OPERATING CHARACTERISTICS AND ENGINEERING APPLICATIONS OF TRANSFERRED ARCS

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ABSTRACT

This paper summarizes the major findings of a number of studies performed in these laboratories on the characteristics and behaviour of transferred arcs, which have in turn been used as the basis for the design of plasma reactors capable of meeting the engineering, technical and economic requirements of Industry.

In a search for new techniques of extractive metallurgy which would be more efficient and less polluting than existing conventional processes, consideration was given to the use of plasmas as both high-temperature heat sources and gaseous reactants. Emphasis in this search was placed on the production of ferroalloys directly from the mineral concentrates (for example, ferromolybdenum, ferrovanadium, ferroniobium, ferrochrome, etc.). A critical study of the scientific and patent literature was therefore carried out and after several years of experimental work on reactor design during which most existing or proposed designs were either considered or actually tested, a transferred arc system was developed which was the only system, from an industrial point of view, capable of meeting the following constraints of technical and economic viability:

1. The system must be highly energy efficient. This is probably the most important limitation imposed on the plasma system, owing to the high cost of electrical energy.

2. Product purity specifications should be met. Many products of metallurgical or chemical processing reactions must meet stringent purity specifications. In these cases, the conversion rate of the reactants to yield the desired product must be nearly 100%.

3. The physical form of the product must be industrially acceptable. Some types of plasma generators are limited to the formation of solid products in a finely divided form. Plasma systems capable of yielding a product in a molten form which can then be cast as ingots should be preferred, since the latter can be more easily transformed into the desired final shapes.

4. Capital and operating costs should be reasonable. The plasma system should be simple and not require extensive feed preparation or extensive effluent treatment. Operation should be continuous and susceptible of complete automation. Percent on-stream operation should be high with low requirements for maintenance. The life of

the electrodes should be reasonable and replacement should require a minimum of time.

5. Working and environmental conditions should be of high standard. The working environment of a plasma system should be relatively free from noise and heat stress, and from toxic fumes and dust. The gaseous effluents emanating from the plasma system should be susceptible of treatment to recover and recycle the dust, to recover its useful heat and to eliminate chemical pollutants.

In its final form, the transferred arc system which was successfully developed consists of a cathode assembly in which the plasmagen gas flows around the cathode tip as a sheath gas, and of a bottom anode consisting of a molten pool of the desired product. The heart of the system was found to be the plasma column established between the two electrodes, and the performance and efficiency of the operation was found to depend almost entirely on the effectiveness of the utilization of the plasma column as the heat source. Thus, Figures 1 and 2 show the characteristic voltage-versus-current curves, with plasma column length as a parameter, for argon and nitrogen, respectively. Worthy of notice is the much larger power which can be imparted to a nitrogen column, for otherwise constant operating conditions (current, electrode gap, plasmagen gas rate of flow).

Figure 3 shows the distribution of the power supplied to the system between the cooling of the cathode, the energy radiated from the plasma column and the energy supplied to an anode of molten copper, as a function of the arc length, for argon and nitrogen plasmas. The energy released at the anode is of course entirely useful energy since it is used to maintain the reacting system at the proper reaction temperature while supplying the endothermic heat of reaction, if the latter is required. This energy is supplied to the anode through the following mechanisms: electronic recombination (work function, Thomson effect and anode fall) accounting for about 65-70% of the total; convection from the hot plasma gas (about 25%) and radiation from the plasma column (about 5 to 10%). A very interesting finding was that electron recombination occurred over a very small area of the anode surface, only a few square millimetres in area.

The energy radiated by the plasma column increases as the length of the plasma column increases. Thus, it can become of the same order of magnitude as the energy released at the anode. If this energy can be usefully utilized, for example for the thermal pretreatment of the raw feed material, then the overall energy utilization of the system can be quite high. Figure 4 shows the percent power distribution.

Three unavoidable sources of heat losses still exist: the first heat loss is that required to cool the cathode; the second is the sensible heat lost in the effluent gases; the third is the heat loss through the walls of the reactor to the surroundings. Concerning the first, it is noticed from Figure 2 that the heat removed to keep the cathode cool accounts for less than 10% of the total energy supplied. It has been shown to be almost constant for a variety of operating conditions (arc length, current, plasma gas flow rate). It has also been shown experimentally that this heat can be recovered almost entirely by using the cold plasma forming gas as the cooling medium for the cathode, rather than cooling water. Heat losses through the walls and the roof of the reactor and crucible can be minimized by elimination of water cooling in these sections, and by the use of heavy insulation. Finally, the heat loss in the effluent gas is small, because of its comparatively low temperature level and of its small heat capacity.

