during the last decade have made the dc arc furnace economically feasible. The rectifiers alone for a 100 MVA furnace would only cost approximately £15,000 (International Rectifier, 1984), although the capital cost of converting a furnace to dc operation is likely to be much higher due to the initial requirement for both ac and dc operation for comparison purposes. DC furnaces would have a number of advantages over those using ac including increased melting efficiency, since the anode roots would always be situated on the bath, and increased arc stability due to the continuous current flow.

DC arc furnaces of up to 15T capacity, rated at 7 MW, using single, centrally mounted, graphite cathodes have been developed (MAN, 1983). The design is reportedly being scaled up to a capacity of 100T and rating of 50 MW, and to even larger furnaces incorporating several cathodes.
It is likely, however, that these furnaces will require separate power supplies for each electrode although no details of the supply configuration have been published.

The Elred process, developed by ASEA in Sweden, uses a 30T dc arc furnace rated at approximately 10 MW in the final reduction of iron ore concentrate with coal. Powdered feedstock is fed into the furnace through a hollow graphite cathode (Stickler, 1982) and the process should be relatively easy to scale up by using larger electrodes and higher currents. However, this configuration is not suitable for melting scrap directly and is only likely to be used as a gas heater similar to the SKF Steel/Westinghouse arc heating system in blast furnaces (Chapter 4).

Generally the use of dc in arc furnaces offers advantages over ac, such as increased melting efficiency. However, the main disadvantage of dc remains in providing a safe, reliable, electrical connection to the bath and methods in use include a conducting hearth in the Elred process (Stickler, 1982) and an air cooled anode (MAN, 1983).

The use of multiple electrodes in dc arc furnaces would result in a number of improvements, including:

(i) increased total current capability;
(ii) improved energy distribution in the bath due to the increased number of arc roots;
(iii) reduced erosion of the electrodes due to lower individual electrode currents. Bowman, (1972) reported that, whilst evaporation of the electrodes was directly proportional to the arc current, the total electrode consumption was not, above a critical current of approximately 30 kA.

In addition, the multiple dc arcs could be operated from separate supplies, provided transformers with matched outputs were available, or from a single supply, thereby reducing capital costs.
8.2.2.1 High-current, free-burning dc multiple arcs.

A series of tests has been carried out to investigate the behaviour of three parallel, free-burning dc arcs between separate graphite cathodes, 12 mm in diameter, and a common graphite anode at currents of the order of 200A - 300A per arc (Fig. 8.8). (This configuration also approximately simulated one half-cycle of operation in one phase of an ac arc furnace equipped with multiple electrodes (8.2.1)).

Fig. 8.8: Operation of multiple, parallel, free-burning dc arcs between three consumable graphite cathodes and a common anode, (a) schematic, (b) in operation.
The power supply circuit, specifically designed for the operation of multiple arc discharges, is shown schematically in Fig. 8.9 and comprises a single 443 kVA transformer with six separate three-phase secondary windings, each rated at 74 kVA, six saturable reactors to limit and control the arc current in the range 100A dc to 350A dc and six three-phase diode bridge rectifiers.

Multiple arcs were initiated by shorting the cathodes directly onto the common anode. Results indicated that, in all cases, as the arc lengths were increased, the arc columns tended to coalesce due to the electromagnetic attraction between the parallel currents and that the arcs became unstable due to shunting and double-arching between the arc columns and distortion due to convection such that one or more arcs were extinguished. The instability was greatest at the smallest separation between the electrodes, corresponding to the highest electromagnetic forces between the arcs, the columns coalescing to produce effectively a 1 kA arc, which has a higher electrical conductivity than the separate arcs and represents a preferred path. The separation between the cathodes was varied over the range 32.5 mm to 90 mm and tests were carried out at a current of approximately 300A per arc to determine the maximum length at which stable multiple arcs could be operated. Tests were also carried out on a single free-burning arc for comparison (Fig. 8.10). In the limiting case, as the electrode separation is reduced to zero, a system with only a single arc will exist (Point A, Fig. 8.10) and only unstable multiple arcs may be operated in the region indicated by the dotted line AB (Fig. 8.10) up to electrode separations of approximately 30 mm. As the electrode separation is increased further, the obtainable arc length will increase, approaching that of a free-burning arc in region C (Fig. 8.10). Stable operation of separate multiple arcs will be possible at large electrode separations although this distance may be impractically large at very high currents. At currents of 300A per electrode, the force between two vertical arcs, 90 mm apart, is of the order of 0.2 N/m which is sufficient to cause the arcs to coalesce. However, at 10 kA per electrode, as required in an industrial arc furnace with three electrodes, for example, the force would be more than 900 times greater at the same electrode separation, and a force of 0.2 N/m could only be obtained at an electrode separation of 100 m, which is impractical. In existing furnaces, the arcs are typically 100 mm long, with the electrodes on a pitch circle diameter of
Fig. 8.9: Schematic of multiple output dc power supply.
(Open-circuit voltage 200V dc, maximum current 350A per arc)
Fig. 8.10: Variation of the maximum length of three stable coalesced multiple arcs with electrode separation at currents of 300A per cathode.
1.6 m (Schwabe, 1976) and the arcs are relatively stable despite the electromagnetic forces, which may be due to the increased stability of high current arcs and the stabilising effects of plasma jets at the electrodes. It is likely, therefore, that stable, high current, multiple dc free-burning arcs could be applied in existing arc furnaces.

8.2.2.2 Application of multiple consumable electrodes in dc arc furnaces.

The technique of operating multiple, free-burning dc arcs from a single power supply can be readily applied to existing ac and dc furnaces. Three main possibilities exist:

(i) conversion of existing three-phase ac furnaces to dc operation by the addition of three sets of stabilising impedances and rectifiers, together with a suitable anode connection to the bath;

(ii) as in (i) together with replacement of each large electrode by an array of smaller diameter electrodes carrying the same total current;

(iii) modification of dc arc furnaces such as those developed by MAN or 3lred to accommodate arrays of multiple electrodes carrying the same total current.

Only the first of these would utilise existing furnace roofs and would result in improved stability and melting efficiency whereas the latter two would also reduce consumption of the electrodes and improve the energy distribution over the bath but would require modification of the furnace roof. The optimum practical number of multiple electrodes in an array is three, since this is the minimum number required for a symmetrical configuration without unduly increasing the mechanical complexity of the system. The position of the electrodes will be a compromise, as in conventional ac arc furnaces, since the separation between the electrodes should be as large as possible to minimise instability. However, this would tend to increase damage to the refractory lining due to radiation from arcs too close to the periphery of the bath.

Use of a conducting hearth, or crucible, in a dc furnace would enable the anode connection to be made above the level of molten metal, which would be safer than an anode inserted through the bottom of the furnace, and tends
to increase arc stability since any interaction between the arc current and the magnetic field produced by current flowing in the hearth or crucible would tend to maintain the anode roots away from the side walls of the furnace (Fig. 8.11).

Results of tests, and discussions on multiple free-burning dc arcs with consumable electrodes have shown the feasibility of the technique for use in large arc melting or smelting furnaces, either in the conversion of existing furnaces to dc operation or in the development of new dc arc furnaces, where advantages such as increased stability, improved melting efficiency, reduced electrode consumption, and improved energy distribution may be obtained.
3.2.3 Multiple non-consumable electrodes for use in dc arc melting and smelting furnaces.

The use of dc plasma furnaces, in which temporally and spatially constrained arcs are established and maintained between plasma torches and a molten bath, for bulk steelmaking and smelting has been described (Chapter 4) and reviewed (Sayce, 1971; Hamblyn, 1977; Aubreton et al, 1978; Rykalin, 1980; Bhat, 1981; Barcza et al, 1981). The largest known plasma furnace has a capacity of 30T and rating of 20 MW (Meyerson et al, 1976) incorporating four water-cooled, inert gas stabilised, plasma torches operating at currents of 7.5 kA each. Scale-up has generally been achieved by using more torches, for example a 100T plasma furnace, incorporating six torches, each carrying 10 kA, is reportedly being developed in the USSR (Bhat, 1981). Increasing the number of torches, however, increases the capital cost and size of the furnace since interaction between the arcs is prevented in order to maintain stable operation (Meyerson et al, 1976).

The maximum operating current of commercially available plasma torches is approximately 10 kA (Foster-Wheeler, 1981; Bhat, 1981) although short term operation of Tetronics torches at 14 kA has been reported unofficially although the cathode lifetime is then only 2–3 hours. These currents are significantly lower than the 30 kA to 40 kA per electrode or higher required in a large arc furnace, and the 100 kA used in submerged arc smelting furnaces.

