The Dissipation of Energy in D.C. Transferred-arc Plasma Systems and the Consequences for the Production of Ferro-alloys

by

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Synopsis

The advantages of plasma systems over three-phase submerged-arc furnaces in their application to the production of ferro-alloys are examined briefly.

The interaction between an arc and the metallurgical conditions in a plasma furnace is different from that in a submerged-arc furnace, particularly in the utilization of the energy of an arc.

Experiments on the dissipation of energy in a transferred plasma arc are described, and the results, which give rise to the following conclusions, are given.

There is a large dissipation of energy at the anode (up to 80 per cent), largely because the energy developed in the arc column is directed downwards onto the anode.

The major factors affecting the relative proportion of energy dissipated at the anode are:

- the type and geometry of the cathode, since a strong cathode jet increases the proportion of energy directed at the anode,
- the arc current, since an increased arc current increases the proportion of energy at the anode,
- the arc length, since an increased arc length decreases the proportion of energy at the anode, although a large proportion of the energy is still directed through the anode region,
- the arc-supporting gas, since the use of nitrogen, a diatomic gas, results in a higher transfer of energy to the anode than for argon, a monatomic gas.

The dissipation of energy from the arc column (radiation energy) is relatively small. As long as the arc column is well collimated and directed downwards onto the anode (or the metal bath of the furnace), the exposed arc column does not cause extensive wear of the refractories. The major problems relating to the refractories in a transferred-arc furnace are slag attack on the walls of the furnace, refractory wear caused by convection energy generated in the arc column, and radiation to the roof of the furnace from the hot anode region and the molten bath.

It is important for the reduction reactions to be carried out in the hot anode region, or as close as possible to it, so that the energy at the anode will be quenched. This is particularly important in ferro-alloy production in the open-bath mode.

INTRODUCTION

Since about ten years ago, plasma-arc technology has been receiving a great deal of attention as a new type of electrothermal process for metallurgical operations. The three-phase a.c. furnace, which has been in operation for many years, can be regarded as a type of plasma-arc furnace, but this term is generally applied to systems in which the arc is controlled either by a specialized torch or by the use of direct current. Many of the new developments in plasma-arc systems have been applied in the steel industry to the melting of scrap[1-4] and the production of iron[5,6]. However, in South Africa, with its abundant reserves of raw materials and its well-established ferro-alloy industry, it was to be expected that this industry would take a keen interest in the application of plasma technology to the production of ferro-alloys[7-11]. This has indeed been the case, and a comprehensive pilot-plant facility[12] and two small-scale production units[13,14] are currently in operation in this country.

Two distinctly different types of plasma can be applied to the production of ferro-alloys. The first of these is the PLASMASMELT process, developed by the SKF Steel Engineering AB in Sweden, which uses a coke-filled shaft furnace, similar to a blast furnace, but much smaller[15]. The raw materials in fine form are injected pneumatically into the tail flame of non-transferred-arc heaters situated round the base of the shaft furnace. Electric current is contained in the arc heater, and only high-enthalpy gas is introduced into the reaction zone. This type of system has not been applied in South Africa, but has received a lot of attention.

The second type of plasma system, which is being applied in South Africa to the production of ferro-alloys, is the transferred-arc furnace, which is similar in concept to the submerged-arc furnace that has been in use in the ferro-alloy industry for many years. The major difference between the two systems is that, unlike the submerged-arc furnace, where the arc is buried in the charge of raw materials, the transferred-arc plasma system utilizes an open-bath mode of operation in which the arc is exposed. Direct current is generally used, arcs being established between the molten bath, acting as the anode, and one or more electrodes or plasma torches that are introduced through the roof or side walls of the furnace.

The relative advantages and disadvantages of the transferred-arc plasma system and the submerged-arc furnace have been discussed elsewhere[11]. In summary, the major advantages of the plasma-arc system are that it allows *independent* control of the feed rate of the raw materials and the input of power, raw materials can be treated direct, and the time constants of the system are relatively short, which means that a greater degree of control over the process (particularly the process chemistry) is possible. The major disadvantage of the plasma system is that, since it is an open-bath system, the refractories are exposed direct to the extremely hot arcing regions and the molten bath. In this context, the transferred-arc plasma furnace is similar to open-arc scrap-melting furnaces, and some of the operating strategies used in these furnaces will probably have to be employed in transferred-arc plasma furnaces. In contrast to submerged-arc furnace, which usually are relined only every four to six years, scrap-melting furnaces are usually relined every few months. Water-cooled panels are being used fairly extensively to reduce refractory wear in scrap-melting furnaces. The loss of heat to the water-cooled panels is appreciable, but can be offset by operation at higher power levels, which increases the throughput and actually reduces the net utilization of energy in megawatt-hours per ton of product.

Whether water-cooled panels will eventually have to be used in transferred-arc furnaces will depend largely on how the energy from the arc can be used so that refractory wear due to overheating can be minimized. The interaction between the metallurgical conditions in the furnace and the arc in a plasma furnace differs from that in the conventional submerged-arc furnace. Aspects such as whether the reactions can take place close to the arc-root area or have to be performed in the bath need to be resolved. It is therefore crucial for the mechanism of energy dissipation within and surrounding an arc to be thoroughly understood. There are many types of arcing systems. In this context, however, only high-current d.c. transferred-arc systems will be considered.

ENERGY EFFICIENCY

Before the actual mechanisms for the dissipation of energy within a transferred-arc plasma are discussed, the relative energy efficiencies of the various processes used in the production of ferro-alloys must be considered and related to the transferred-arc plasma furnace.

The operation of a ferro-alloy process whether as an open-bath or submerged-arc system does not have a significant effect on the energy efficiency of the process provided that a conventional refractory-lined furnace is used. A far bigger change in energy efficiency can be achieved by the use of the energy contained (mostly as carbon monoxide) in the gas produced in the reduction reaction. Curr and Marjoribanks[16] developed a computer programme using standard thermodynamic principles to evaluate various process routes for the production of ferrochromium. They showed that the consumption of electrical energy can be reduced from 3,77 MWh/t for a conventional submerged-arc furnace to 1,81 MWh/t for the Showa Denko process, in which the raw materials are preheated and prereduced in a rotary kiln before being hot-charged to a submerged-arc furnace. This is a substantial reduction in the requirements of electrical energy and is partly offset by the need for additional but much cheaper energy sources (e.g., coal) to be used in the kiln. In another process (Outokumpu Oy), a rotary kiln uses the furnace off-gas mainly for preheating and some prereduction, with a resulting improvement in efficiency. It should be noted that, although all these processes included a submerged-arc furnace as the final stage, a transferred-arc plasma furnace could also be used to achieve similar benefits. However, the plasma furnace has two major advantages. Without costly agglomeration, preheating processes tend to produce large quantities of fine material. The plasma furnace can treat such fine material direct because of its open-bath mode of operation, whereas, in a submerged-arc furnace, fine material can cause blockages in the burden of raw materials, which result in furnace eruptions. Control and measurement of the degree of prereduction in the rotary kiln is difficult; consequently, the subsequent control of the process chemistry in a submerged-arc furnace is very difficult. In the plasma furnace, the open-bath mode of operation allows for better control.