In summary, it can be said that, when properly designed, the efficiency of energy utilization, of a transferred arc system, based on the energy supplied to the busbars, can easily exceed 80%.

There is another engineering consideration of some importance which should be mentioned, and that is the voltage-versus-current characteristic of the system. To obtain the power level required for a given application at a given rate of throughput, it is desirable to work at the highest voltage possible which can be sustained by the plasma column. A good understanding of the phenomena involved is provided by a knowledge of the radial and axial velocity and temperature profiles established in the plasma column, as illustrated by Figures 5 and 6. Thus, increasing the inlet velocity of the plasmagen gas past the cathode tip increases the temperature of the plasma column and the voltage across the latter. Similarly, a higher voltage is sustained if the plasmagen gas is introduced at 45° to the vertical just below the cathode tip. A lower voltage is measured if a 60° injection is effected. In this case as well, an increase in voltage is accompanied by an increase in temperature, and a slower temperature radial decay. It is also interesting to note that the column voltage drop is little affected by an increase in current, at least for currents less than 800 amperes, and that the voltage gradient in the column tends towards a maximum value of 10 V/cm at the higher values of inlet gas velocity (typically over 80 m/s) irrespective of the current.

Very much larger voltages are sustained when diatomic gases such as N_2 or H_2 are used, owing to the additional levels of energy provided by the dissociating molecules. Even larger voltages are observed when the H_2O is the plasmagen gas. The higher particle densities (number of charge carriers per cm^3) exhibited by these gases result in plasma columns of smaller diameter than, say, for argon, at a given power level. The energy radiated by these narrower columns to the surroundings is however considerably larger for a given column length. Finally, still larger increases in column voltage can be achieved by injecting the powdered feed material into the plasma column, below the cathode tip.

As far as the electrodes are concerned, no problem is encountered at the anode. If a cathode tip of thoriated tungsten is used, care must be taken that its temperature does not exceed its normal boiling point of 3 700 K. This can be insured by (1) good internal cooling; (2) a plasmagen gas injection velocity of at least 50 m/s and (3) a current density at the arc root not exceeding about 2 000 amperes/mm^2. For aggressive atmospheres (oxygen, steam, etc.), zirconia or zirconia-coated high-temperature metals offer reasonable life.

Best operation is obtained when the product in the crucible is tapped intermittently. For example, for a crucible capable of holding product resulting from eight hours of operation, tapping of its contents should be effected every four hours, during which approximately half of the charge can be removed. Should the material being treated be of such a nature that a slag layer should be formed on top of the molten product, this can be easily removed through tap holes. Product free from slag can then be removed through a lower tap hole.

A number of applications have been studied in this plasma system. The following are three examples on the production of ferromolybdenum, ferrovanadium and ferrocolumbium, respectively.

Molybdenum Production

Molybdenite concentrate (~55% Mo, 39% S) was fed into the plasma reactor with a plasma gas of nitrogen and an arc length of 11 cm. A product containing 0.085% sulphur was obtained. Industrial specifications call for a higher limit of 0.15% S. Chemical analysis of the impurities contained in the feed molybdenite concentrate and in the final product is shown in the following Table. It is important to note that considerable elimination of impurities (lead, antimony, bismuth, copper, phosphorus, etc.) occurred, in addition to the removal of sulphur. More volatile impurities (magnesium, sodium, potassium) are completely eliminated.

Impurities	Pb	Sb	Bi	Cu	P
Molybdenite, %	0.02	0.08	0.0042	0.288	0.01
Mo Ingot Produced, %	0.0057	0.021	0.0026	0.0287	0.003
Elimination, %	84	85	66	94	83

Ferrovanadium Production

Vanadium pentoxide was treated in the plasma reactor using argon and nitrogen plasma gas and an arc length of 5.5 cm with iron and carbon (1981 test). The product contained 79.4% V, 18% Fe and 0.6% C. This product was therefore very close to the 80% ferrovanadium required by the steel industry.

Ferroniobium Production

Pyrochlore (62% Nb_2O_5) was treated in the plasma reactor using argon and nitrogen plasma gas and an arc length of 7 cm with iron and carbon (1981 test). The product contained 43% Nb, 46% Fe and 2.6% C.

FEATURES OF TRANSFERRED ARC REACTOR DESIGN

1. A very high residence time to permit the reaction to go to completion is provided by the high capacity of the crucible. Reaction is expedited by the large amount of heat released at the anode arc root. This feature can be put to good use for the purpose of carrying out further reaction after the feed is stopped.

