

Plasma-arc Technology for Ferroalloys, Part II

D. R. MAC RAE

Bethlehem Steel Corporation, Bethlehem, USA

This paper, the second part of a series, updates the technology with an emphasis on the selection of plasma-smelting furnaces for the production of ferroalloys and on related plasma applications for melting and heating.

The configurations of transferred and non-transferred arcs are reviewed, and the trends in the design of plasma-arc reactor systems and plasma-processing technology are outlined. Current industrial plasma installations are listed, and plasma reactors for the production of ferroalloys are discussed in detail. The paper ends with a list of over one-hundred publications.

Introduction

The article 'Application of Plasma Technology to Ferroalloy Processing'¹ was published in 1987. It discusses the rationale and fundamentals for the production of ferroalloys by plasma-carbothermic smelting reduction, and describes the processing fundamentals and the process developments for plasma-smelting applications, as well as relevant commercial developments, for ferrochromium, ferromanganese, ferrosilicon, ferromolybdenum, and ferrovanadium. The present paper updates the technology with an emphasis on the selection of plasma-smelting furnaces for the production of ferroalloys and on related plasma applications for melting and heating. This is therefore Part II of the topic.

Background

Over the past twenty years, plasma-arc technology has emerged as an alternative to the high-temperature processing of fines and bulk materials at power levels from 500 kW to 30 MW. In contrast, the power levels of plasma torches in powder spray-coating technology and cutting of metals are in the range 10 to 40 kW. Commercial uses have been established not only for the production of ferroalloys but also for the melting of specialty steels and refractory metals, and for temperature control of the tundish melts for continuous casters. There has been a substantial investment in pilot-plant development and industrial installations of plasma processes for the treatment of stainless- and carbon-steel plant dusts.

The present era of plasma technology was initiated during the 1960s as a result of the availability of plasma heaters that were developed to simulate re-entry conditions for the testing of space-vehicle materials. These heaters operated at high power levels of up to 10 to 30 MW, which provided the incentive for considering their use for large-scale industrial applications. Whereas these torches were used for the high-temperature heating of gases, plasma-arc heaters and furnaces of up to several megawatts were also being developed for the argon melting of specialty metals and steels.

The promise of plasma technology for industrial applications was its ability to generate high temperatures and the

accompanying high heat fluxes while maintaining control of the chemical potential of an oxidizing, reducing, or inert gaseous atmosphere. In addition, there was the perception that the plasma state could enhance the reaction kinetics owing to the existence of activated gaseous ions and radicals. Plasma-generated activated nitrogen [(N) and (N)⁺] species have been used to increase the dissolution of nitrogen in steel melts above normal equilibrium levels. This so-called 'plasma' effect has not been commercialized. Also, it was anticipated that, by a rapid quenching, unique reaction products could be produced selectively. For example, the rapid quenching of plasma-melted zircon sands can produce a non-equilibrium solid from the silica phase that can be leached to produce a zirconium oxide product. But, rapid quenching techniques in mineral processing have had very limited application. In general, the application of plasma-arc technology has been as a high-temperature, high-heat-flux source of energy. The ability to regulate the energy input under controlled gas conditions favours the development of materials processing that eliminates or minimizes the environmental impact.

Plasma Heaters: Transferred and Non-Transferred Arcs

Plasma technology can clearly be divided into two distinct heater configurations: heaters designed for the bulk heating of condensed phases including both melts and solids, and heaters designed for the bulk heating of gases. Both types of heaters can be used for the heating of powders through the transfer of heat by melt conduction and/or gaseous convection. The condensed-phase heaters used for the processing of melts are termed 'transferred'-arc heaters since the arc is transferred from an electrode to the workpiece such as a metal melt that serves as the other electrode. The gas heaters developed for the testing of re-entry materials are termed 'non-transferred' since the arc remains within the heater barrel solely to heat up the gas. These modes of heating are shown in Figure 1, and their characteristics are described in Table I. The unifying characteristic is that both heaters involve a working gas in the arc environment. For a non-transferred arc, the working gas can be the bulk gas

TABLE I
MODE OF ARC ATTACHMENT: TRANSFERRED AND NON-TRANSFERRED

	Transferred	Non-transferred
Gas flow/power ratio	Low	High
Gas type	Inert/reactive	Inert/reactive
Power level	40 MW	6 MW
Current voltage limits	100 000 A 1 000 V	3 000 A 10 000 V
Heater efficiency	90 to 100 %	75 to 85 %
Reactor function	Bulk heating	Gas heating
Reactor design	Crucible	Shaft
Scale-up	Graphite electrodes	Multiple-heater units