Thus, transferred-arc furnaces offer distinct advantages in the processing of ferro-alloys; but these advantages are related to the open-bath mode of operation with its underlying weakness with respect to refractory life.

THEORETICAL ASPECTS OF ENERGY DISSIPATION IN AN ARC

Many factors affect the properties of an arc, and, although this has been the subject of a large number of investigations, many aspects are still not fully understood. This paper is not intended to present a review of the literature on the d.c. high-current arc; the literature is extensive, and only those papers that are particularly relevant to the dissipation of energy within an arc are discussed. Many of the investigations have centred on the analysis of some particular aspect of the arc (anode, cathode, etc.), whereas the emphasis in the investigation described here was on the effect of the energy of an arc on its surrounding area, viz the furnace. Of particular interest are the properties of the very high-current arc (I>10 kA, V>100 V) as used in production-size furnaces. In investigations carried out by the arc-research laboratory of the British Steel Corporation[17,18], these current and voltage levels were approached, but the very precise plasma diagnostic measurements, which have been carried out at much lower levels of current and voltage, could not be performed. Therefore, an analysis of the high-current arc has to be based on extrapolation from measurements made at substantially lower levels of current and voltage.

The d.c. arc can be divided into three regions—the cathode, the arc column, and the anode—and the energy content associated with each region can be deduced from a typical potential-gradient curve (Figure 1)[19]. A fairly steep voltage gradient occurs near the cathode (cathode-fall voltage), a much flatter gradient is associated with the arc column, and finally a very steep voltage gradient occurs very close to the anode (anode-fall voltage). The anode-fall and cathode-fall regions occur over a very narrow region (less than 1 cm).

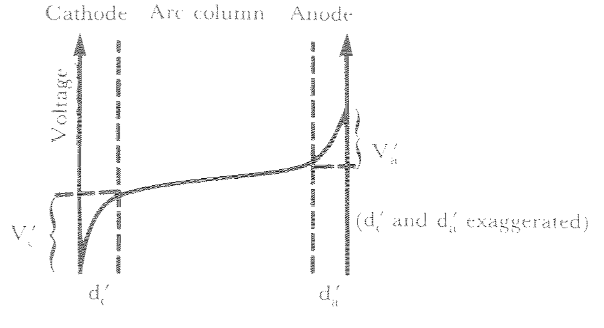

Figure 1. Typical distribution of potential along an arc (after Pfender[19])

For high-current, high-voltage arcs, the region of the arc column is extended, whereas the electrode-fall regions remain largely constant with respect to the voltage drop. Thus, the arc column is the dominating energy source for these large arcs.

Cathode region

The cathode region is relatively unimportant in terms of energy dissipation (approximately 2 to 3 per cent of the total energy) and is not given much attention here. The major function of the cathode is to provide enough electrons to sustain the arc current, and the stability of the arc is heavily dependent on the conditions at the cathode. The cathode-fall potential is usually between 10 and 30 V and is largely dependent on the cathode material, not on the current. For high-current arcs, refractory cathodes are employed (carbon, tungsten, thoriated tungsten), and the emission is thermionic.

Arc column

The arc column is a high-temperature (above 10 000 K) region of ionized gas and, for high-current high-voltage arcs, is the region where most of the arc energy is generated. The dominant form of energy generation if joule heating. The voltage gradient along the column depends on the electrical conductivity, which itself depends on several factors, primarily the temperature and the type of gases in the column. The relation between temperature and conductivity for an argon plasma at atmospheric pressure[19] is shown in Figure 2.

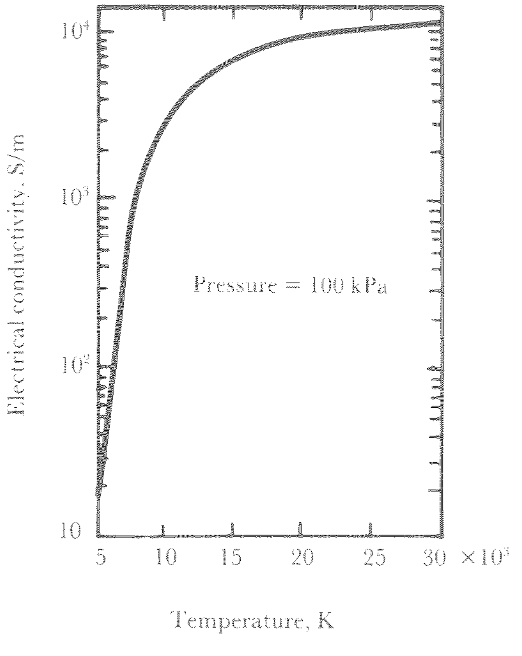

Figure 2. Electrical conductivity of an argon plasma (after Pfender[19])

The temperatures of the gases in the arc column are usually high enough to be in the flat region of the conductivity curve. Therefore, for a high-current arc, an increase in the temperature leads to only a small increase in the conductivity. An increase in the arc current therefore generally causes a proportional increase in the cross-sectional area of the arc column rather than an increase in the temperature of the arc column. Any action that reduces the temperature of the column (e.g., the introduction of relatively cold raw materials) will reduce the conductivity, and this will increase the voltage gradient along the arc column.

Anode region

Many studies have been made of the heat-transfer mechanism at the anode, and a brief review is given here. This is largely based on the analysis by Pfender[19], Shoeck and Eckert[20], and Schoeck[21]. The anode can be regarded as a flat surface with heat entering or leaving the surface, and the following equation applies:

$$q_a = q_{con} + q_{rad} + j_e \left[\tfrac{5}{2}\left(\frac{kT_e}{e}\right) + V_a + \phi_a \right]$$

where

q_a is the heat transfer to the anode,

q_{con} is the local heat flux by conduction and convention,

q_{rad} represents the radiational heat flux, and the last term (in brackets) combines all the current effects, i.e.,

j_e is the electron current density,

k is Boltzmann's constant,

T_e is electron temperature,

e is the charge of an electron,

V_a is the anode fall potential, and

ϕ_a is the work function of the anode material.

The last term in brackets can be lumped together as an equivalent voltage U.

There have been numerous debates on the magnitude of U. However, for high-voltage, high-current arcs, it needs to be noted only that U is not large[19] (6 to 10 V). General guidelines are not easily given for the other terms since the anode surface (e.g., copper plate, molten bath) would have a major influence on q_{con}, and the temperature and emissivity would have a major effect on q_{rad}. These variables would depend on the particular conditions of the arc.