2. Refractory contamination of the product in the crucible is minimized by the provision of a salamander or layer of frozen product along the walls and bottom of the crucible.

3. Because of the simplicity of construction, design parameters have been established for scaling up of the reactor, for 50 kW, 300 kW and 3 MW, respectively.

4. Stirring of the bath for larger reactors can be provided by multiple anodes and/or magnetic stirring. The latter method is well known in the art.

5. There is considerable flexibility as to the choice of plasma forming gas: argon and nitrogen have been both thoroughly studied and their operating characteristics determined, as shown in Figures 1 and 2. Hydrogen can be used if a reducing atmosphere is required. It also provides a flame with a very large energy content. Methane and carbon monoxide can also be used if reducing conditions are required. Similarly, it has also been shown that a plasma of chlorine gas can be used to produce a chloride compound, for example, to convert ZrO_2 to $ZrCl_4$.

6. The design eliminates most or part of the volatile impurities. Thus, in the production of molybdenum, magnesium, sodium and potassium are totally eliminated. Copper, lead, zinc, arsenic, bismuth and antimony impurities are greatly reduced. Thus, a feed containing high percentages of impurities can be upgraded to yield a product of acceptable quality.

7. The reactor can also be used for remelting and upgrading operations, or for the treatment, at low additional energy cost, of a stream of molten metal for elimination of volatile impurities.

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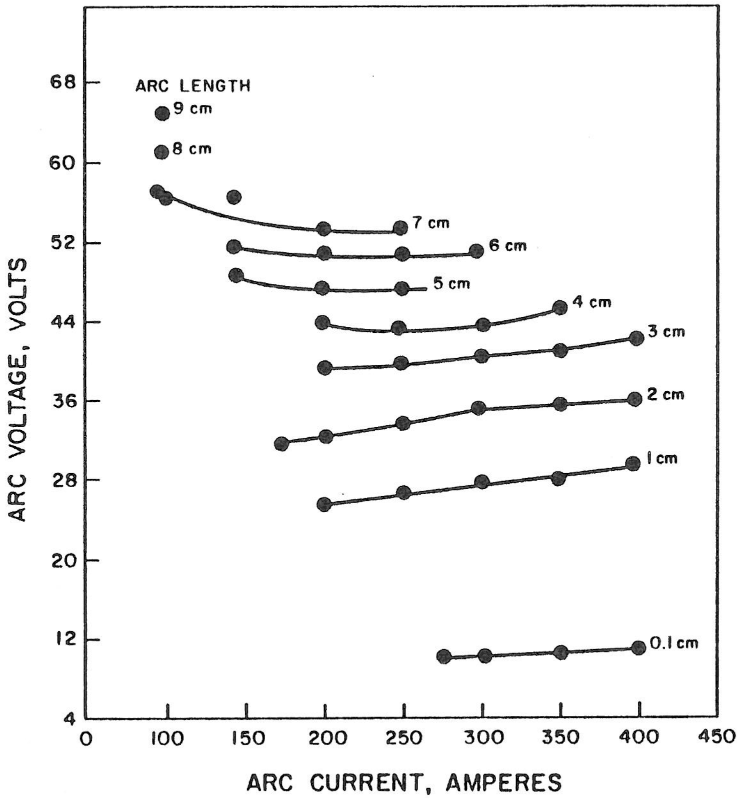