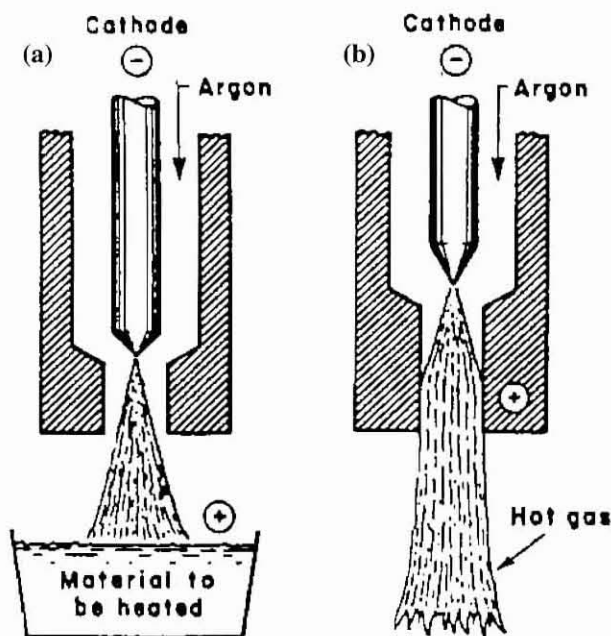


FIGURE 1. Plasma heaters
(a) Transferred mode of arc attachment
(b) Non-transferred mode of arc attachment

that is to be heated. For a transferred arc, the relative flowrate of the working gas injected into the heater can be much smaller.

Over the past twenty years the major trend in the design of plasma reactors has been the increased use of transferred-arc systems. Low flowrates of gas decrease the total energy requirements. If an expensive argon atmosphere is required, the low flowrates further minimize the costs. The size of the downstream equipment for gas handling, cooling, and clean-up is minimized, which may represent substantial savings in capital and operating costs. Low gas volumes may be dictated by the thermodynamic conditions (gas partial pressures and temperatures) that are critical for processes involving metal volatilization, intermediate gaseous species, and condensing of products.

Trends in the Design of Plasma-arc Reactor Systems

Plasma-arc reactor systems are built around the plasma-arc device, which may be referred to as a heater, torch, generator, or gun. The plasma-arc reactor, which may be a simple melter or a more complex smelter, includes a reactor chamber such as a crucible or hearth furnace, or may be a space such as the reaction-zone cavity formed in front of plasma

tuyères in shaft furnaces. The mode of arc attachment, as either transferred or non-transferred, is only the first of several design options for the plasma device or heater. In addition to the attachment mode, design options include the electrode materials (e.g. copper, tungsten, graphite); water-cooled or non-water cooled electrodes; a.c. or d.c. operation; the electrode polarity for d.c. arcs, or for single or multiphase a.c. arcs; the composition and feed rate of the working gas; powder feeding upstream, within, or downstream of the fully developed arc and/or through the electrode body; arc stabilization by magnetic, mechanical, and/or aerodynamic means. A multitude of plasma devices have been designed based on various arrays of options, and have been patented and promoted for high-temperature processing applications, including the production of ferroalloys. It is not the intention in this paper to critically dissect all the possible devices. It is sufficient to note that the selection of the plasma device strongly determines the reactor configuration and design of the process system. The purpose of this paper is to outline the development of plasma ferroalloy processing and to describe the direction that the plasma-reactor designs have taken.

A major feature that distinguishes a plasma-arc reactor from the conventional electric-arc furnace is the influence of the gas phase on the reactor design². This distinction is apparent if experiences with plasma reactors are considered in the analysis of submerged-arc operations using hollow electrodes through which gases and/or solids are fed into the reaction space of the arc attachment. For the design of a plasma-arc reactor, a convenient starting point can be a consideration of the role of the gas phase in heat and mass transfer and any chemical reactions involved. The factors to be decided on are the

- (1) type of gas: inert or reactive;
- (2) the flowrate: low or high;
- (3) the interaction with the reactants: chemical or physical;
- (4) the importance as a heat-transfer medium; and
- (5) the effect on arc stability.

Inappropriate plasma reactors were designed when the concept of 'plasma enhanced reactions' via the excited gas species was in vogue and the direct contact of particulates 'passing through the arc' was emphasized. Also, non-transferred gas heaters have been inappropriately used for bulk processing when the low gas flowrate of a transferred-arc system would have been a distinct advantage. The trend in simplification is also evident in the designs of transferred-arc reactors in which the water-cooled tungsten cathodes have been replaced by hollow (non-water-cooled) graphite electrodes¹⁰. A major breakthrough in the use of transferred heaters for the processing of solid fine particulates was the development of hollow graphite electrodes by Mintek/ASEA. This development eventually resulted in the 30 MW (40 MVA) ferrochromium installation at Middelburg Steel & Alloys (MS&A) in Krugersdorp, South Africa. This evolution in reactor design occurred recently in the development of the plasma processing of electric-arc furnace dust, which uses hollow graphite electrodes⁶⁷ instead of water-cooled tungsten cathodes. The relative advantages of graphite-electrode operation are as follows:

- lower consumption of gas
- no source of water in the furnace reactor
- no limit on current-carrying capability
- possible use of nitrogen to replace argon
- capital saving on deionized water circuit and on instru-

mentation

- may operate with foaming slags
- no energy loss through cooling of the electrodes
- no skilled repair required.