Cathode plasma jet

In transferred-arc plasma systems, there is usually some constriction of the cathode region relative to the arc column, and this results in the formation of a cathode jet. The current density is usually highest at the cathode. This causes a radial compression (as a result of electromagnetic forces) of the arc column close to the cathode. The high current density at the cathode is related to the efficiency of electron production. Maecker[22] developed a theory for the cathode-jet phenomenon based on the fact that the radial pinch force is proportional to the square of the current density. As the current density drops off with distance from the cathode, the radial force is reduced, and this causes a pressure gradient that induces the ambient gas to flow into the cathode region and then to be 'pumped' away from the cathode, and, depending on the strength of the jet and the length of the arcs, the stabilizing influence can be extended to the anode region. Arc jets occur wherever there is a constriction, and hence increase, in the current density of the arc column. They can also occur at the anode if spot attachment takes place, and in a.c. arcs.

One of the torches commonly used in d.c. transferred-arc systems is the water-cooled torch employing a thoriated-tungsten cathode. In this torch, the cathode tip is tapered, which causes a very high current density at the tip. This, in conjunction with the arc-supporting gas, which is introduced through a nozzle surrounding the cathode, results in a strong jet. Carbon electrodes are also commonly used in d.c. transferred-arc systems. For these electrodes, the Maecker force is likely to be less pronounced. However, for the very high-current d.c. transferred-arc where the arc attachment at the cathode covers the entire cross-section of the electrode, a marked pinch effect has been observed at the cathode, and substantial Maecker forces must be present in this mode of operation[23].

Simplified heat-transfer model for d.c. transferred arc

It is assumed that, as a result of very high current density (i.e., when the current is high in relation to the size of the cathode) or by constriction of the cathode (i.e., the water-cooled tungsten torch), the cathode jet gives rise to a stable arc column with significant Maecker forces causing a pumping action near the cathode. It is also assumed that the arc column is sufficiently long for the major generation of energy to be accomplished via joule heating in the arc column. The arrangement of the model is shown in Figure 3. If the radiation component q_{rad} is ignored, virtually all the resulting

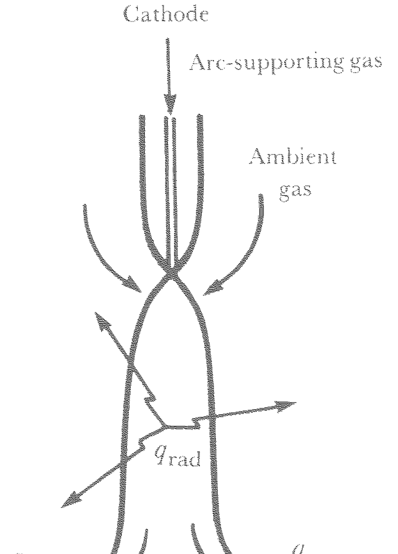

Figure 3. Approximate model of heat transfer for d.c. transferred arc

energy of the arc can be regarded as being directed towards the anode region, mostly as high-temperature ionized gas. The electron-heating component for the anode may be fairly small, but the convection and radiation components q'_{con} and q'_{rad} can be significant. If the radiation component is between 20 and 30 per cent of the total energy[17,18], between 70 and 80 per cent of the total arc energy (the cathode loss is 2 to 3 per cent) is directed onto the anode and the region immediately surrounding it. If the anode is a molten bath, the major heat-transfer mechanisms will be radiation over the whole expanse of the bath and convection between the hot plasma gas escaping from the arc-anode area and spreading out across the molten bath. There will also be radiation from the hot gas as it spreads out. In the ideal arrangement, where the arc column is vertical, the plasma gas will spread evenly in a radial fashion outwards from the arc. However, if the arc column is slanted in any direction, an arc flame will be generated and there will be large increases in the proportion of energy in this direction. This is the mechanism of formation of hot spots, which has been well documented in the operation of melting furnaces[24].

If the relative proportions of the different components in a heat-transfer model for a plasma arc are estimated, the terms of cathode heating and anode-electron heating can be accounted for. However, the remaining components q_{rad} and q_{con}, which in a high-current, high-voltage arc are the dominant components, are established less easily. Radiation is determined from the Stefan–Boltzmann equation.

$$q_{\text{rad}} = \epsilon\,\sigma(T_1^4 - T_2^4)$$

where

ϵ is the emissivity,
σ is the Stefan–Boltzmann constant, and
T_1 and T_2 are the respective temperatures of the radiator and the absorber provided they have the same emissivity.

In the arc column, T_2 is much smaller than T_1 and can be neglected. However, the problem is still complex in that there are difficulties in the establishment of temperature and emissivity and, particularly for high-current arcs, of whether the arc column can be regarded as being optically thin (viz, no radiation is reabsorbed within the arc column). Therefore, in the assessment of radiation, direct measurements must usually be relied upon.

The simplified arc model considered above is consistent with a much more complex model proposed by Chang and Szekely[25] and Szekely *et al.*[26], which is based on the principles of magnetofluid mechanics and is not detailed here. Those workers used the model to calculate the energy-transfer conditions for an 18 MW, 50 kA, d.c. transferred arc with a molten-bath anode. The results are shown in Figures 4 and 5. The gas-velocity field shown in Figure 4 is downwards onto the bath and radially outwards, as proposed in the simplified model above. The dominant energy term is convection, radiation being a minor component. This low radiation component, which was based on measurement reported by Morris *et al.*[27], is much lower than that measured at the arc research laboratory of the British Steel Corporation[17,18].

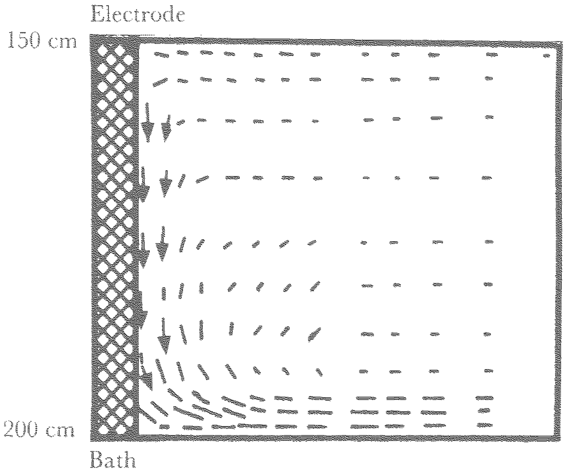

Figure 4. Predicted velocity field in the plasma region of an electric-arc furnace (after Szekely et al.[26])

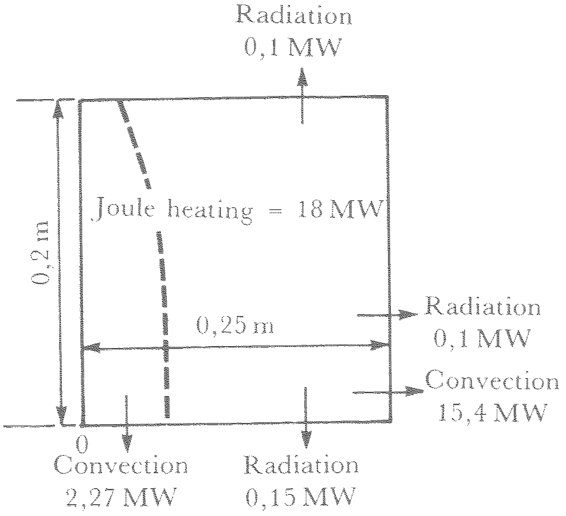

Figure 5. Energy balance for the impingement zone of an 18 MW furnace with an arc of 20 cm diameter (after Szekely et al.[26])

EXPERIMENTAL RESULTS

As a complement to the investigation on the mechanisms of heat transfer from an arc, a calorimeter system was constructed to represent the geometric arrangement of a typical d.c. transferred-arc furnace. The emphasis was on the measurement of the overall transfer of energy to the furnace as a whole rather than on one particular aspect (e.g., the anode). Calorimetry has been used on numerous occasions as a tool in plasma diagnostics, particularly in studies of heat transfer in anodes and cathodes[28-33].