The high-current plasma torches available today utilise thoriated tungsten cathodes, 10 mm to 12 mm in diameter, and it is possible to propose a compact, for example 100 mm in diameter, non-consumable, dc, multiple cathode assembly of three water cooled cathodes mounted in a common body with a total current capability of 30 kA. Possible areas of application include:

(i) dc arc furnaces, where the use of non-consumable electrodes may reduce the operating cost and would eliminate contamination by the electrodes, particularly carbon pick-up in the melt;

(ii) plasma furnaces, where the increased operating current and ability to operate using a single power supply would allow furnaces with higher power ratings to be developed;

(iii) supplying additional power to conventional ac arc furnaces to increase efficiency and output;

(iv) dc smelting furnaces.
8.2.3.1 Stability of high current, dc, coalesced multiple arcs.

The plasma torches developed in the USSR and by Tetronics are unusual in that they are described as spatially stabilised, but essentially unconstricted arcs (Dresvin, 1977) since the very high temperatures resulting from forced constriction of arcs by a nozzle as in conventional plasma torches are not required in steel melting processes. The aim of the present work is to develop a device of this type, but incorporating three separate cathodes, capable of higher current operation.

A preliminary series of tests was carried out using three initially uncooled, and subsequently water-cooled, thoriated tungsten cathodes to investigate the behaviour of parallel, coalescing arcs at currents up to 350A dc per arc, relevant to the development of a compact, high current, non-consumable multiple electrode assembly. The water-cooled cathodes consisted of tungsten rods, 10 mm in diameter, surrounded by water jackets and were mounted in and insulated from a water-cooled copper body (Fig. 8.12). The tips of the cathodes protruded 1 mm to 2 mm from the front face to facilitate ignition of the arcs using consumable or non-consumable auxiliary electrodes or by short-circuiting the cathodes to a graphite anode. A vortex flow of argon was used to stabilise each arc on the axis of the cathode in a similar way to that used in plasma torches employed in fabrication processes.

Stable operation of three coalesced arcs was obtained at currents up to 50A per electrode with stabilising gas flow rates of 15 l/min per arc. At higher currents, the discharges became unstable, a condition characterised by excessive noise, erosion of the nozzle and extinction of one or more arcs. The instability was attributed to interaction between the gas flows and magnetic fields produced by the arc currents. The electromagnetic forces between the vertical components of current in the three arcs caused the columns to move together such that they were no longer parallel to the axial component of the gas flow surrounding each arc, which tended to maintain the arcs co-axial with the cathodes, so that opposing forces were acting on the arc columns and cathode roots causing instability (Fig. 8.13). Spatial stability was improved by increasing the gas flow rate but progressively higher and higher flow rates were required to overcome the electromagnetic attraction between the arcs as the operating current was increased, for example in excess of 80 l/min of argon per electrode was required at 150A per arc, which was considered to be excessive for a practicable device.
Fig. 8.12: Section through the high-current, non-consumable, multiple cathode assembly (UK Patent Application No. 2,095,490A, 1984)
A second series of tests was carried out using three separate, water-cooled, gas shrouded, thoriated tungsten cathodes to investigate the effects of geometry (angle, symmetry and separation), gas flow rate and magnetic forces on the stability of high current coalescing arcs. Results indicated that the coalesced discharges were always unstable at currents above 150A per arc with the electrodes positioned vertically, almost horizontally, and in linear and trefoil configurations, at gas flow rates up to 80 l/min per arc in atmospheres of air and argon.

Fig. 8.13: Comparison of current and gas flows for single and multiple coalesced arcs.
(a) single arc - no interaction
(b) multiple arcs - attractive force due to vertical components of arc currents causes arcs to move so that current and gas flow are no longer co-axial, leading to instability.

The calculated force of attraction between two arcs carrying currents of 150A at various angles of inclination are shown in Table 8.6. The lowest force is \(1.5 \times 10^{-3}\) N/m, which is comparable to that causing arcs to coalesce at much lower currents (10A) (Chapter 6) although in this case both the current and separation between the arcs were much larger and the magnitude...
of the stabilising effect of the gas flows cannot be readily determined due to MHD effects at the cathode roots and entrainment of some of the gas into the arcs. The coalesced discharges were noisy during operation and the cathode roots were observed wandering randomly over the surfaces of the electrodes, away from the pointed tips, causing shunting and double-arching to the inconel gas shrouds. Stable multiple arc discharges could only be maintained if the arcs remained separate, with vertical electrodes, which occurred at separations in excess of approximately 100 mm at currents of 150A - 170A per arc (Fig. 8.14).

<table>
<thead>
<tr>
<th>Current (A)</th>
<th>Angle of inclination to the vertical</th>
<th>Components of current I_v(A)</th>
<th>I_h(A)</th>
<th>Force of Attraction (N/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>Vertical</td>
<td>150</td>
<td>0</td>
<td>50 x 10^{-3}</td>
</tr>
<tr>
<td>150</td>
<td>45°</td>
<td>106</td>
<td>106</td>
<td>25 x 10^{-3}</td>
</tr>
<tr>
<td>150</td>
<td>80°</td>
<td>26</td>
<td>148</td>
<td>1.5 x 10^{-3}</td>
</tr>
</tbody>
</table>

Table 8.6: Variation of the force between two arcs with the angle between them at a nominal electrode separation of 90 mm.

Fig. 8.14: Stable, separate multiple arcs operating at currents of 150 - 170A per arc, with argon flow rates of 40 l/min per electrode, with arc lengths of 60 mm at an electrode separation of 100 mm.
The electrode configuration with separate gas shrouded arcs arranged in a trefoil was identical to that utilised in the plasma furnace described earlier (8.1) where three stable, coalesced dc arcs were maintained between three water-cooled, gas shielded, tungsten cathodes (the plasma torches) and a common anode (the crucible); with one important difference - the cathodes of the plasma torches were located upstream of constricting nozzles. The three separate cathodes were subsequently modified so that the electrodes were recessed within the gas shrouds by 15 mm and tests showed that three stable coalesced arcs could be operated at currents up to 170A per arc at arc lengths up to 180 mm with stabilising gas flows of 90 l/min of argon per arc in a trefoil arrangement. These tests were carried out in an atmosphere of argon to facilitate easy ignition of the arcs and to improve stability. Tests were then carried out with the electrodes mounted in the water-cooled copper block and results showed that three, stable, coalesced arcs could be maintained at currents up to 350A dc per arc, with gas flows of 30 - 60 l/min per arc provided the cathodes were recessed 15 mm within the common nozzle (Fig. 8.15). The arcs coalesced immediately in front of the nozzle, producing a single 1 kA arc to the anode, and were much quieter than in previous tests, indicating improved stability.

These results indicate that spatial stability of the cathode roots is essential for stable operation of multiple coalesced arcs since with recessed cathodes the vortex gas flows spatially locate the arcs and cathode roots on the axes of the electrodes, preventing movement towards the walls of the nozzle. The arcs only moved off-axis outside the nozzle, where the stabilising effect of the gas was reduced - the resultant component of gas flow being towards the anode (Fig. 8.16). This is in contrast to the earlier case of protruding cathodes where the arc roots were effectively free to move since the gas flows could diverge from the cathodes upstream of the arcs. The behaviour of two coalescing arcs is shown in Fig. 8.16 and the results are also applicable to three arcs. Initially the gas flows and arc columns are parallel between the cathodes and point A (Fig. 8.16(a)), however, the arcs are attracted together by a force proportional to $I_v^2$ (the vertical component of current in each arc) and the arcs move together since the horizontal components of gas flow $G_H$ cancel out leaving a resultant flow towards the anode. Eventually the condition shown in Fig. 8.16(b) is reached in which a balance must exist between the vertical components of gas flow $G_V$ and the force between the arcs proportional to $I_v^2$ (where $I_v' < I_v$). In both cases the arcs within the nozzle remain co-axial with the cathodes.
Fig. 8.15: Stable multiple coalesced arcs with recessed cathodes —
current 350A/arc, argon flow rate per electrode 50-60 l/min,
arc length 55 mm.
Fig. 8.16: Schematic representation of the interaction between arcs and gas flows showing the spatial stability of the cathode roots due to recessed cathodes, (a) first stage of coalescence, (b) resultant stable condition.
8.2.3.2 Design and principle of operation of a high-current, non-consumable, dc arc heater incorporating multiple cathodes.

Stable operation of coalesced multiple arcs at currents up to 350A per arc (8.2.3.1) demonstrated the feasibility of a compact, high-current, non-consumable, multiple electrode assembly and enabled the design of the water-cooled cathodes and the main body of the device, together with the method of operation, to be completed. The torch is shown in its final form in Fig. 8.17, with the water cooling and gas supply systems shown in Fig. 8.18, and the power supply, including power, control, ignition and pilot arc circuits shown in Fig. 8.19.