The stated disadvantages are that there is a consumption of the graphite electrode, and the insulation of the electrode and roof seal is critical.

It is inevitable that this spread of plasma technology to less complex high-temperature applications and the dominance of less complex plasma devices will continue. To paraphrase Albert Einstein, 'Plasma reactors should be made as simple as possible but not too simple', or, in steel-makers' vernacular, 'KISS' – Keep It Simple.

Trends in Plasma-processing Technology

The major process trend has been the increasing development of simple heating applications. Twenty years ago the high expectations for plasma technology included the most complex of high-temperature chemical-reaction systems such as the smelting of chromite ore. Today, the greater market potential for repeated installations has emphasized the development of simple systems for maintaining the temperature of melts or providing an incremental energy input at high temperatures, for example in continuous-casting tundishes and in steelmaking-refining ladles. A sign of the technical maturity of plasma technology has been the repeated installation by several vendors of the same development, such as tundish melt heating.

The widespread use of plasma-processing technology is just beginning. In the field of pyrometallurgy, it is quite

common for the development and adoption of new processes to take upwards of ten to twenty years. This is due to the inherent difficulties involved in the development of high-temperature processes, the maturity of the entrenched technology, and the substantial capital investment that is required for new facilities. In addition, plasma processing has had this technological 'identity crisis', which has involved inappropriate applications and has been viewed as 'a solution looking for a problem'. Initially, inappropriate applications grew out of overly broad and ambitious expectations for a new and 'glamorous' processing tool. Two highly visible current 'problems' for plasma processing are the increasing demands for cleaner and higher-quality metallurgical products, and the environmental demands in the treatment of hazardous materials.

Present Industrial Plasma Installations

The present electrical capacity for the plasma-furnace production of ferrochromium and ferromanganese is about 100 MW, as shown in Table II. In addition, there is commercial capacity of about 25 MW for the melting of ferroalloy revert fines, slags, and stainless-steel dusts. There are indications of a gradual growth in plasma-smelter capacity with the recent upgrade in 1989 of the MS&A ferrochromium smelter from 14 to 30 MW, and the proposed installation of a 12 MW ferrochromium smelter at MacAlloy in Charleston, S. C. The SwedeChrome plant of 48 MW has not been operating since 1990 owing to economic conditions. The processing of ferroalloy and stainless fines is established technology.

TABLE II
INDUSTRIAL PLASMA INSTALLATIONS FOR THE PRODUCTION OF METALS AND ALLOYS

Process	Feed	Product	System	Power capacity	Start-up	Plant location	Reference
Plasma crucible smelting	Cr ore	FeCr	ASEA/Mintek	14 MW	1983	Middelburg Steel & Alloys, Krugersdorp, SA	15
	Crushed fines			(Upgraded from 14 to 30 MW)	1989		18
	Cr concentrates	FeCr		12 MW [MacAlloy plant]	199?	South Carolina Research Authority, Charleston, S.C.	22
Plasma blast furnace smelting	Mn ore	FeMn	Aerospatiale	3 x 1,5 MW	1984	SFPO, Boulogne-sur-Mer	27
	Cr ore	FeCr	SKF Plasma-chrome	8 x 1,5 MW	1986		
	Crushed fines			4 x 6 MW (two shafts)	1988 (mothballed in 1990)	SwedeChrome, Malmo Sweden	24, 25
	Iron ore	Fe	Aerospatiale	6 x 2,0 MW	1987	Lorfonte (HFRSU), Lorraine	74
Reduction/melting	Ferroalloy crushed fines	FeMn	Freital/Voest-Alpine (Mintek)	3 MW	1983	Samancor, Meyerton, S.A.	30
	Baghouse fines	Cr, Ni, Mo, Fe	SKF Plasma-Dust	3 x 6 MW	1986	ScanDust, Landskrona, Sweden	48
	Crushed fines process slag	FeCr charge feed	Tetronics R&D	1,5 MW	1988	Ferbasa, Brazil	19
	AOD/EAF dust	Cr, Ni, Mo ZnO	Tetronics R&D	3 MW	1989	British Steel, Sheffield	49a
	EAF dust	Zn, Pb, Cd	Tetronics R&D	2 MW	1989	Florida Steel, Jackson, TN	66, 67
	EAF dust	Zn, Pb, Cd	Tetronics R&D	3 MW	1989	Nucor-Yamato, Crawfordsville, AR	66, 67
	Stainless dust	Cr, Ni	Tetronics R&D	7 MW	1991	Multiserve, Italy	49b
	EAF dust	Cr, Ni, ZnO	Hollow-graphite cathode (pilot)	1 MW	1989	Mintek, S.A.	71
	EAF dust	Cr, Ni	Hollow-graphite cathode (pilot)	1,5 MW	1990	Chiba Works, Kawasaki	50
	Automobile-emission catalysts	Pt	Tetronics R&D	3 MW	1984	Multi-Metco Anniston, AL	81

The melting and refining of alloy scrap, particularly titanium scrap and sponge, is a very promising growth area for plasma processing. As noted in Table II, the simple plasma heating of continuous-casting tundish melts to control the temperature at which the steel is cast has shown significant growth over the past five years, and promises to become standard practice. Industrial by-product resource, recovery, and recycle, and the treatment of hazardous materials, have spawned many plasma-based processes for which the ultra-high temperature capability, the gas environmental control, and the ability to treat fines are unique and attractive processing features.