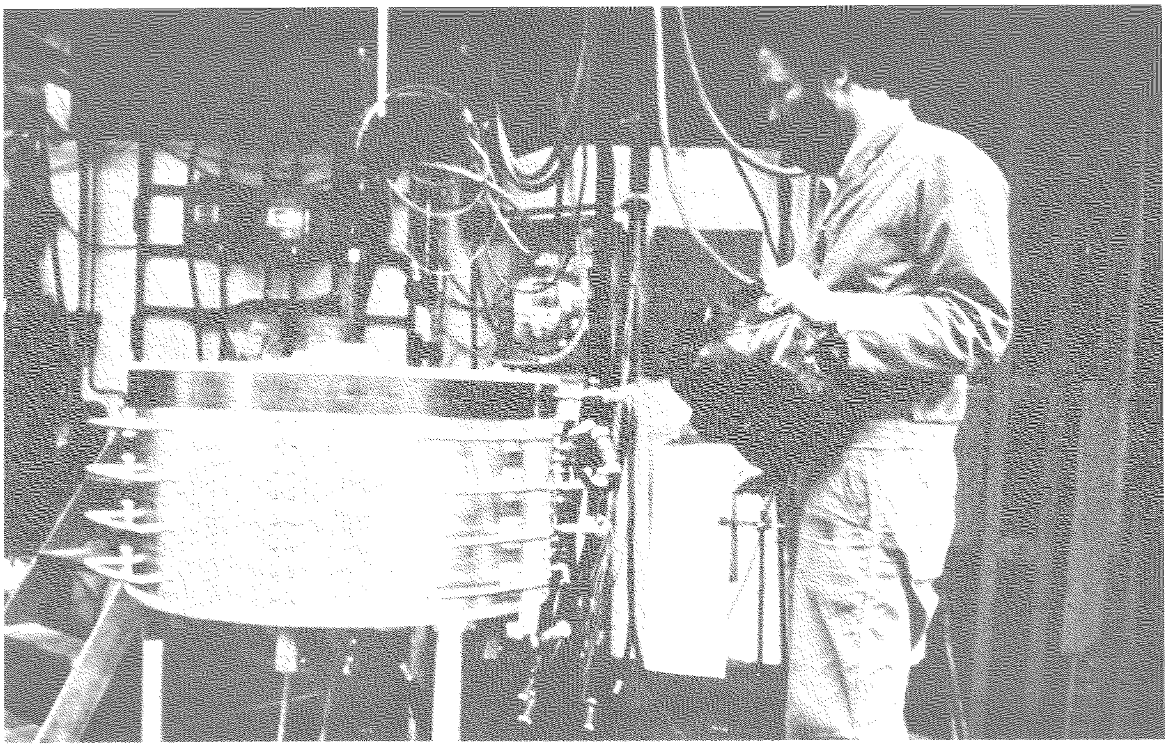

Figure 6. Photograph of the calorimeter system

Figure 6 is a photograph and Figure 7 a diagram of the calorimeter system, which consists of a circular bath comprising a water-cooled base, four cylindrical water-cooled panels, and a water-cooled roof. A hole in the roof with a refractory insert permits a plasma torch or electrode to be introduced into the furnace. A separate water-cooled anode assembly was placed in the centre of the base of the calorimeter so that an arc could be established between the electrode and the anode. All the water circuits were monitored for inlet and outlet temperatures with 100 Ω resistance transducers made of platinum, and the flows were monitored with magnetic flowmeters or turbine flowmeters. The arc voltage and current were also monitored, and all the signals were sampled continuously by a computer system so that an entire campaign could be recorded. The overall accuracy of the measurements was about 1 per cent. The plasma-arc torch consists of a water-cooled thoriated-tungsten cathode with a water-cooled copper jacket. An arc-supporting gas (argon or nitrogen) was introduced through a nozzle surrounding the cathode. The constants of the calorimeter and plasma torch are summarized in Table 1.

Calorimeter system with 100 kVA supply

Initially, the calorimeter was connected to a 100 kVA d.c. power supply consisting of a three-phase on-load tap-changing tranformer, three variable-tap a.c. inductors, and a six-pulse diode-bridge assembly. It was necessary for the connections from the positive and negative leads to the calorimeter to be symmetrical, as shown in Figure 8, so that preferential slanting of the arc column in one

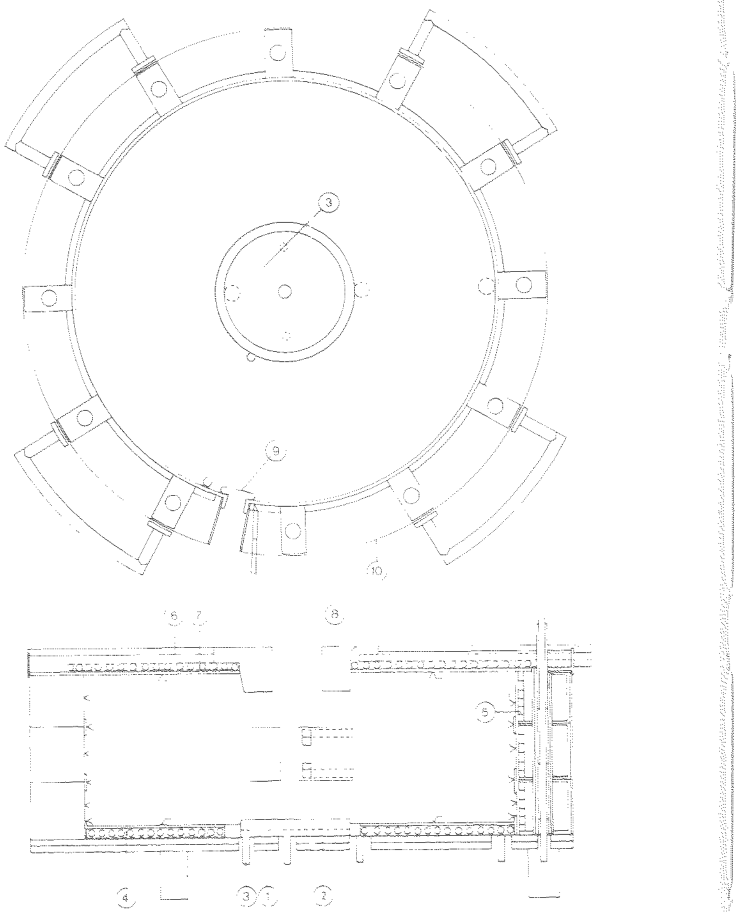

Figure 7. Diagrammatic representation of calorimeter system

TABLE 1
Calorimeter and plasma-torch constants

Calorimeter		Torch	
Bath diameter	= 0,76 m	Cathode diameter	= 10 mm
Side-panel height (× 4)	= 0,1 m	Flat at front face	= 1 mm
Anode diameter	= 0,2 m	Taper	= 20 °
Anode area	= 0,031 m^2	Nozzle aperture	= 8 mm
Base area	= 0,42 m^2	Jacket diameter	= 29 mm
Side-panel area (× 4)	= 0,24 m^2		
Roof area	= 0,43 m^2		