FIGURE 1

VOLTAGE-CURRENT CHARACTERISTICS
FOR ARGON PLASMA

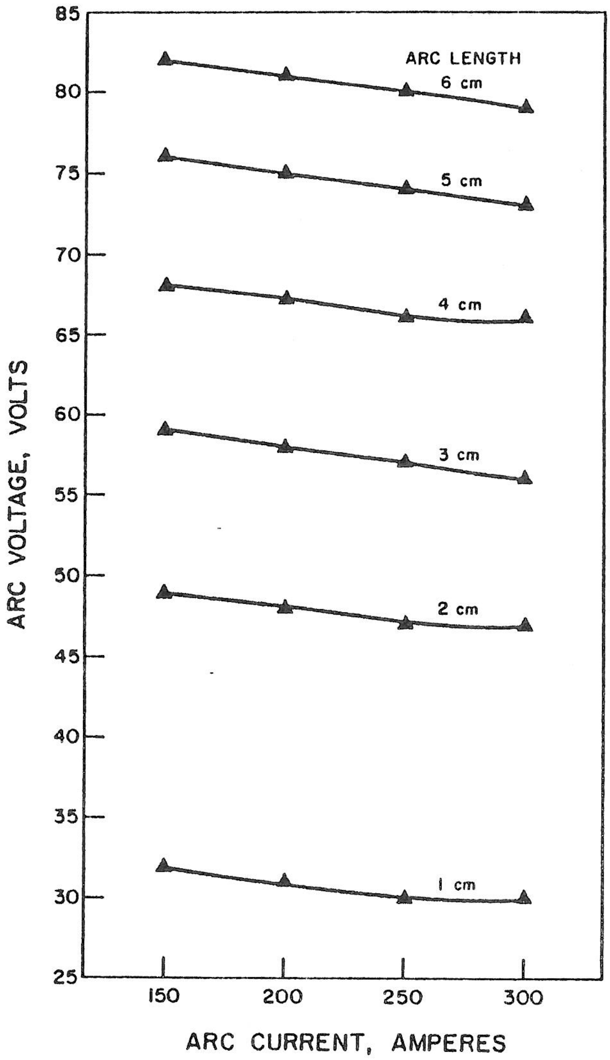

FIGURE 2

VOLTAGE-CURRENT CHARACTERISTICS

FOR NITROGEN PLASMA

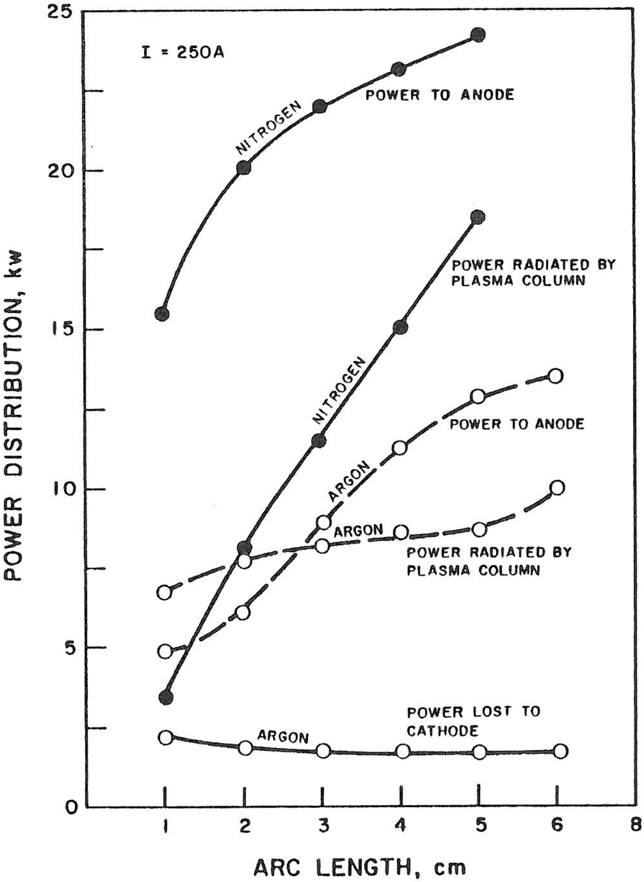

FIGURE 3

POWER DISTRIBUTION IN PLASMA
REACTOR, FOR ARGON AND NITROGEN
PLASMAS

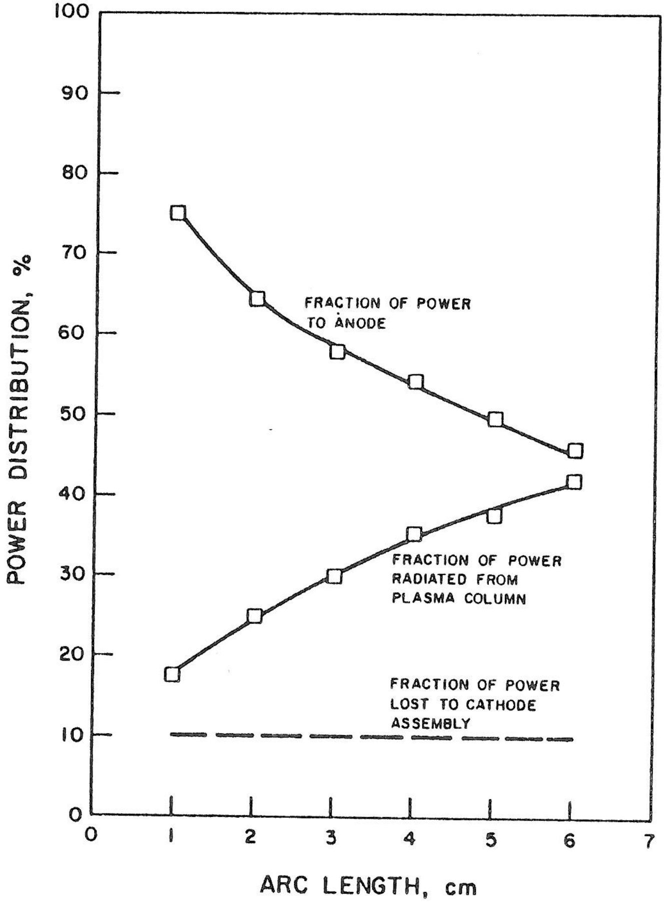

FIGURE 4

PERCENT POWER DISTRIBUTION FOR A NITROGEN PLASMA COLUMN, OVER A RANGE OF 150-350 AMPERES.

ANODE CONSISTS OF MOLTEN COPPER.