In addition to these industrial installations, there are several plasma-based metallurgical processes now under development including the following:

	Reference
• <i>Magnesium production</i>	
– Mintek/Samancor, S.A.; 2 to 3 MW (demo)	54
– Billiton Research, 600 kVA (Cameron and co-workers)	55, 56
• <i>Remelting/smelting of silicon-metal fines</i>	
– Mintek	36
– SINTEF	37(a), (b)
– Dow Chemical	35
– Kawasaki Steel	38
• <i>Melting and recovery of aluminium metal</i>	
– Hydro Quebec; PEC/Alcan	63, 64
– Center for Materials Production, EPRI	65
• <i>Recovery of zinc from residual dusts</i>	
– Plazmet (Houston, Texas)	70

Plasma Reactors for Ferroalloy Production

The industrial potential of plasma-arc reactor systems for the production of ferroalloys was established³ with the development during the early 1970s of a 1 MW facility for the carbothermic reduction of vanadium oxides, which produced standard-grade ferrovanadium⁴³. This pilot-plant facility operating at 0.5 MW produced ferrovanadium at a projected rate of 1 million pounds a year. This was sufficient to supply 10 per cent of the US consumption, or all of Bethlehem Steel's ferrovanadium requirements for the production of vanadium-alloyed steels. Bethlehem Steel had just developed a process for the extraction of vanadium oxides from a South American source of iron-ore pellets. The plasma-ferrovanadium process provided the potential for fully integrated vanadium sourcing from the ore through to the steel product.

The design of the plasma-ferrovanadium system included the 'falling film' plasma reactor, as shown in Figure 2. This reactor had been developed at 1 MW for producing steel direct in a 'one-step' process by the reduction of iron-ore concentrates with mixtures of hydrogen and natural gas. The product⁷² was pure iron (0.006 per cent C, 0.06 per cent Si, 0.005 per cent S, 0.001 per cent P, 0.007 per cent Cu). The economic incentives for this process were the low cost of natural gas at that time and the anticipated decline in the costs of electrical energy. The 'falling-film' plasma reactor was unique in that the basic design was a non-transferred arc heater in which the hydrogen and natural gases had the multiple function of stabilizing the arc as well as heating and reducing the iron oxides. In addition, the gases conveyed the iron oxide into the arc environment. The falling-film concept allowed the residence time of the iron oxide in the reactor to be independent of the residence time

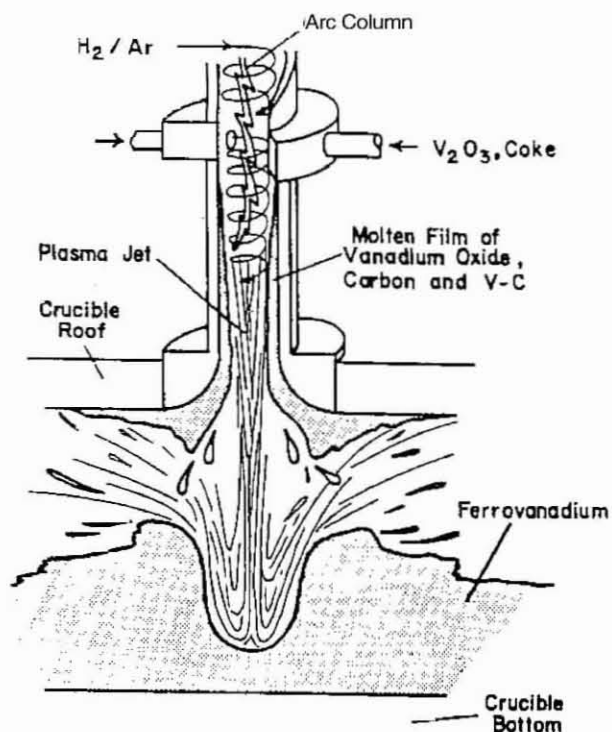


FIGURE 2. Falling-film 1 MW plasma reactor for the production of ferrovanadium⁴³ (a non-transferred heater operated with the arc transferred to the falling-film)

of the gas phase. In comparison, for the reduction of vanadium oxide by solid carbon, the function of the gas phase was to stabilize the arc and transfer the energy for the reduction reaction. The carbon reductant was included in the solids feed, and there was no stoichiometric relationship between the gas and the vanadium oxide as there was in the reduction of iron oxide⁴.