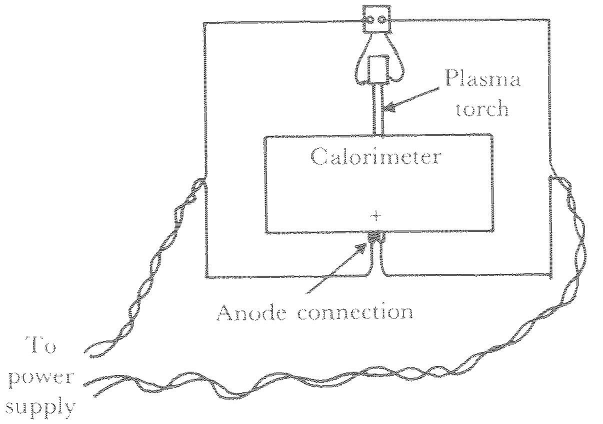

Figure 8. Symmetrical connection of current leads to the calorimeter to avoid slanting of the arc

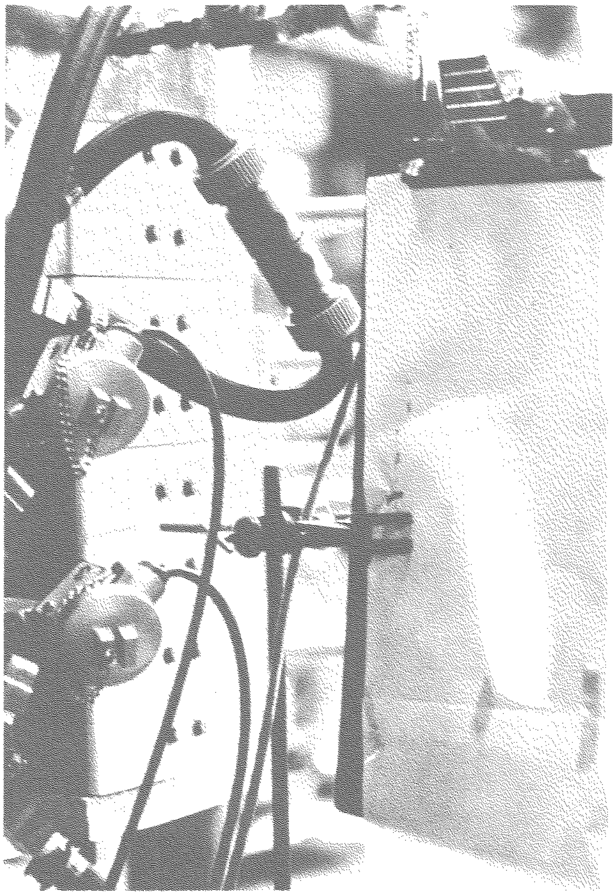

Figure 9. Photograph of an inverted image of the arc showing slanting

direction could be avoided. This slanting effect was observed by the use of a pinhole that was placed approximately halfway up one of the side panels, permitting an image of the arc to be seen on a white sheet of paper. The slanting of the arc can be seen clearly in a photograph taken when the leads were not connected symmetrically (Figure 9).

Experiments at various arc lengths were carried out on the system with the water-cooled plasma torch. Argon or nitrogen was used as the arc-supporting gas. The results are summarized in Tables 2 and 3, and some graphical results are shown in Figures 10 to 12. Two of the side panels were connected in series to form one circuit, and the base was connected to the bottom side panel. It should be noted that the anode is not an anode in the strict sense, since the area of the copper surface is much larger than that of the anode attachment. So the anode assembly also receives the heat flux of convection and radiation immediately surrounding the area of the anode-root attachment. Also, the central anode plate, which is 2 cm higher than the base, reduces the amount of heat transferred to the base by convection, whereas that transferred by radiation is largely unaffected.

The following are the major conclusions.

- Figure 10 shows the voltage–current relation for the d.c. transferred arc, which is typical for these systems. For an arc of fixed length, the current can be varied over a wide range without a significant change in the voltage. Figure 11 shows the linear relation between the volt-