The cathodes initially consisted of solid thoriated tungsten, 10 mm in diameter, surrounded by a water jacket (Fig. 8.20(a)). However, the tips of the electrodes cracked and spalled due to thermal shock and these were replaced by hollow-bodied cathodes with heat-shrink fitted tungsten tips to allow more effective cooling (Fig. 8.20(b)). The water pipes within the cathodes were designed to produce a high velocity of water flow at the rear of the tungsten tips, resulting in efficient heat transfer from the cathode roots.

The cathodes were electrically isolated from each other and the common body of the whole assembly by PTFE and nylon insulators, which also produced gas-tight seals at the rear of the cathodes.

Passivated cooling water was supplied from a closed-loop system (Fig. 8.18) comprising a 320 litre (70 gallon) reservoir and a multi (20) stage rotary pump with a capacity of 36 l/min at a pressure of 1.65 MPa (240 psi). The measured total flow through the electrodes etc was 20.3 l/min, limited by the constrictions within the device.

The gas system (Fig. 8.18) incorporated variable area flowmeters for the independent measurement and control of the flow of stabilising gas supplied to each cathode, in the range 0–170 l/min of argon, and a large manifold to act as a reservoir. The argon was introduced into the cathode chambers (Fig. 8.17) so as to produce a vortex flow with an axial component in the 2.5 mm wide annular region surrounding the cathodes to stabilise the arcs on the axes of the electrodes.

The power supply (Fig. 8.19) has been described briefly earlier (8.2.2.1) and consisted of a 443 kVA three-phase transformer with six separate three-phase secondaries, each rated at 74 kVA, six saturable reactors to limit and control the arc current in the range 100A to 350A dc,
Fig. 8.17: Schematic section through the high-current, dc, non-consumable, multiple electrode assembly.
Fig. 8.18: High pressure water-cooling and stabilising gas supplies for the high current multiple electrode assembly.
Fig. 8.13: 443 kVA multiple arc power supply showing power, control, ignition and pilot arc circuits.

- S/C/B MC PFC
- 415V, 3Ø
- 415V mains on R
- L 240V 220V
- 240V 220V
- 48V 39A
- 10000uF
- 3 cathodes (bias supply)
- 300pF, 8kV
- nozzle
- 3 cathodes (pilot arc supply)
- hf ignition supply

- E.stops gas MC shunt trip S/V
- H2O gas pressure switches
- MC/aux
- BOC
- plasma supply
- 400V dc o/c
- hf unit

- 200V ac 353A
- anode
- cathode
- 1
- 6 off etc.
- 6
- 5
- 4
- 3
- 2
- 1
- BR1 BR2 BR3 BR4 BR5 BR6
- key switch
- MC

(hf ignition supply)
Fig. 8.20: High current cathodes, (a) solid tungsten and water jacket, (b) hollow copper body with tungsten tip.
and diode bridge rectifiers equipped with transient protection (zenamics, capacitors and ferrite beads) and thermostats interlocked to the control circuit. The secondary windings of the main transformer could be connected in delta or star, for flexibility, giving outputs of 350A/100V or 203A/173V per arc respectively although in this case the delta connection was used throughout. Two supplies could be connected in parallel to each electrode to give an output current capacity of 700A per electrode, 2100A in total. The control circuit included a thermal–magnetic circuit-breaker fitted with a shunt trip (emergency stop), and a contactor (zero-voltage release) interlocked to pressure switches in the water and gas systems to prevent operation of the multiple electrode assembly without cooling water or gas shrouding the cathodes.

It is undesirable and impractical to short-circuit non-consumable electrodes to the bath in a furnace in order to establish an arc in the same way as with graphite electrodes since the electrodes and nozzle would be damaged. In this case, the cathodes were recessed within the nozzle by 15 mm so that drawing arcs between the cathodes and the anode was not possible. Practical considerations also precluded the use of auxiliary starting electrodes and necessitated pilot-arc ignition and arc transfer as in conventional dc plasma torches. Generally this would require separate, insulated nozzles for each cathode but this would be difficult to construct, and in practice a common nozzle, with three HF and pilot arc connections was used. The HF and pilot-arc circuits (Fig. 8.19) both constituted additional multiple discharge systems: simultaneous breakdown and ignition of the three pilot arcs was obtained from a single commercially available high voltage spark oscillator HF unit incorporating capacitive stabilisation of the spark discharges (8.1), and the arcs were operated from a 5.0.0. 400V dc plasma supply which included resistors to stabilise and limit the individual pilot-arc currents to approximately 20A.

Throughout these and earlier tests (8.2.3.1), where the angles between the cathodes were varied over a wide range, the anode consisted of a graphite plate 280 mm x 150 mm x 30 mm and electrical connections were made either

(i) to the periphery of the anode, such that interaction between the vertical component of arc current and the magnetic field produced by current flowing through the anode would tend to move the anode roots of the arcs together (Fig. 8.21(a)), or

(ii) to the centre of the anode, at the point of coalescence of the arcs, where the electromagnetic interaction would tend to move the anode roots apart (Fig. 8.21(b)).
Fig. 8.21: Anode connections, (a) peripheral, (b) central.

No separation or instability at the anode roots was observed, however, for either connection, indicating that the force of attraction between the arcs, proportional to $I_v^2$, predominated.

8.2.3.3 Characteristics of operation of a high-current dc non-consumable multiple arc electrode.

The multiple cathode assembly (8.2.3.2) has been operated at currents up to 400A per electrode, 1.2 kA total, with arc voltages and lengths up to 60V and 125 mm respectively (Fig. 8.22) dissipating powers of approximately 70 kW in atmospheres of argon and air. The arcs transferred to the anode over a maximum distance of 35 mm at individual pilot-arc currents of 20A dc.

A series of tests was carried out to determine the operating characteristics of the device so that its behaviour at much higher currents, for example 10 kA per cathode, may be predicted.
Fig. 8.22: High-current multiple electrode in operation (total current 1.2 kA, arc voltage 60V, arc length 125 mm, argon flow rate 50–60 l/min per arc).
Measurements included the variation of:

(i) arc voltage with arc current at varying arc lengths and constant gas flow rate (Fig. 8.23);

(ii) arc voltage with arc current at varying gas flow rates and constant arc length (Fig. 8.24);

(iii) arc voltage with arc length at varying currents and constant gas flow rate (Fig. 8.25).

The arc voltage/current characteristics (Figs. 8.23 and 8.24) were essentially constant voltage, i.e. horizontal, over the ranges of current and gas flow rate investigated, the voltage only varying with arc length (Figs. 8.23 and 8.25) as expected. At a constant gas flow rate, however, (Fig. 8.23) the characteristics exhibited a slight positive slope, particularly at short arc lengths, which may have been due to vapour or ions emitted from the relatively close graphite anode. At constant arc length (Fig. 8.24) the arcs only exhibited a downward sloping characteristic, similar to that of a free burning arc, at the lowest gas flow rate, indicating that the characteristics of the arcs were affected by the stabilising gas, which imparted a degree of constriction and spatial constraint to the arcs. The variation of arc voltage with arc length (Fig. 8.25) showed no unexpected features and indicated a combined electrode fall voltage \( V_c + V_a \) (Chapter 2) of between 9.5V and 15V deduced from the intercept on the voltage axis.

An energy balance was also carried out by measuring the rise in temperature of the cooling water and results showed an efficiency, defined as:

\[
\text{Efficiency} = \frac{\text{Electrical power input} - \text{losses to the electrodes}}{\text{Electrical power input}} \times 100\% \tag{8.3}
\]

of 80% at an input power level of 55 kW. The losses (11 kW) were consistent with the power input to the cathodes from the fall regions of the arcs, i.e. \( 3 \times V_c \times I \) are assuming a cathode fall voltage of 10V.

The performance of the multiple electrode assembly at the level of current required for use in an arc furnace can be predicted from its characteristics at low currents (Fig. 8.23, 8.24 and 8.25). The arc voltage is essentially independent of arc current at arc lengths in excess of 50 mm (Fig. 8.23) as would be used in arc furnaces. The voltage gradient
Fig. 8.23: Variation of arc voltage with arc current at varying arc lengths and constant gas flow rate.
(Gas flow rate 68 l/min per arc).
Fig. 8.24: Variation of arc voltage with arc current at varying gas flow rates and constant arc length. (Arc length 55 mm).
Fig. 8.25: Variation of arc voltage with arc length at varying currents and constant gas flow rate.
(Gas flow rate 68 l/min per arc).
in the arc column varies in the range 0.8 V/mm to 0.84 V/mm at arc currents up to 360A per electrode (Fig. 8.25) indicating an arc voltage of between 80V and 105V for arc lengths of 100 mm to 125 mm in an argon atmosphere, however, these values do not take account of the effects of metal vapour etc. which would be present in an arc furnace and it is likely that the arc voltage may be three or four times higher in practice. The estimated power output of a multiple electrode assembly operating at a total current of 30 kA is of the order of 10 MW.