The development of the falling-film reactor for carbothermic reduction was extended to the production of ferroniobium, ferrochromium, ferromolybdenum, and ferroboration, the processing of ilmenite ores, and the carbon reduction of iron oxide concentrates. In that programme, from 1967 to 1981, it was apparent that there were no 'plasma effects' that could be attributed to highly excited gas species, but that the reactions followed conventional thermodynamic analyses. The uniqueness of the reactor was as a source of high temperatures and high heat fluxes. In this context, it is, in fact, more suitable to refer to these types of systems as 'electric arc reactors' rather than 'plasma reactors'.

The gas-stabilized non-transferred arc has inherent economic disadvantages associated with the cost of the feed gas, the increased sensible heat lost to the off-gas, and the increased cost of handling and cleaning a larger volume of exhaust gas than just the product gas of the reaction. The ferrovanadium development used argon as the arc-stabilizing gas. In further developments, carbon monoxide, as the process product gas, was demonstrated to be a suitable working gas⁴⁴. A plant installation for the recycling of carbon monoxide product gas would require a cleaning, storage, and compression loop, which increases the gas cost, particularly for a small facility. The use of the non-transferred arc instead of a transferred arc results in higher heating losses to the cooling water, and therefore a less efficient use of the input power. For example, the efficiency of water-cooled torches is about 80 per cent for non-trans-

ferred-arc operations as compared with 95 per cent for transferred-arc operations. The efficiency of transferred-arc, graphite electrodes that are not water-cooled and have minimal heat losses is nearly 100 per cent. It was also apparent that, although the reduction of iron oxide with hydrogen and natural gas dictated a non-transferred design for the heating of the reactant gases, a transferred arc to a bulk melt could also be used for carbothermic reactions⁴⁰.

In 1979, ASEA announced the ELRED process for the production of iron using coal of non-metallurgical grade^{73a,b}. The iron oxide fines were prereduced in a fluidized bed. Final smelting reduction occurred in a d.c. furnace with the arc transferred from a hollow graphite electrode to the iron melt, which had a bottom anode connection. The prereduced concentrate and char were fed through the hollow electrode to the arc/melt region, as shown in Figure 3^{73c}. The scale-up potential and relative simplicity of the ELRED process using a transferred-arc furnace had eclipsed Bethlehem's programme to develop a plasma-steelmaking process using a solid carbon reductant.

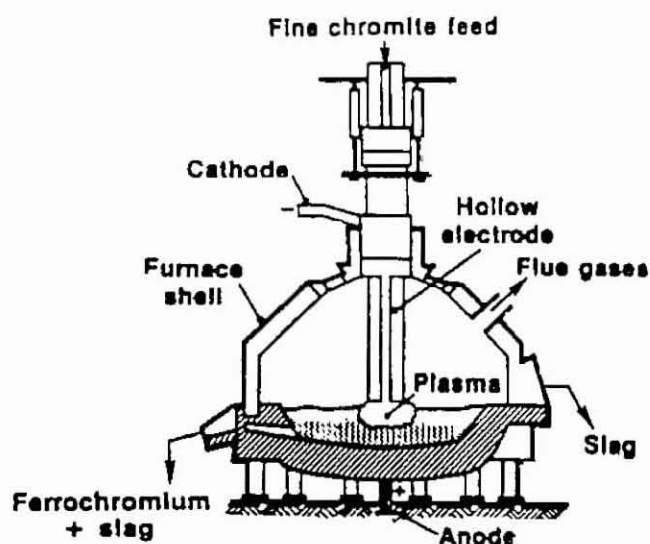


FIGURE 3. ASEA hollow graphite-electrode reactor developed by Mintek and MS&A up to 14 MW and 30 MW for the production of ferrochromium^{15,18,73c}

At that time, the implications of the ELRED development for the plasma production of ferroalloys were discussed⁵ with representatives from the National Institute for Metallurgy, now Mintek. By July 1979, Mintek had already initiated programmes with MS&A for the plasma reduction of chromite ores using the transferred-arc system of Tetronics Research & Development (TRD) with its characteristic preheating cathode assembly, as shown in Figure 4¹³. Mintek also installed a 100 kVA non-transferred a.c. furnace based on the extended arc-flash reactor¹⁴, shown in Figure 5, which had demonstrated the feasibility of reducing chromite-ore fines in an open-bath process^{12a,b}. Following extensive pilot-plant testwork at Mintek supported by MS&A, it was announced¹⁵ in December 1982 that a plasma smelter developed by Mintek using the ASEA ELRED hollow graphite cathode principle was to be installed at MS&A with a power level of 12 to 14 MW for the production of ferrochromium. The upgrade³⁰ in 1989 by MS&A from 12 to 30 MW accomplished the projection³ made by Mintek in 1977 that the production of ferrochromium from friable chromite ores was the most impor-