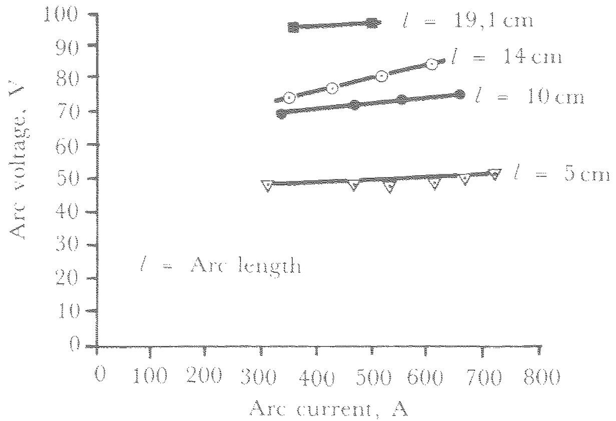

Figure 10. Voltage–current characteristics for argon

TABLE 2

Calorimeter results at an argon flowrate of 15 l/m

Arc length cm	Tap position	Voltage V	Current A	Power kW	Cathode		Jacket		Anode		Base and bottom ring		Middle ring		Top two rings		Roof	
					kW	%	kW	%	kW	%	kW	kW/m^2	kW	kW/m^2	kW	kW/m^2	kW	kW/m^2
19,1	12	98	492	48,2	1,3	2,7	1,7	3,6	26,2	54,8	4,5	6,8	2,9	12,1	5,8	12,1	5,4	17,0
19,1	11	97	363	35,2	0,9	2,6	1,4	4,0	16,4	46,9	3,6	5,5	2,7	11,2	5,2	10,8	4,8	15,1
14	12	85	601	51,1	1,6	3,2	1,8	3,6	28,4	56,1	4,8	7,3	3,0	12,5	5,7	11,9	5,3	16,7
14	11	82	518	42,5	1,3	3,1	1,6	3,8	23,7	56,3	3,8	5,8	2,4	10,0	4,8	10,0	4,5	14,1
14	10	79	448	35,4	1,1	3,1	1,5	4,3	19,8	56,4	3,0	4,6	1,9	7,9	4,0	8,3	3,8	11,9
14	9	77	391	30,1	0,9	3,1	1,4	4,8	15,5	53,3	2,6	3,9	1,7	7,1	3,6	7,5	3,4	10,7
10	12	75	673	50,5	1,9	3,8	2,4	4,8	30	60,4	4,1	6,2	2,5	10,4	4,6	9,6	4,2	13,2
10	11	74	581	43,0	1,6	3,6	2,0	4,7	25,8	60,5	3,2	4,8	2,1	8,9	4,2	8,8	3,8	11,9
10	10	73	500	36,5	1,3	3,6	2,2	6,1	20,8	57,6	2,7	4,1	1,9	7,9	3,7	7,7	3,5	11,0
10	8	70	344	24,1	0,9	3,6	1,8	7,4	12,8	53,9	1,6	2,4	1,2	5,0	2,8	5,8	2,8	8,8
5	11	52	731	32,0	2,1	5,6	2,2	5,9	23,2	62	2,2	3,3	1,8	7,5	3,2	6,7	2,7	8,5
5	10	50	664	33,2	1,8	5,5	2,0	6,1	20,5	62,1	1,9	2,9	1,6	6,7	2,8	5,8	2,4	7,5
5	9	49	614	30,1	1,6	5,4	1,8	6,1	18,5	62,2	1,7	2,6	1,4	5,8	2,6	5,4	2,2	6,9
5	8	48	533	25,6	1,4	5,5	1,5	5,9	16,1	63,4	1,3	2,0	1,1	4,6	2,2	4,6	1,8	5,7
5	7	49	469	23,0	1,2	5,3	1,4	6,1	14,4	63	1,2	1,8	1,0	4,2	1,9	4,0	1,7	5,3
5	4	48	296	14,2	0,8	5,7	1,3	9,2	8,2	58,2	0,7	1,1	0,5	2,1	1,3	2,7	1,3	4,1

TABLE 3

Calorimeter results at a nitrogen flowrate of 15 l/m

Arc length cm	Tap position	Voltage V	Current A	Power kW	Cathode		Jacket		Anode		Base and bottom ring		Middle ring		Top two rings		Roof	
					kW	%	kW	%	kW	%	kW	kW/m^2	kW	kW/m^2	kW	kW/m^2	kW	kW/m^2
20	14	118	560	66,1	1,5	2,3	2,4	3,7	38,3	59,2	5,5	8,3	3,3	13,7	6,9	14,4	6,8	15,8
20	13	118	460	54,3	1,2	2,2	1,9	3,6	31,5	58,9	4,4	6,7	2,7	11,2	5,9	12,3	5,9	13,7
14	13	102	603	61,5	1,7	2,8	2,2	3,6	38,1	62,3	4,7	7,1	2,8	11,7	5,9	12,3	5,8	13,5
14	12	99	486	48,1	1,3	2,7	1,9	4,0	28,8	60,3	3,6	5,5	2,4	10,0	4,8	10,0	5,0	11,6
14	11	100	340	34,0	0,9	2,7	1,3	3,9	20,4	60,5	2,2	3,3	1,5	6,3	3,6	7,5	3,8	8,8
10	12	88	591	52,0	1,6	3,1	2,1	4,1	33,0	64,2	3,4	5,2	2,2	9,2	4,5	9,4	4,6	10,7
10	11	83	513	42,6	1,4	3,3	1,8	4,2	26,0	61,3	2,9	4,4	1,9	7,9	4,2	8,8	4,2	9,8
10	10	81	441	35,7	1,2	3,4	1,5	4,3	21,5	61,3	2,3	3,5	1,5	6,3	3,5	7,3	3,6	8,4
16	9	83	325	27,0	0,9	3,3	1,3	4,8	16,5	61,3	1,6	2,4	1,1	4,6	2,7	5,6	2,8	6,5
5	11	66	639	42,2	1,8	4,3	2,1	5,0	27,3	65,2	2,0	3,0	1,5	6,3	3,6	7,5	3,6	8,4
5	10	66	561	37,0	1,5	4,1	1,7	4,6	24,7	67,3	1,7	2,6	1,3	5,4	2,9	6,0	2,9	6,7
5	9	66	492	32,5	1,3	4,0	1,6	5,0	21,8	67,7	1,5	2,3	1,0	4,2	2,5	5,2	2,5	5,8
5	8	65	409	26,6	1,1	4,2	1,4	5,4	17,6	67,4	1,1	1,7	0,8	3,3	2,0	4,2	2,1	4,9
5	7	65	309	21,0	0,9	4,4	1,1	5,3	13,7	66,5	0,9	1,4	0,6	2,5	1,7	3,5	1,7	4,0
5	6	63	262	16,5	0,7	4,3	1,0	6,1	10,8	66,3	0,6	0,9	0,5	2,1	1,3	2,7	1,4	3,3
5	5	63	178	11,2	0,6	5,5	0,8	7,3	6,9	63,3	0,4	0,6	0,3	1,3	0,9	1,9	1,0	2,3

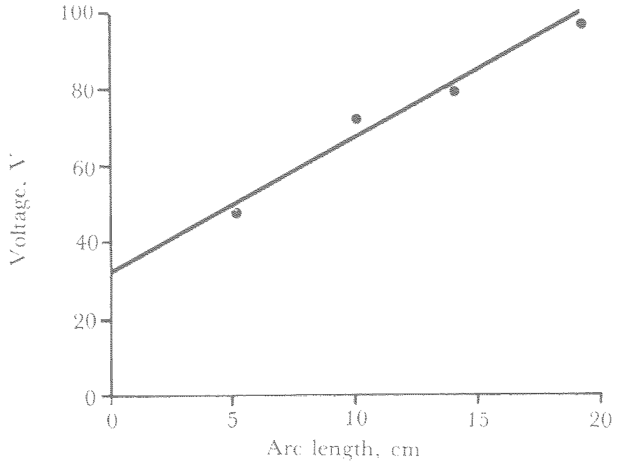

Figure 11. Voltage–arc length characteristics for argon

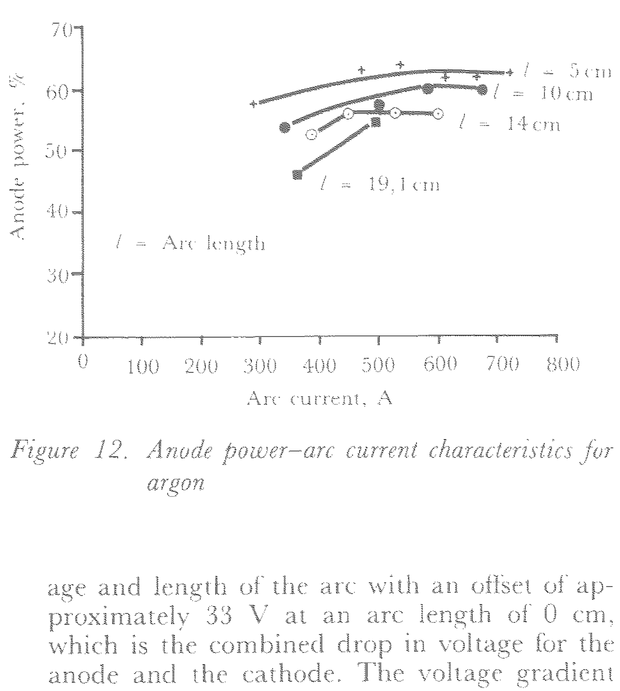

Figure 12. Anode power–arc current characteristics for argon

age and length of the arc with an offset of approximately 33 V at an arc length of 0 cm, which is the combined drop in voltage for the anode and the cathode. The voltage gradient for the column is 330 V/m.