8.2.3.4 Scaling-up the dc non-consumable electrode assembly for use in arc furnaces.

The operating characteristics of the multiple cathode assembly (8.2.3.3) indicate that its performance should be very similar at substantially higher currents, however, changes in three areas of its design must be considered:

(i) the total power losses to the three cathodes from the fall regions will increase from 11 kW at arc currents up to 400A per cathode, to 300 kW at 10 kA per cathode, assuming a cathode fall of 10V. This will require a cooling water flow rate of the order of 110 l/min which is more than five times that used at present. The higher flow rate may be obtained by using larger diameter (for example 20 mm) cathodes, with less internal constriction, or a pump operating at a higher pressure. The design of the cathodes may also be improved to provide a larger surface area for cooling behind the tungsten tips.

(ii) the electromagnetic forces of attraction between the arcs will increase by a factor of approximately 900 as the current is increased to 10 kA per cathode from the present value which may cause instability, requiring increased gas flow rates which would increase the running costs. The stabilising effect of the gas could be increased at relatively low flow rates by use of constricting nozzles for the arcs.

(iii) the transfer of arcs over a maximum distance of 35 mm as carried out in this work will be insufficient to prevent damage to the nozzle from molten metal and slag in an arc furnace. Transfer of arcs over greater distances can be achieved by increasing the pilot-arc current, for example conventional plasma torches developed by Arcos (1977) can be operated at currents up to 600A in the non-transferred mode, producing arc lengths up to 100 mm in argon.
8.3 Summary and Conclusions

Investigations have been carried out in two areas of application of multiple arc discharges; (i) a plasma reactor and (ii) arc furnaces, and the results and conclusions are summarised here.

8.3.1 Design and operation of a reactor incorporating multiple plasma torches.

Three plasma torches have been operated in the transferred mode from the same power supply in atmospheres of air and argon using argon as the stabilising gas. The non-transferred pilot arcs and hf ignition system have also been operated from common supplies. This mode of operation has not been described before. Other plasma furnaces incorporating multiple plasma torches (Chapter 4) use separate supplies for each torch. Operation from a single source offers considerable savings in the capital cost of plasma furnaces. The use of coalesced multiple arcs has advantages over furnaces using single plasma torches owing to the increased stability of the anode root and formation of a larger region of high energy intensity in which feedstock can be melted rapidly.

The behaviour of long (300 mm) coalesced arcs between three plasma torches and a common anode has been investigated and the conditions for stable operation are that the torches must be arranged in the furnace with a high degree of symmetry and at such an angle that the point of coalescence of the arcs is on, or closest to, the base of the crucible (anode). In addition, balanced gas flow rates must be used in each torch so that a stable coalesced anode root is established on the crucible.

A furnace incorporating multiple plasma torches operating from a common power supply has been developed from these results and is in use in industry for melting feedstock at temperatures in excess of 1200°C, with a power rating of 100 kW and arc currents of the order of 180 A per torch.

8.3.2 The application of high current multiple electrodes in arc furnaces.

The application of multiple arcs operating from a common power supply in conventional ac and dc arc furnaces has been considered. In both cases the use of multiple electrodes would reduce electrode consumption since the individual electrode currents would be lower, and the increased number of
arc roots on the bath would improve the energy distribution. In ac furnaces the use of multiple electrodes would also reduce the amount of graphite required for a given total current capability by approximately 20%. However, it is likely that these advantages would be outweighed by practical considerations such as increased mechanical and operational complexity.

The dc arc furnace, with consumable graphite electrodes, has become economically feasible and advantages over ac furnaces including reduced electrode erosion, increased stability and melting efficiency have been claimed. At present, existing dc arc furnaces utilise single graphite cathodes but it is likely that dc multiple electrodes will find applications in new, larger, furnaces and in the conversion of existing three-phase ac furnaces to dc operation.

Tests have been carried out to investigate the behaviour of multiple free-burning dc arcs and results indicate that stable separate and coalesced arcs can be maintained at currents of 400 A per arc at arc lengths up to 90 mm. Further work is required in this area to investigate the variation of arc stability with arc length and electrode separation as the currents are increased to the levels required for operation in an arc furnace.

Application of the principles of multiple discharges to dc plasma torches incorporating non-consumable tungsten cathodes has led to the development of a water-cooled, non-consumable electrode assembly which may be suitable for use in arc melting or smelting furnaces. The main advantage of this type of electrode would be elimination of the cost of the electrodes altogether. The stability of high current, inert gas stabilised, arcs was investigated as part of this work and results of an extensive series of tests, together with a consideration of the interaction between the spatially stabilising gas flows and the electromagnetic forces of attraction between coalescing multiple arcs, showed that recessed cathodes were required for stable operation at currents above 100 A per arc. The multiple electrode assembly consists of three water-cooled tungsten cathodes, shielded by argon, mounted in a common torch body only 100 mm in diameter. The device has been operated at currents up to 400 A per electrode, 1200 A total current, dissipating powers of the order of 55 kW, and producing a single coalesced arc up to 125 mm in length stabilised by gas flows of 50 – 60 l/min of argon per electrode. The measured efficiency is approximately 80%. Novel features include a common nozzle for the three
cathodes, multiple hf ignition and multiple pilot-arcs operating from a single auxiliary supply. The operating characteristics indicate that scale-up to higher operating currents should be straightforward, with a theoretical current capability of 30 kA. The compact size of the device may enable the diameter of the bath of large furnaces to be reduced, with a corresponding increase in power density and melting efficiency. Scale up to even higher currents may be achieved simply by increasing the number of electrodes, for example to six for a current capability of 60 kA.

The principles of operation of the plasma reactor and the high current multiple electrode assembly described in this Chapter have been published in the following papers:

(i) 'Power supply design for multiple discharge arc processes',

(ii) 'Multiple arc discharges for metallurgical reduction or metal melting',

(iii) 'High current multiple electrodes for use in arc furnaces',
CHAPTER 9

DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS
This thesis is a study of the theory of operation, behaviour and applications of multiple electric arc discharges, supplied from a common power source, operating in close proximity to each other so that the arc columns interact.

Stable separate and coalesced multiple arcs have been operated from a common power supply. The conditions for the stable operation of multiple parallel arcs have been determined by investigating the behaviour of separate and coalescing parallel arcs. Tests have been carried out using a pair of vertical free-burning arcs, stabilised by resistors, between graphite electrodes in air at atmospheric pressure at currents of the order of 10A per arc to determine how the magnitude and position of the stabilising resistors relative to the arcs affected the stability. Coalescing arcs stabilised on one side only, either adjacent to the anodes or cathodes, produced stable three-root discharges since one of the arc roots on the opposite side of the coalescing region to the stabilisation was extinguished due to the negative dynamic resistance of the arc. Stable coalesced discharges with multiple anodes and multiple cathodes could only be maintained when the stabilisation was equally distributed on both sides of each arc, which effectively provides electrical isolation between all the arc roots of the same polarity and prevents the formation of preferential conducting paths. The stability of separate parallel arcs operating from a common supply was not affected by the position of the stabilising resistors provided each arc was individually stabilised. These results also indicated that stable arcs could be maintained under conditions where the ratio of open-circuit voltage to arc voltage varied over the range from 4:1 to less than 1.5:1, the latter being significantly lower than the ratio of 2:1 normally considered necessary for stability. The behaviour of coalescing arcs has been considered as an unbalanced Wheatstone bridge and analysed using a computer. Results indicated that, for coalescing arcs, each resistor stabilised the arc root and part of the arc column between the respective electrode and the region of coalescence, showing, for example, that a six-root coalesced discharge would require six stabilising resistors. These results are relevant to a number of industrial processes including plasma and arc melting furnaces incorporating multiple cathodes and a common anode, and for the production of large volumes of ionised gas, for processing particulate material, utilising multiple anodes and cathodes. Investigations have been carried out in these areas.
A unique high-power multiple arc dc plasma torch or non-consumable electrode assembly incorporating three water-cooled, inert gas shielded, tungsten cathodes operating from a common supply, mounted in a 100 mm diameter body and recessed within a common nozzle, has been designed and developed. The device has been operated at total currents up to 1.2 kA, dissipating powers of the order of 55 kW, with stable coalesced arcs up to 125 mm long. Novel features include a common nozzle for the three cathodes, three separate pilot arcs operating from a single auxiliary supply and simultaneous ignition of three arcs using a single high frequency (hf) spark oscillator. This type of arc heater is potentially capable of operation at total currents up to 30 kA, with a power rating of 10 MW, and its characteristics at currents up to 400A dc per cathode indicate that scale-up to these levels should be straightforward.

Industrial applications include plasma furnaces, in which higher power ratings may be achieved, and as a non-consumable electrode replacing the graphite electrodes in arc furnaces supplied with dc. Potential advantages over conventional ac and dc arc furnaces include increased stability, increased melting efficiency, operation of furnaces with inert atmospheres, reduced contamination of the melt, reduction of the diameter of the bath resulting in an increased power density, reduction of electrode costs, and reduced capital costs of the power supplies for new furnaces.