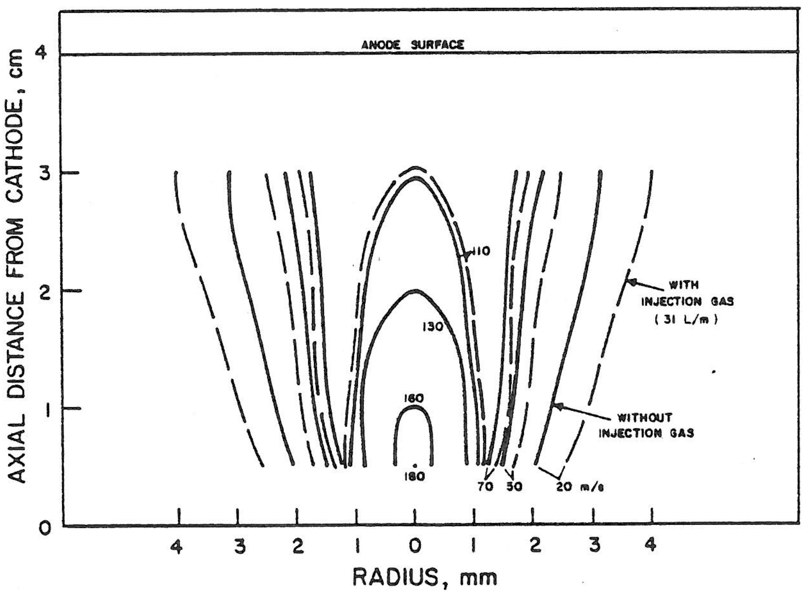

FIGURE 5

CONSTANT VELOCITY CONTOURS FOR AN ARGON PLASMA COLUMN

(Arc Length: 4cm; Current: 350 A;
Inlet Argon Velocity: 20.5 m/s)

(with and without injection of additional argon around plasma)

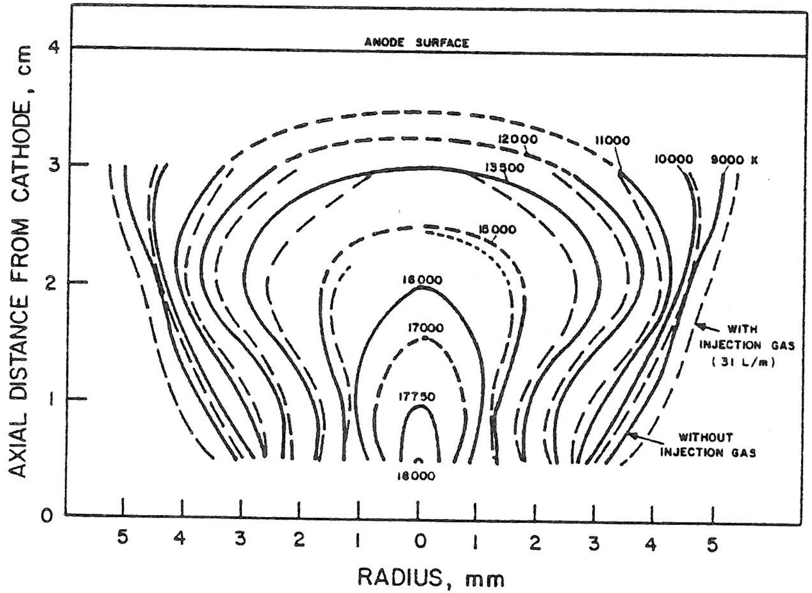

FIGURE 6

ISOTHERMAL CONTOURS OF AN ARGON PLASMA COLUMN

(Arc Length: 4 cm; Current: 350A;
Inlet Argon Velocity: 20.5 m/s)

(with and without injection of additional argon around plasma)