- A significant proportion of the arc energy is transferred to the anode plate despite its small area. Nitrogen is a diatomic gas, and the heat transfer to the anode is higher than it is for argon, which is a monatomic gas. An increase in the arc length results in a significant reduction in the proportion of energy transferred to the anode.
- The heat transfer to the cooling water for the cathode is low and largely proportional to the current. Therefore, even at high currents, the proportion for long arcs is low (less than 3 per cent). A significant amount of energy is absorbed by the cooling water in the jacket (approximately 30 per cent more than for the cooling water at the cathode). However, this component is likely to be significantly greater in a hot furnace.
- The heat transfer to the rest of the furnace in terms of kilowatts per square metre is fairly similar except for the base and bottom ring. This could be attributed to the fact that the anode is higher than the base, as mentioned earlier. The heat transfer to the roof compared with that to the top two rings is higher for argon, whereas it is only marginally higher for nitrogen. The effect also becomes less marked for shorter arcs. Schoeck[21] has shown that the radiation from an argon arc is higher than it is for a nitrogen arc, and this suggests that there is more radiation to the roof than to the side walls. It also suggests that radiation is much less dominant than convection. A large proportion of any radiation energy from the arc would be transferred to the anode owing to its close proximity to the arc. Therefore, argon injection should result in an increase in energy to the anode when compared with nitrogen injection, whereas the opposite actually occurs.
- If the equivalent anode voltage U referred to earlier is assumed to be 8 V, the transfer of energy to the anode by all the combined current effects is substantially lower than that measured at the anode. For example, for a 14 cm argon arc at 601 A, $UI = 4{,}8$ kW, which is only 17 per cent of the total. A substantial amount of energy is therefore received by convection and radiation.

Calorimeter system with 3,2 MVA power supply

The 100 kVA power supply was limited in terms of its maximum voltage and current. It was therefore decided that the calorimeter system should be transferred to a large power supply that had become available[12]. This is a Thyristor-controlled power supply capable of supplying up to 3600 A and 750 V. The calorimeter system is limited with respect to high-voltage operation owing to its height, which is only 40 cm. Operation at high currents is possible, provided that the anode can absorb the increased energy and current without being damaged. A new anode was constructed with larger water passages to allow higher flowrates, and some initial experiments were done. A water-cooled torch similar to that used previously but designed for operation at higher currents (approximately 3000 A), was used. These initial experiments were done in an attempt to establish an upper limit for the current, and it was found that a long arc must be ensured before the current is increased. If this is not done, the anode is damaged very quickly.

A summary of the results is given in Table 4. The calorimeter was operated with the roof off so that the anode could be closely observed. The last column in the table is therefore the total heat that was not accounted for, most of which was lost through the roof opening.

The following conclusions can be drawn from the results.

- With a larger torch at higher currents, the dissipation of heat at the anode is directly proportional to the current and virtually in-

TABLE 4

Results with a power supply of 3,2 MVA and nitrogen (at 26 l/min) as the arc-supporting gas

Arc				Anode		Base and bottom two rings		Top two rings		Power lost to cathode, jacket, and roof	
Length cm	Voltage V	Current A	Power kW	kW	%	kW	kW/m^2	kW	kW/m^2	kW	%
7	65	420	27	22	81	1,9	2,1	1,8	3,7	1,3	5
17	115	620	71	41	58	5,6	6,2	4,0	8,3	20,4	29
22	155	600	93	41	44	7,5	8,3	4,9	10,2	39,6	43
27	180	580	104	41	39	8,6	9,6	6,2	12,9	48,2	46
17	115	740	85	50	59	6,3	7,0	4,3	9,0	24,4	29
22	145	720	104	48	46	10,8	12,0	6,1	12,7	39,1	38
27	150	700	105	45	43	25,1	27,9	7,4	15,4	27,5	26
22	130	920	120	63	53	23,1	26,1	7,3	15,2	26,6	22
27	150	920	138	66	48	25,7	28,5	9,0	18,8	37,3	27
32	170	920	156	66	42	29,1	32,3	10,8	22,5	50,1	32
32	160	1080	173	71	41	37	41,1	12,6	26,3	52,4	30

dependent of the length of the arc (Figure 13). This phenomenon was not apparent in the previous experiments.

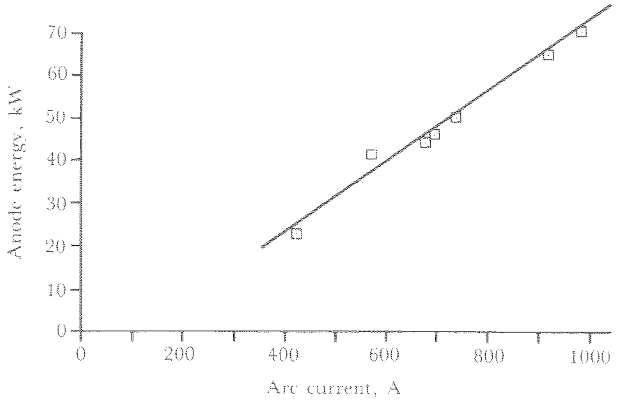

Figure 13. Relation between heat transfer to the anode and arc current

- With the roof off and a long arc, an appreciable amount of the energy is lost—more than was predicted from the results of the experiments with a closed top. With a 27 cm arc at 580 A, an energy density for the roof of, say, 15 kW/m^2 (compared with 12,9 kW/m^2 in the previous experiments, where the energy density for the roof was approximately 20 per cent higher than for the top ring) accounts for only 6,5 of the 48,2 kW lost. This implies that, in effect, mixing takes place within the furnace when it is closed, and supports the contention that the dominant mechanism of energy transfer is convection. As the water-cooled panels would absorb most of the radiant energy without any significant reradiation, radiation would not be affected by the removal of the roof, and so convection must be the dominant component.
- There is an anomaly in the results after the 27 cm arc at 700 A, which is seen as a dramatic increase in transfer of energy to the base and bottom two rings (10,8 to 25,1 kW). All the results after this point show a large transfer of heat to the bottom region of the furnace, which is reflected by a net reduction in the percentage of heat lost through the roof despite the high power. The reason for this is as follows. A crater was established in the copper surface of the anode, which caused a preferential slanting of the anode attachment similar to that observed as in Figure 9, despite the symmetrical connection of the positive and negative leads to the calorimeter. The slanting of the anode attachment would direct a large proportion of the hot gas from the arc column onto the base and lower rings, at high velocity, thus increasing the heat absorption in that region.