A prototype industrial plasma furnace, rated at 50 kW, incorporating three dc plasma torches carrying currents of approximately 100A per torch in the transferred mode, connected to a common power supply has been designed, built and tested. The torches produced coalesced arcs up to 230 mm long in a pure argon atmosphere with a stable anode root on the base of a conducting crucible. This mode of operation has not been described before. Novel features include the simultaneous ignition of three pilot-arcs using a single hf unit, the use of a consumable starting electrode to facilitate transfer of the arcs over long distances and the generation of a large volume region of very high intensity where rapid melting of feedstock can occur. Initial melting trials have been carried out at temperatures up to 1100°C and the system has subsequently been uprated to 100 kW with arc currents of 180A per torch, and has been in operation in industry for three years, processing materials at 30 kg/hr.

Large volume coalesced multiple arc discharges up to 30 mm in diameter have been produced in air at atmospheric pressure by a horizontal discharge system incorporating six pairs of graphite electrodes, each
carrying currents in the range 10A to 20A dc, and dissipating total powers up to 18 kW. The uniformity of the discharges has been investigated by single-exposure photography, a conducting paper analogue and a spectroscopic method. Electrode configurations with the anodes and cathodes grouped together produced diffuse discharges which apparently filled the central region between the electrodes. The variation in intensity across the discharges has been determined spectroscopically, and in the preferred arrangement of the electrodes the intensity varied by only 17.7% from the peak value across a region approximately 20 mm in diameter, compared with variations of up to 90% for other configurations and an approximately Gaussian intensity distribution for a single arc. The spectroscopic technique used to determine the intensity distributions of the large volume coalesced multiple arc discharges is based around a commercially available scanning monochromator which enables complete spectra in the range 300 nm to 1100 nm to be displayed on an oscilloscope, and the variation of the relative intensity of any spectral line within this range to be measured and recorded. Measurements were carried out on the horizontal multiple arc discharges at a wavelength of 418 nm, corresponding to the molecular band spectrum of Cyanogen which is emitted by arcs between graphite electrodes in air. This spectrum was identifiable in the radiation emitted by all the discharge configurations. A high degree of repeatability between the spectra indicated the existence of temporal stability within the discharges. A mechanical traverse, collimator and flexible fibre-optic light-guide were used to spatially scan the discharges. The high degree of uniformity obtained over a relatively large diameter arc discharge indicated the suitability of a horizontal discharge reactor for heating gas or processing particulate material with potential advantages including uniform heating, high throughputs and reduced temperature gradients. A larger version of this type of heater including a power supply featuring continuously variable arc current and a water-cooled reactor assembly has been designed at the University and built by Plasma Systems Ltd. The equipment has been installed in the Metallurgy Department at Cambridge University and will be used for carrying out chemical and metallurgical reactions in a fluidised bed. The system is rated at 50 kW, with typical arc currents and voltages of 50A and 120V respectively, and produces discharges up to 150 mm in diameter in an argon atmosphere. The discharges remain diffuse and have not shown any tendency to contract into a single arc, and are spatially stabilised in the plane of the electrodes against the effects of convection by a dc magnetic field.
The application of multiple graphite electrodes in existing ac or dc arc melting and smelting furnaces has been considered. Replacement of a single 0.6 m diameter (> 30 kA) graphite electrode in one phase of an ac arc furnace by multiple electrodes with the same total current carrying capacity would result in a 20% reduction in the amount of graphite required owing to poor utilisation of the available cross section in the large electrode due to skin effect. Other potential advantages include reduced electrode erosion and an improved energy distribution over the bath, however, the technique would be too complex mechanically for use in three phase furnaces, since modification of the furnace roof and additional stabilising inductors would be required. Instability may also occur due to electromagnetic attraction between the parallel arcs connected to each phase. The technique may be applicable to small ac arc furnaces or dc arc furnaces which incorporate single electrodes at present.

Several other important investigations have been carried out during this work which may have already been embodied in the work described above. However, these may also be relevant to other arc processes and are summarised here.

The behaviour of coalescing high current free-burning and gas stabilised arcs has been investigated, including a study of the interaction between electromagnetic forces and gas flows. High frequency arc ignition units with multiple capacitively stabilised outputs have been developed for use with multiple plasma torches etc. Multiple output dc power supplies rated at up to 443 kVA have been designed and built for the operation of multiple coalesced arcs.

Reviews of the theory of arcs, plasma devices and measurement techniques applicable to arcs have been carried out. The review of arc processes includes the relevant theoretical aspects of free-burning arcs at atmospheric pressure such as details of the arc roots and arc column, the electrical and thermal characteristics of arcs and the requirements for stability. The section on multiple arcs contains a unique review of previous work in this area, and indicates that applications of multiple arcs have generally been limited to welding, using separate ac or dc supplies for each arc. A review of measuring techniques applicable to arcs has been carried out with particular reference to the determination of the uniformity or temperature distribution of large volume horizontal
coalesced arc discharges. Electrostatic and magnetic probes were excluded since they disturb the discharges and only non-contact methods including photography and spectroscopy were considered in detail. The effects of persistence of luminosity have also been considered. An up-to-date critical review of high power industrial and scientific plasma processes has been carried out in order to examine potential applications of multiple arcs in this area. Laboratory size plasma devices, which are often difficult to scale up, have been specifically excluded from this review. Existing plasma processes have been considered in terms of their principles of operation rather than the actual process or products and includes arcs used for chemical synthesis, commercially available dc plasma torches, plasma furnaces for melting, arc heaters for re-entry simulation including the use of multiple electrodes, and magnetically rotated arc heaters. An annotated bibliography of selected reviews of plasma processes, together with papers and patents on multiple arc discharges has also been compiled and is presented in Appendix 1.
The main achievements of this work can be summarised as follows.

(i) stable operation of separate and coalesced multiple arcs from a single power supply;

(ii) determination of the conditions for the stable operation of multiple arcs from a common power supply;

(iii) design and development of a high current (1.2 kA) plasma torch or non-consumable electrode, incorporating three tungsten cathodes, potentially capable of carrying currents up to 30 kA, and the associated power supply, pilot-arc and hf ignition systems;

(iv) design and development of a prototype plasma furnace rated at 50 kW incorporating three dc plasma torches, operating in the transferred mode from a single power supply, producing coalesced arcs up to 230 mm long;

(v) production of a large volume coalesced horizontal multiple arc discharge up to 30 mm in diameter, with a variation in uniformity of only 17% from the peak value, suitable for gas heating or processing particulate material;

(vi) development of a spectroscopic method for determining the uniformity of large volume coalesced multiple arc discharges;

(vii) design and construction of power supplies rated at up to 443 kVA with up to six separate outputs;

(viii) simultaneous ignition of multiple arcs using a single hf unit;

(ix) compilation of an annotated bibliography of selected reviews of plasma processes together with papers and patents on multiple arcs.
As a consequence of the work carried out and the results obtained, the following recommendations for further work can be made.

(i) High current dc plasma torch or non-consumable electrode assembly.
   (a) testing of individual cathodes at currents up to 10 kA.
   (b) scale up operating current to 30 kA using three cathodes, and higher currents using a larger number of cathodes.
   (c) optimisation and adaptation of the design for use in the harsh environment of an arc furnace.

(ii) Horizontal multiple arc discharges.
   (a) investigation of the variation of uniformity with the number of electrodes used, for example three pairs or four pairs, to determine the optimum number required.
   (b) an accurate measurement of the temperatures of the discharges in atmospheres of air and argon by comparing the relative intensities of appropriate spectral lines with a standard source such as a tungsten ribbon lamp.
   (c) replacing the graphite electrodes by water-cooled, gas shielded, tungsten cathodes and copper anodes.
   (d) scale up to higher operating currents, for example 400 A dc per pair of electrodes.
   (e) design and construction of a plasma reactor for heating gas or processing particulate material.

(iii) Multiple consumable electrodes for use in ac arc furnaces.
   (a) a more extensive study of skin and proximity effects in graphite electrodes carrying currents up to 30 kA, including a study of the effects of introducing multiple electrodes on the total reactance of the supply.
   (b) a study of the variation of the electromagnetic forces between multiple parallel arcs and the maximum attainable arc length with the number of electrodes and arc current for different electrode separations and configurations. Only three cases were investigated in this work.
(iv) Other areas.

(a) a general investigation of electrode configurations and the behaviour of systems in which the forces between anti-parallel arcs would cause the arc columns to repel each other and an assessment of the feasibility of this type of discharge for use in lamps etc. where coalescence of the arcs may be undesirable.

(b) an investigation of the range of the ratio of open-circuit voltage to arc voltage over which stable separate and coalesced arcs can be operated.