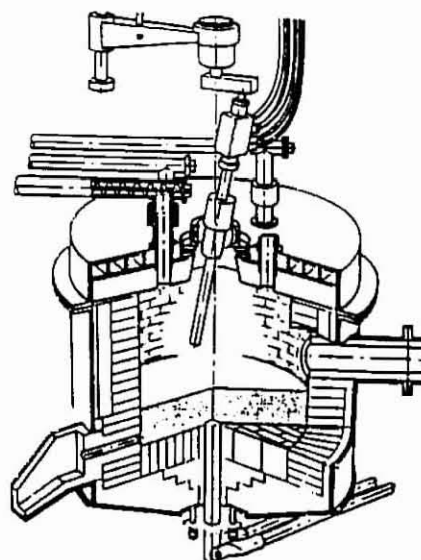


FIGURE 4. Tetronics Research & Development (TRD) sweeping-arc plasma furnace at 1 to 3 MW with gravity/roof particulate feeding for the melting of ferrochromium fines¹⁹ and tundish heating⁸⁸⁻⁹⁰

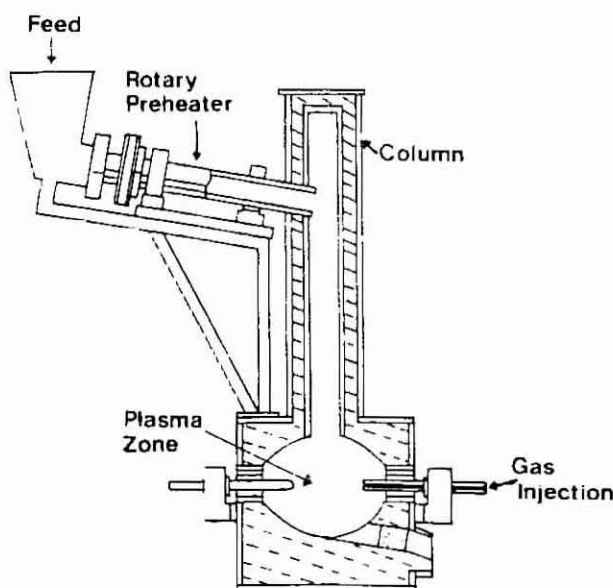


FIGURE 5. EAFR (extended arc-flash reactor) horizontal graphite electrodes with a non-transferred arc used at 100 kVA for ferrochromium trials¹⁴

tant plasma ferroalloy application and would require a furnace rated at 20 to 40 MW.

The multi-megawatt scale-up of the Bethlehem plasma reactor, which was projected to be a lengthy and costly development, was not undertaken. A d.c. furnace, the 'plasma reactor', had been operated by ELRED at Avesta in Sweden at the 10 MW level without solids feed, and scale-up to 50 MW was planned although it was never commercialized. Solids feeding was demonstrated at the metallurgical research station, MEFOS, in Luleå, Sweden, with a 3 to 4 MW hollow electrode furnace. ASEA has continued to develop and market the d.c. furnace for scrap melting. Such scrap melters are now being installed up to the 80 MW level (UNARC furnaces supplied by MAN GHH)⁶. Commercial installations of plasma systems for the production of ferroalloys also include the SwedeChrome plant based on SKF gas heaters, shown in Figure 6^{24,25}, and the

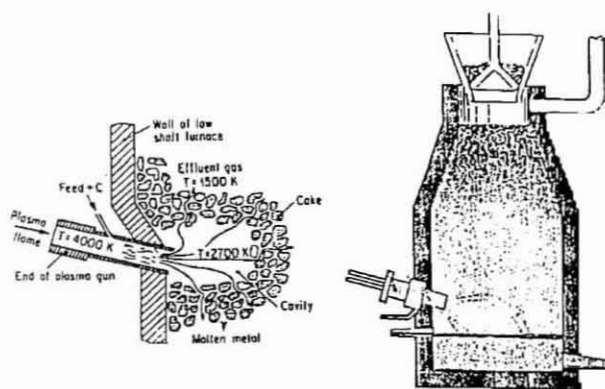


FIGURE 6. SKF 'SwedeChrome' shaft furnace using four 6 MW non-transferred gas heaters with tuyère injection of solids^{24, 25}

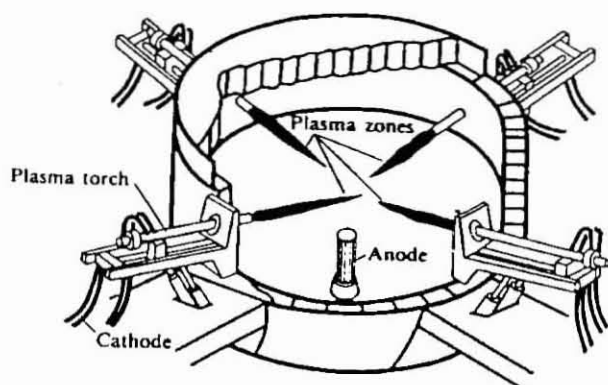


FIGURE 7. Voest-Alpine (Freital) transferred-arc furnace using water-cooled tungsten-cathode arc heaters for the melting of ferromanganese fines³⁰

Samancor Metalloys ferromanganese plant³⁰ based on the Voest-Alpine transferred-arc design, shown in Figure 7 but with a single vertical cathode.