EFFECT OF THE CALORIMETER ROOF

Some interesting features are observed when the results obtained for the calorimeter when its roof was on are compared with those obtained when its roof was off. The calorimeter surfaces (black oxidized copper) have a high emissivity and are at a very low temperature in relation to the temperature of the arc; so they retransmit a small fraction of the received radiation. The removal of the roof would therefore have a small effect on the relative amounts of radiative energy absorbed by each copper surface, and any significant change in the relative proportions of energy transmitted to each panel would be a result of heat transfer by convection. Some typical results are compared in Figure 14. The total proportion of energy transferred to the roof in a closed calorimeter (10 per cent) is much smaller than that transferred when the roof has been removed (28 per cent). This implies that heat transfer by convection is much more dominant than heat transfer by radiation.

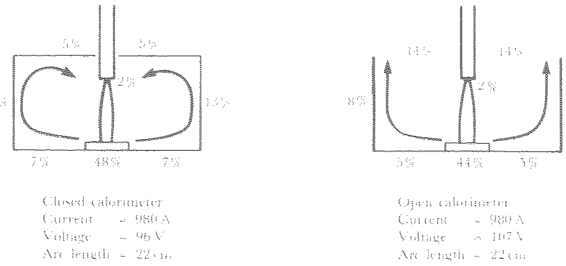

Figure 14. Comparison of heat transfer to water-cooled panels in a closed calorimeter and a calorimeter with the roof off

DISCUSSION WITH REFERENCE TO FERRO-ALLOYS

For the high-current, high-voltage d.c. transferred-arc system, a large proportion of the energy—predominantly convection energy—is channelled through the anode region. Unfortunately, the transfer of heat by convection to a molten bath is not particularly good except in the region of high gas velocity close to the anode root. However, if the anode energy could be appreciably 'soaked up' by the bath, a major reduction in the heat loading to the rest of the furnace would be effected and the refractory wear would be reduced.

There are two processes in which it may be possible for the high energy transfer to the anode region to be exploited. The first of these is the ASEA system, which consists of a hollow graphite electrode located centrally in a conventional, circular, open-bath furnace[4,5]. The hearth of the furnace is electrically conductive, and a d.c. arc is set up between the electrode and the bath. A symmetrical arrangement of the busbars ensures that the arc is kept vertical. The raw materials are fed down the electrode direct into the arc region; thus, there is a potential for an increased heat transfer in this region to promote rapid reduction reactions. It has not yet been established whether this effect is significant. The other process in which the high energy transfer to the anode region could be exploited is the expanded precessive-plasma system proposed by Tetronics Research and Development Ltd[34]. Here, a torch consisting of a water-cooled tungsten cathode is used, and the arc is precessed so that the anode root travels in a circle over the molten bath. Thus, the energy from the anode spreads out into the bath, and, if the raw materials are dropped onto the region traced out by the anode, some preferential increase in heat transfer to the reduction reactions could occur.

Another important aspect of the d.c. transferred-arc plasma system is the energy density. In a submerged-arc furnace, the resistance of the arc under each electrode is fixed by the geometry of the furnace, the process itself, and the feed rate of the raw materials[35]. The electrodes are large and must be separated so that no significant inter-electrode conduction can take place. The resulting furnace is therefore fairly large. A typical 40 MW submerged-arc furnace producing ferrochromium would have the parameters shown in Table 5[35].

TABLE 5

Typical constants for a 40 MW ferrochromium furnace

Electrode diameter	1,8m
Electrode current	100 kA
Electrode-bath voltage	190 V
Bath diameter	11 m
Power factor	0,7

The ASEA d.c. transferred-arc system can supply the same amount of power to the furnace with only one electrode operating at 100 000 A and 400 V. Since only one electrode is used, the furnace could be very small. The size of the furnace would be dictated by the size of the bath needed for the required reactions to take place and for sufficient material to be contained to allow a realistic tapping interval to be used. The latter constraint could be removed if a continuous tapping procedure were adopted. These are very speculative schemes since the optimum power density still has to be established. Nevertheless, there is potential for a considerable reduction in the size of existing furnaces for the same throughput. This would have a major effect on the capital costs because the size of the furnace affects the entire infrastructure round it in terms of buildings, raw materials, feed systems, etc.

In the d.c. transferred-arc plasma system, the conducting path required at the anode presents a problem, since some form of electrically conducting medium must be introduced between the hot molten bath and the positive busbar connection. ASEA have proposed a system in which the hearth is constructed from electrically conductive refractory bricks with a copper plate in the base of the furnace[4]. In other schemes, use is normally made of a metal rod (or several metal rods) inserted vertically through the refractory lining of the hearth.

With the very high energy intensities immediately below an arc, damage to the anode connections could occur fairly easily; so it is probably best for the anode connections to be located away from the area of the arc root and for reliance to be placed on a 'metal heel' in the bath to distribute the current.

CONCLUSIONS

- The d.c. transferred-arc furnace is a feasible system for the production of ferro-alloys, and is particularly well suited to incorporation in the energy-saving preheating and prereduction schemes recently established.
- In contrast to the submerged-arc furnace, a transferred-arc system can attain relatively high voltages that can be readily controlled. Thus, by operation at current levels already established, very high power densities can be achieved.
- Most of the energy in a high-power arc is convective energy (i.e., hot gas at velocity), which is directed onto the anode region or bath of the furnace. Mechanisms must be sought for the absorbtion of as much as possible of the energy in this region, since the remaining portion will spread out into the rest of the furnace and attack the refractories.
- There is some disagreement about the level of radiation from an arc, but it appears to be about 20 per cent of the total. Further measurement is required to quantify this component more precisely. Radiative energy has the disadvantage that it is directed in all directions. If the arc could be buried in some way (e.g., by the promotion of a foaming slag), a significant proportion of this energy could be absorbed. The feeding of raw-material fines round the electrode, and the promotion of a dense fume, would lead to the additional absorption of the radiation.
- The open-bath mode of operation has the major disadvantage that the refractories are exposed to the high-energy plasma arc. In the long term, methods established by the steel-melting industry to contain refractory costs will probably have to be employed.
- The d.c. transferred-arc system has the distinct advantage that a high degree of independent control over the power input and the feed rate of raw materials is possible, as well as control over the chemistry of the product. However, the short time constants of the process make it necessary for a far more sophisticated infrastructure to be established than is currently in existence on submerged-arc furnaces. For instance, if the power input were greater than that required for the raw-material feed, there would be a fairly rapid increase in the temperature, which, if undetected, would result in damage to the refractories. In a submerged-arc furnace, the feed rate and power input are self-regulating, and the refractories are protected.
- Slanting of the arc column towards the refractory walls must be avoided, since this causes an appreciable increase in the transfer of heat in the direction of the slant and, consequently, in refractory wear.

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