(c) a study of electrode configurations suitable for the production of a three-dimensional coalesced arc discharge.
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APPENDIX 1

An annotated bibliography of literature relevant to the theory and applications of electric arcs and arc heaters.

The major sources of information concerning the theory and applications of electric discharges in general, and high pressure atmospheric (arc) discharges in particular are listed in terms of key books, reviews and patents. A section has also been included on multiple electric discharges due to their specific relevance to this thesis.

Monographs and Books

   (Monograph on electric arcs. First major textbook, includes mathematical representation of the arc characteristics etc).

   (Text on ionisation and transport processes etc. in electric discharges).

   (Text on the theory of arc discharges).

   (General text on electric discharges with particular emphasis on low pressure discharges).

   (Text describing the theory of mercury vapour discharges).
(Text on electrical breakdown phenomena including ionisation etc).

(Standard text including the theory of glow and arc discharges and ionisation processes).

(Monograph on theory and applications of vacuum and inert gas arcs).

(Text on the physics of ionisation processes etc. occurring in electric discharges).

(Standard text on discharges, including the theory of glow and arc discharges, ionisation etc. and a section on stability).

(Text on the design of circuit breakers and high current contacts. Also includes information on electrode erosion).

(Important monograph on electric arcs. Summarises arc theory up to 1957 and includes sections on the arc column, transition regions and methods of establishing arcs).

(General physics text on plasma. Includes kinetic theory and sections on electric discharges and plasma torches).
(Important source of information concerning Eastern European and Russian plasma technology. Also includes details of Western arc heaters and processes and an extensive theory section).

(General text on electric arc discharges at low and high pressures including the electrode regions, the arc column and stability).

(Introduction to the physics and theory of electric discharges - corona, glow, and arc).

(Recent text including details of Russian high-current plasma devices and induction-coupled discharges, and an extensive section on the energy balance in electric arcs).

(Recent text on electric discharges - corona, glow, and arc. Also includes details of applications).
Reviews, Conference Proceedings, Patents etc.


8) John, R.R., and Bade, W.L., 'Recent advances in electric arc plasma generation technology', ARS Journal, Vol. 31, No. 1, pp 4-17, 1961. (Review of arc processes used for chemical synthesis, processing refractory materials, re-entry simulation, high temperature research, and space propulsion. Includes survey of factors affecting the performance of arc heaters such as convection and radiation losses, electrode and column processes and the effects of magnetic fields.)

9) Skifstad, J.G., 'Summary of published literature concerned with electric arc phenomena pertinent to plasma jet devices', AD 286 366, US Dept. of Commerce, distributed by Clearinghouse for Federal Scientific and Technical Information, 1962. (Extensive review of electric arc theory and characteristics including free-burning and constricted arcs and a comparison between the two.)

10) AGARDGRAPH, 'Arc heaters and MHD accelerators for aerodynamic purposes, Vol. 84, Parts 1 and 2, Special meeting NATO advisory group for aeronautical research and development, 1964. (Set of specially commissioned papers on re-entry type arc heaters and related devices. Some applications of multiple electrodes proposed.)

12) AVCO Corp. Report 'Experiments to establish current-carrying capacity of thermionic-emitting cathodes', AVSSD-0043-67-RR, for NASA, Ames Research Centre, Moffett field, Cal., USA, 1967. (Extensive report on a series of experiments on thermionic cathodes carrying currents up to approximately 1500A. Relevant to the design of cathodes for high-current plasma torches similar to those developed by Tetronics and Freital).


15) Brown, R.L., Everest, D.A., Lewis, J.D. and Williams, A., 'High-temperature processes with special reference to flames and plasmas', J.Inst.Fuel, pp 433-439, Nov. 1968. (Review of flames and plasma heating systems for high temperature processes including thermodynamic considerations; heating techniques such as preheated flames, plasma jets, and augmented flames; and applications such as chemical synthesis, extractive metallurgy and spheroidising etc).
16) Ludwig, H.C., 'The plasma jet in chemical processing', Instruments and Control Systems, Vol. 41, pp 81-88, 1968. (Review of the application of electric arcs in chemical processing, including a summary of arc physics, the design of arc heaters, energy balances and problems which may be encountered).


19) Guile, A.E., 'Arc-electrode phenomena', Proc.IEE, IEE Reviews, Vol. 118, pp 1131-1154, 1971. (Extensive review of the characteristics of the electrode regions of arcs, including a discussion of thermionic and non-thermionic cathode emission processes (field emission). Applications such as mercury arc rectifiers, gas blast circuit-breakers, arc welding, arc heaters and plasma torches are also described).

20) Sayce, I.G., 'Advances in extractive metallurgy and refining', Inst. of Mining and Metallurgy, London, 1971. (Review of developments in plasma technology relevant to extractive metallurgy. Includes details of laboratory and industrial scale arc heaters and processes such as ore benefication, chlorination, reduction, melting and refining).
(Review of plasma techniques, including heat and mass transfer considerations for the treatment of powdered feedstock in processes such as spheroidising, plasma spraying and extractive metallurgy).

(Review of the design, operation and applications of flame and plasma reactors for processing materials. Commercial processes for the manufacture of acetylene, carbon black, etc. are described together with the designs of high power arc heaters such as the Ionarco reactor).

(as for No. 20 by the same author. An updated version).

(Recent review of the technology for plasma generation and plasma furnaces with particular reference to extractive metallurgy and refining using high power (>1MW) arc heaters).

(Recent review of plasma technology which describes laboratory size arc heaters and some of the larger industrial units, together with a brief discussion of extractive metallurgy).

(Recent brief review of plasma processes including discussion of heat transfer in plasma furnaces).
(Extensive review of Russian and Western arc plasma generators, high frequency generators, plasma reactors and plasma arc furnaces and their application to the recovery of metals, remelting, processing powders and chemical syntheses. Includes details of electrode configurations for operation at currents above 1000A).

(Review of plasma torch applications including welding, cutting, spraying, extractive metallurgy and chemical synthesis. Includes all well known industrial installations).

(Extensive, recent review of methods of plasma generation - arcs, plasma torches and plasma furnaces including systems with multiple torches operating from separate supplies).

(Describes disadvantages of conventional submerged arc furnaces and potential advantages of using plasma. Gives details of major plasma installations in use).

(Recent superficial review of the theory of plasma processes, including brief descriptions of the major high-power plasma installations in operation today such as SKF Steel, Freital, Bethlehem Steel and Tetronics).

Multiple electric discharges

(1) Published papers


9) Anon, 'Multiple electrode TIG welding', Welding and Metal Fabrication, pp 269-271, May 1975. (Multiple welding arcs operated initially using individual stabilising resistors, but subsequently separate thyristor controlled power supplies for each arc).

10) Brown, K.W., 'Commutated current multiple arc welding', Welding Institute Research Report P/70/75, Welding Institute, July 1975. (Two adjacent dc welding arcs connected to anti-phase transformer windings to reduce magnetic interaction between the arcs. Continuous low current pilot arcs operate from a common power supply incorporating individual stabilising resistors).


13) Hinkel, J.E., and Forsthoefel, F.W., 'High current density submerged arc welding with twin electrodes', Welding Journal, pp 175-180, March, 1976. (Two coalesced arcs apparently maintained between two electrodes (without individual stabilising impedances) and a common workpiece. Stabilisation is probably provided by the series resistance of the electrodes).


(Description of the development and operation of a high pressure arc heater incorporating two cathodes carrying currents of the order of 1000A).

(Multiple coalesced dc arc discharge produced between six anodes and six cathodes using separate power supplies for each pair of electrodes).

(as reference 18).

(High pressure (10 MPa) multiple arc discharge investigated. Unsubstantiated results indicate that the arc roots oscillate between the electrodes at high frequencies).

(Describes high power (60 MW, 5400A) re-entry arc heater incorporating six anodes and six cathodes to reduce electrode erosion. The arcs are individually stabilised using resistors).
(The conditions for the stable operation of multiple coalesced arc discharges from a common power supply are described).

(The principles described in 18,19 and 22 are applied to glow discharges used to excite CO₂ lasers, producing increased power per unit length of discharge, reduced erosion of the electrodes and increased beam diameter).

(As reference 23).

(Sandall patent (reference 8) not granted since prior art reportedly showed all the relevant features although no single reference showed all the features).

(Work on multiple electrodes reportedly being carried out to increase the current capability of dc plasma torches).

(The application of multiple arcs to the production of large volume discharges and plasma furnaces is described).

(The principles of multiple arcs are described together with applications including large volume discharge reactors, ac and dc arc melting and smelting furnaces, and plasma furnaces incorporating multiple plasma torches).
(Results of measurements of the uniformity of the discharges described in 18 and 19, and in Chapter 7).