The technical feasibility of the plasma carbothermic reduction of oxides to produce ferroalloys was demonstrated by all the reactors shown in Figures 2 to 7. The choice is basically between operation with a transferred or non-transferred arc, and whether a water-cooled electrode and heater design is required. The primary consideration for the selection of a plasma (or for that matter) reactor system for pilot-plant development is 'can the reactor be scaled-up for an industrial operation?'. For the commercial production of ferroalloys, the most successful plasma system has been demonstrated to use the basic, unsophisticated design, as shown in Figure 3, of a vertical non-water-cooled, hollow graphite electrode (HGE) with a d.c. arc transferred to a conductive melt. This ultimate design of a plasma ferroalloy reactor as demonstrated by the MS&A 30 MW facility follows the 'Keep It Simple' principle.

Scale-up to the multi-megawatt range is the unique feature of the hollow carbon d.c. electrode, particularly for the production of ferrochromium. The single carbon electrode can sustain d.c. currents at least up to 100 000 A. In comparison, the water-cooled tungsten electrodes used in the Voest-Alpine and TRD systems operate at 5000 A with a reasonable lifetime of about 150 hours and with an upper limit of about 10 000 A. For these transferred-arc systems, the power levels are therefore limited to about 4 to 5 MW, corresponding to operating voltages of 400 V. The SKF non-transferred gas heaters with water-cooled copper electrodes for the SwedeChrome plant are rated at 6 to 7 MW.

Industrial production using non-transferred arc technology beyond several megawatts requires the use of multiple torches, as shown by the SKF SwedeChrome plant²⁴ and the SFPO ferromanganese blast furnace²⁶.

Aside from the flexibility that scale-up capability provides, the two outstanding advantages of the hollow graphite electrode system are the absence of cooling water and the low flowrates of arc gas. These design advantages result in lower investment costs for the auxiliary systems, both for water supply and discharge, and for the cleaning and handling of the exhaust gas. The absence of water-cooling is a particularly important safety advantage since any possible water-melt explosion risk is eliminated. The energy-efficiency advantage of the hollow graphite electrode system is obvious since there are no energy losses due to the sensible heating of water and no losses of excess operating gas. This is of particular importance with the use of a high-grade energy source such as electricity. As noted in Figure 8 for the SKF process, the energy utilization based on the ferrochromium and gas products is about 67 per cent. In comparison, for the Middelburg 30 MW operation, the energy utilization is about 85 per cent.

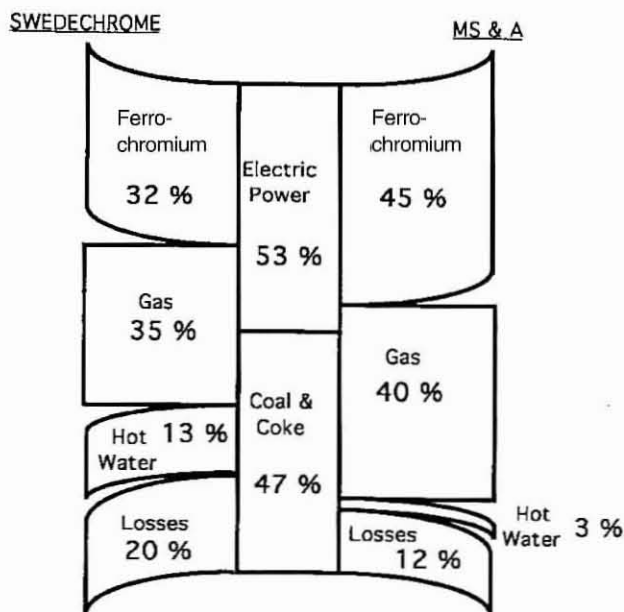


FIGURE 8. Energy flow diagrams: SwedeChrome and MS&A plants for the production of ferrochromium

Although industrial-worthy water-cooled heaters, both transferred and non-transferred, have operated reliably, carbon electrodes are less susceptible to damage resulting from operating conditions and rough handling during installation, both of which can cause water leaks, electrical faults, and short electrode lifetimes. This is particularly apparent in larger-scale operations with dusty surroundings producing tonnage products, in comparison with small power-level torches, which are often used in ultra-clean environments typical of the production of low-volume specialty metals.

Recent Developments in Plasma-ferroalloy Production

The plasma production of ferroalloys is a well-established technical fact. Some commercially driven changes have been noted with the expansion of the MS&A ferrochromi-

um plant and the closing of the SwedeChrome facility. The technology is maturing, and there is a certain attitude of confidence as expressed by the plans to install a 12 MW ferrochromium plant in South Carolina²². There have been a number of speculative development projects, such as the Voest-Alpine/Dow Corning pilot-plant efforts to produce silicon and ferrosilicon³³, and the Davy McKee 5 MW ferromanganese remelter³¹. These efforts are to be encouraged since the technology is still young and advances can still be made, particularly in the understanding of how best to optimize the reaction systems and so improve the yield and decrease the net consumption of energy.