(Describes use of multiple electrodes in ac and dc arc furnaces, and in particular the development of a high-current non-consumable multiple electrode assembly as described in Chapter 8).
(ii) **Patents**

1) Schmidt, F., 'Improvements in and relating to alternating current arc welding apparatus', British Patent No. 220,840, 1924. (Separate arcs operated from separate supplies in a similar configuration to a direct arc furnace).

2) Zack, M., 'Improvements in or relating to arc welding', British Patent No. 280,558, 1928. (Multiple welding arcs operated from separate transformer windings with individual stabilisation).

3) Siemens Electric Lamps and Supplies, 'Improvements relating to high pressure metallic vapour electric discharge lamps', British Patent No. 476,818, 1937. (Two coalesced arcs operated from separate, phase shifted power supplies).

4) General Electric Co., 'Improvements in or relating to high-pressure metal vapour electric discharge lamps', British Patent No. 486,768, 1938. (Multiple (2 or 3) arcs operated from separate supplies. Operation from common supply described. Use of distributed stabilisation implied but the benefit is not described).

5) General Electric Co., 'Improvements in combinations of a high-pressure mercury-vapour lamp and circuit elements adapted to operate it', British Patent No. 523,377, 1940. (Two coalesced, high pressure (35 Atm), phase shifted discharges operated from a common power supply).

6) Westinghouse Brake and Signal Co., 'Improvements relating to electric welding apparatus', British Patent No. 583,708, 1946. (Describes the operation of separate, individually stabilised arcs from separate transformer windings).
7) Union Carbide, "Multiple electrode polyphase arc welding", British Patent No. 695,897, 1953. (Two separate and coalesced arcs operated from separate transformer windings).

8) Manufactures des Glaces et Produits Chimiques de Saint-Gobain SA, Chauny and Cirey, "Improvements in or relating to the manufacture of hydrocyanic acid by electrical discharge", British Patent No. 832,946, 1960. (Multiple coalesced discharges to a common electrode operated from separate power supplies).


11) British Iron and Steel Research Association, "Improvements in or relating to electric arc furnaces", British Patent No. 974,444, 1964. (Operation of six arcs, in three pairs described. Arc currents in each pair flow in opposite directions due to the use of anti-phase transformer windings connected in double star or double delta).

12) Union Carbide, "Improvements in or relating to systems for supplying electrical power to metallurgical arc furnaces", British Patent No. 1,113,448, 1968. (Describes multiple spatially stabilised arcs operating from separate power supplies).
(Plasma melting furnace incorporating multiple plasma torches operating from separate power supplies described).

(Arc between two dc plasma torches operating from separate power supplies described).

(Description of a three phase arc furnace power supply with a dc supply connected in parallel to eliminate extinction of the arcs at ac current zero).

(Coalesced dc arcs operated from three plasma torches connected to separate power supplies).

(Description of series arcs operating from common and separate power supplies).

(Description of the operation of three separate arcs from three separate, mutually phase-shifted power supplies).
   (Method of operating two separately stabilised welding arcs from a common dc power supply described. The arcs occur during opposite half-cycles of the mains supply and are not simultaneous).

   (Describes operation of separate multiple arcs from a multiphase power supply).

21) Institut Elektrosvarki Imeni EO Patona Akademi Nauk Ukrainskoi SSR,
   (Description of plasma torch with two arcs - to the cathode and nozzle - supplied from separate power sources).

   (Description of multiple ac welding arcs operating from separate transformer windings).

23) Harry, J.E., 'Generating a plurality of electric discharges',
   (Embodiment of all the work in this thesis, including application of multiple discharge techniques to lamps, gas lasers, spark plugs and plasma torches).
Simultaneous equations can be solved using determinants and Cramer's Rule but the solutions can become complex and laborious when the equations contain more than three unknowns since the method requires fourth (and higher) order determinants to be evaluated.

The procedure for solving \( n \) equations and evaluating \((n \times n)\) determinants can be described as follows:

A set of \( n \) linear equations can be written:

\[
\begin{align*}
    a_{11}x_1 + a_{12}x_2 + \cdots + a_{1k}x_k + \cdots + a_{1n}x_n &= K_1 \\
    a_{21}x_1 + a_{22}x_2 + \cdots + a_{2k}x_k + \cdots + a_{2n}x_n &= K_2 \\
    \vdots \quad \vdots \quad \vdots \quad \vdots \quad \vdots \\
    a_{n1}x_1 + a_{n2}x_2 + \cdots + a_{nk}x_k + \cdots + a_{nn}x_n &= K_n
\end{align*}
\]

If \( \Delta \) is the \( n \)th order determinant formed by writing the coefficients \( (a_{ij}) \) of the unknowns \( (x_i) \) in the same order as they appear in the original equations and \( \Delta_k \) is the determinant derived from \( \Delta \) by replacing the elements of the \( k \)th column by the \( k \)th column (in the correct order) then, provided \( \Delta \neq 0 \)

\[
    x_1 = \frac{\Delta_1}{\Delta}, \quad x_2 = \frac{\Delta_2}{\Delta}, \quad \cdots \quad x_k = \frac{\Delta_k}{\Delta}, \quad \cdots \quad x_n = \frac{\Delta_n}{\Delta}
\]

and the unknowns can be evaluated (Cramer's Rule).

An \( n \)th order determinant consists of \( n \times n \) coefficients (or elements) arranged in a square array of \( n \) rows and \( n \) columns such that:
The minor \((D_{ik})\) of an element \((a_{ik})\) of \(\Delta\) is the determinant formed by deleting the elements of the \(i\)th row and \(k\)th column of \(\Delta\). The cofactor \((\Delta_{ik})\) of an element \((a_{ik})\) is the signed minor such that

\[
\Delta_{ik} = (-1)^{i+k} D_{ik} = D_{ik} \text{ if } i+k \text{ is even}
\]
\[
= -D_{ik} \text{ if } i+k \text{ is odd},
\]

and consequently depends on the position of the element within \(\Delta\). The numerical value of a determinant is the sum of the products of the elements and their respective cofactors taken along a given row or column of \(\Delta\):

\[
\Delta = \sum_{k=1}^{n} a_{ik} \Delta_{ik} \quad \text{(expanding along the \(i\)th row)}
\]

\[
\Delta = \sum_{i=1}^{n} a_{ik} \Delta_{ik} \quad \text{(expanding along the \(k\)th column)}
\]

The minor of any element in a fourth order determinant is a third order determinant for which the minor of any element is a second order determinant which can be evaluated easily. The analysis of parallel coalescing arcs (chapter 6) involved the evaluation of fourth order determinants but the occurrence of several zeros in the circuit equations simplified the solutions. For example:
\[ \begin{align*}
\text{AI}_1 + \text{BI}_1 &= 0 + 0 = V \\
0 + 0 + \text{CI}_2 + \text{DI}_2 &= V \\
0 + \text{BI}_1 + (C+E)\text{I}_2 - \text{BI}_2 &= V \\
\text{I}_1 - \text{I}_1 + \text{I}_2 - \text{I}_2 &= 0
\end{align*} \]

\[ (6.8) \quad (6.9) \quad (6.10) \quad (6.11) \]

giving
\[ \Delta = \begin{vmatrix}
A & B & 0 & 0 \\
0 & 0 & C & D \\
0 & B & (C+E) & -E \\
1 & -1 & 1 & -1
\end{vmatrix} \]

Expanding about the first column, which contains two zero elements
\[ \Delta = A \begin{vmatrix}
B (C+E) & E \\
-1 & 1 & -1
\end{vmatrix} + 0 \begin{vmatrix}
0 & C & D \\
-1 & 1 & -1
\end{vmatrix} \]

\[ \begin{vmatrix}
0 & C & D \\
-1 & 1 & -1
\end{vmatrix} = \begin{vmatrix}
(C+E) & -E \\
1 & -1
\end{vmatrix} - B \begin{vmatrix}
C & D \\
1 & -1
\end{vmatrix} + \begin{vmatrix}
0 & C \\
B (C+E) & -E
\end{vmatrix} \]

\[ = -B(-C-D) -1(-CE - D(C+E)) \]

\[ = (BC + BD + CE + CD + DE) \]

and
\[ \begin{vmatrix}
B & 0 & 0 \\
0 & C & D \\
B (C+E) & E
\end{vmatrix} = \begin{vmatrix}
C & D \\
B & -E
\end{vmatrix} + 0 \begin{vmatrix}
0 & C \\
B (C+E)
\end{vmatrix} \]

\[ = B(-CE - D(C+E)) \]

\[ = (-BCE - BCD - BDE) \]

So
\[ \Delta = A(BC + BD + CE + CD + DE) - 1(-BCE - BCD - BDE) \]

\[ = AC(B + E + D) + AD(B + E) + BC(D + E) + BDE \]
APPENDIX 3

Computer Program for the Solution of the Ayrton Equation

The static behaviour of a section of two coalescing arc columns was investigated as part of the analysis of parallel coalescing arcs (chapter 6). The static voltage/current characteristic of an arc is described by the Ayrton equation (chapter 2). A simple computer program was used to determine this characteristic for comparison with the dynamic characteristics of the same region of the arcs (chapter 6).

Consider the Ayrton equation

$$V_a = A + Bx + \frac{C + Dx}{I}$$

where $V_a$ is the arc voltage (V), $I$ is the arc current (A), $x$ is the arc length (mm), and $A$, $B$, $C$ and $D$ are constants which are tabulated in the literature (for an arc between carbon electrodes in air $A = 38.9$, $B = 2$, $C = 16.6$, and $D = 10.5$ (Cobine, 1958)). For an arc 5 mm in length

$$V_a = 38.9 + (2 \times 5) + \frac{16.6 + (10.5 \times 5)}{I}$$

$$V_a = 48.9 + \frac{69.1}{I}$$

Now, let $I = V_a/R_a$, where $R_a$ is the resistance of the arc, so that

$$V_a = 48.9 + \frac{69.1 R_a}{V_a}$$

$$V_a^2 = 48.9 V_a - 69.1 R_a = 0$$

which is of the form

$$ax^2 + bx + c = 0$$
having the general solution

\[ x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \]

giving

\[ V_a = 24.45 \pm \sqrt{597.8 + 69.1 R_a} \] (take the + root)

The computer program was designed to calculate:

(i) the arc voltage \( V_a \), according to the above equation which defines the arc characteristic in terms of the arc voltage and arc resistance, from a specified value of arc resistance obtained from experimental data or published literature,

(ii) the arc current \( I = V_a/R_a \).

A typical value of resistance for a 5 mm long arc was 4.4 \( \Omega \) and the computer calculated values of \( V_a \) and \( I \) for values of \( R_a \) between 0.1 \( R_a \) (nominal) and 10\( R_a \) (nominal), i.e. over the same range of variation as the dynamic characteristics.
The program listing is as follows:

```
WRITE (1,900)
900 FORMAT ('ENTER RARC')
READ (1,*) RARC
WRITE (1,200) RARC
200 FORMAT (1H,1E12.4)
DO 100 I =1, 100
   RX = 0.1 * I * RARC
   VARC = 24.45 + SQRT (597.8 + 69.1 * RX)
   CIARC = VARC/RX
WRITE (1,300) RX, VARC, CIARC
WRITE (5,400) CIARC, VARC
300 FORMAT (1H, 3E12.4)
400 FORMAT (2 (F7.3, 2X))
100 CONTINUE
STOP
END
```
## APPENDIX 4

**Specification of Scanning Monochromator used to Investigate the Intensity Distributions of Multiple Arc Discharges**

### BASIC MONOCHROMATOR

**OPTICAL (6000)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffraction grating</td>
<td>1200 lines/mm blazed at 300 nm</td>
</tr>
<tr>
<td>Optical configuration</td>
<td>Side by side Ebert</td>
</tr>
<tr>
<td>Slit height</td>
<td>5 mm</td>
</tr>
<tr>
<td>Slit bandwidth</td>
<td>2, 5, 10 or 20 nm bandpass</td>
</tr>
<tr>
<td>Maximum optical bandwidth error with slits fixed to monochromator</td>
<td>-0.5 nm + 3.5 nm (all slits)</td>
</tr>
<tr>
<td>Useable wavelength range of monochromator and silicon detector</td>
<td>300 nm - 1100 nm (with wavelength marker unit (6001))</td>
</tr>
<tr>
<td>Wavelength measurement accuracy</td>
<td>±0.5 nm (with wavelength marker unit (6001))</td>
</tr>
<tr>
<td></td>
<td>± 3 nm in range 400 nm - 700 nm (using oscilloscope scale)</td>
</tr>
<tr>
<td>Input/output beam angle</td>
<td>f/6 nominally. Optical axes of input and output beams inclined at 6° to the slit plate normal.</td>
</tr>
<tr>
<td>Spectral scan repetition period</td>
<td>94 ms - 95 ms nominally.</td>
</tr>
</tbody>
</table>

### DETECTOR (6002)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Low noise, blue enhanced silicon detector</td>
</tr>
<tr>
<td>Sensitive area</td>
<td>2.91 mm²</td>
</tr>
<tr>
<td>Response time (10% - 90%)</td>
<td>60 ns typically</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>0.5 A/W typically at spectral peak.</td>
</tr>
</tbody>
</table>
ELECTRICAL (6000)

Built in transimpedance amplifier
Virtual earth, inverting operational amplifier
Gain x Bandwidth typically 20 MHz
Input current 250 pA MAX
Standard amplifier - high gain/medium speed. \( V_{\text{OUT}}/V_{\text{IN}} = 10^3 \pm 5\% \).

Oscilloscope for display
Dual trace, external negative edge triggering
8 or 10 division graticule
Bandwidth 20 MHz
Normal X shift and calibrated time-base 0.5 ms/DIV and 1 ms/DIV.

ACCESSORIES USED

(i) WAVELENGTH MARKER UNIT (6001)
- Calibration scale
- Cursor control
- Wavelength accuracy
- Scan rate control
- 1 and 10 nm indicator pulses
- Moveable cursor pulse
- 4 digit thumbwheel
- \( \pm 0.5 \) nm (using calibration charts)
- Adjustable 10 Hz - 16 Hz (INT/AC/EXT).

(ii) SAMPLE AND HOLD UNIT (6003)
- Display
- Moving coil meter. Scale 0 - 100
- 60 mm scale length. 2.5% accuracy.
- Damped movement (LC time constant approximately 1 s).
- 0 - 10V (for driving chart recorder).
- External output
- Gain
- Switched and variable \( \times 0.5, \times 100 \).
<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>ROFIN Ltd.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Costs (1-1-82)</td>
<td></td>
</tr>
<tr>
<td>6000</td>
<td>£267</td>
</tr>
<tr>
<td>6002</td>
<td>£ 61</td>
</tr>
<tr>
<td>6001</td>
<td>£424</td>
</tr>
<tr>
<td>6003</td>
<td>£145</td>
</tr>
</tbody>
</table>
Reduction in electrode volume requirements resulting from the use of multiple electrodes

For a graphite electrode the skin depth $\delta$ is 166 mm at 50 Hz, assuming a mean electrode temperature of 700K (Samsonov, 1968). At arc currents in excess of 30 kA a typical diameter electrode used is 600 mm (Essmann et al, 1984). Assuming that all the current is carried within the annular skin depth, the current carrying area is given by

$$A = \frac{\pi}{4} (D^2 - (D - 2\delta)^2)$$

where $D$ is the diameter. If this large electrode is replaced by $n$ smaller ones of equal current carrying area, and individual diameter $d$, then we can consider the two conditions:

(i) $d > 2\delta$

$$\frac{\pi}{4} (D^2 - (D - 2\delta)^2) = n \frac{\pi}{4} (d^2 - (d - 2\delta)^2)$$

giving $d = \frac{1}{n}(D - \delta) + \delta$

(ii) $d \leq 2\delta$ - approximating to a uniform current density over the cross section of each electrode.

$$\frac{\pi}{4} (D^2 - (D - 2\delta)^2) = n \frac{\pi}{4} d^2$$

giving $d = 2\sqrt{\frac{(D\delta - \delta^2)}{n}}$

The variation of the amount of graphite required with the number of electrodes is shown in Table A5.1, with $d$ being determined from the appropriate equation.
<table>
<thead>
<tr>
<th>Electrodes</th>
<th>Diameter d (m)</th>
<th>Condition</th>
<th>Total volume per unit length of n (m³ per m length)</th>
<th>Change in total volume required %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.6 (D)</td>
<td>&gt;2δ</td>
<td>0.282</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>0.383</td>
<td>&gt;2δ</td>
<td>0.230</td>
<td>18.4</td>
</tr>
<tr>
<td>3</td>
<td>0.310</td>
<td>&lt;2δ</td>
<td>0.226</td>
<td>19.8</td>
</tr>
<tr>
<td>4</td>
<td>0.268</td>
<td>&lt;2δ</td>
<td>0.226</td>
<td>19.8</td>
</tr>
<tr>
<td>6</td>
<td>0.219</td>
<td>&lt;2δ</td>
<td>0.226</td>
<td>19.8</td>
</tr>
<tr>
<td>50</td>
<td>0.076</td>
<td>&lt;2δ</td>
<td>0.226</td>
<td>19.8</td>
</tr>
</tbody>
</table>

Table A5.1: Graphite savings due to the use of multiple electrodes

These results indicate that replacement of the single graphite electrodes of each phase in an ac arc furnace would result in a saving of approximately 20% in the amount of graphite required to carry the current, irrespective of the number of electrodes, owing to the more efficient use of the available cross section of conductor. For the condition \( d < 2\delta \) (uniform current density), the saving will always be constant since the total cross section of conductor required is constant.