Ferrochromium

The capability for the processing of unagglomerated fines (ore, fluxes, and reductants) is the primary economic advantage of plasma reactors for the production of ferrochromium. The charge can be fine chromium ore, concentrates from friable chromite ore, or crushed ferrochromium fines. In particular, where the chromium content is upgraded by ore crushing and further beneficiation, the fine concentrates that are produced are very suitable as feed for a plasma reactor. The fines feed rate must be matched to the power level. High feed rates with respect to the input power will result in the accumulation of unreacted feed. At low feed rates, excess energy is available, and the temperature will increase, which can result in furnace damage, undesirable reactions, and high requirements of unit energy.

Middelburg Steel & Alloys (MS&A), Krugersdorp, South Africa

The commercially successful MS&A 12 to 14 MW plant has been expanded to 30 MW. The 12 MW plant ASEA d.c. hollow graphite electrode furnace was introduced in December 1983, and replaced an existing 9 MW submerged-arc furnace. The process was initially developed at Mintek on a 1 MW scale, and required further improvements for industrial scale-up^{15,16}. It is common in the development of plasma furnaces that major difficulties are experienced in the conveying and feed-rate control of the fines, and less on electrical problems such as unstable or stray arcs. An extensive analysis of the sensitivity of the balance of feed rate to power as related to the arc-attachment zone has been made by Barcza, Curr, and Jones¹⁷.

Improvements on the MS&A 12 MW plant included better control over the feed rate to closely match the power level, and monitoring of back-pressure in the electrodes and selection of the appropriate diameter to minimize electrode blockages. Changes were also made in the design and operation of the gas-cleaning system and the off-gas ducts. Modifications to the slag chemistry also helped to decrease the carryover of dust in the exhaust. The chromium recovery was 90 to 95 per cent. The consumption of energy was slightly higher than for a submerged-arc furnace but, with scale-up, the consumption of energy would be similar to that for the submerged arc furnace. Other developmental work has included the production of a high-chromium (75 to 80 per cent), high-carbon ferroalloy to form a superchromium slag (Cr:Fe 10 to 20:1). This slag was produced in the plasma furnace by selective reduction of iron out of chromite ore to produce a semi-stainless alloy⁷ (20 per cent chromium).

At the end of 1988 after a five-year developmental period, the 12 MW (16 MVA) operation was upgraded to 30

MW (40 MVA) at a cost of \$10 million¹⁸. The 40 MVA plasma furnace installed at Krugersdorp replaced the 16 MVA d.c. plasma-arc furnace. The prevailing market demand for ultra-low silicon and phosphorus alloy and for low-silicon alloy, and the abundant availability of low-cost feed fines and the increased thermal efficiency with scale-up, were economic incentives for this further expansion. The plant was recently bought by Samancor and is now called Palmiet Ferrochrome Division.

Mannesmann Demag, Dalmacija Plant, Dugi Rat, Yugoslavia

Chromium-ore fines of up to 28 per cent of the feed mix of coke, quartz, and ore were fed in a test trial through a hollow electrode of a 20 MW submerged-arc a.c. ferrochromium furnace. The test results were encouraging in that the chromium recovery increased, there was a high smelting rate due to faster smelting in the arc, and a means was established for the recycling of baghouse dust and ferrochromium reverts²⁰. No further trials have been reported.

Strictly speaking, this development in a submerged-arc furnace should perhaps not be included in a discussion of plasma reactors; that is, there was no discussion of the arc characteristics or reaction-zone kinetics that would have been influenced by the feed of solids or gases through the arc region. From this standpoint, the designation of an electric-arc process as a plasma-arc process becomes purely subjective. It is quite reasonable, though, to regard this work as an outgrowth of the MS&A d.c. hollow graphite electrode open-bath process for the production of ferrochromium.

South Carolina Research Authority, Charleston, S. C.

The hollow carbon electrode plasma furnace is now being developed for domestic raw materials in the USA. In 1989, the Strategic Materials Office of the U.S. Defense Logistics Agency funded the development²¹ of a 1.5 MW plasma furnace for the production of ferrochromium²¹. The facility is sited at the MacAlloy plant in Charleston, S. C. The intention of the programme is to establish a domestic ferrochromium capability using US chromium-ore sources. Low-grade US ores can be upgraded by crushing and beneficiation to produce a 40 per cent chromium oxide concentrate. The processing of these concentrates in conventional submerged-arc furnaces would require costly agglomeration of the fines. The pilot-trials at 1.5 MW successfully completed at the end of 1991²² have provided the design basis for a larger demonstration plant. A 12 MW facility to be sited at MacAlloy is being considered.

A recent evaluation concluded that Bird River chromite ore would be exceptionally well suited to reduction in a plasma furnace²³. It is apparent that the existence of plasma-furnace technology for the processing of ore fines will stimulate reconsideration of other chromite-ore reserves for the production of ferrochromium.

SwedeChrome, Malmo, Sweden

In glaring contrast to the 1988 expansion of the MS&A plant, the 48 MW SwedeChrome plant that started up in October 1987 was shut down in 1989, and reportedly is for sale. Although the ferrochromium market may have been the decisive factor, it is recognized that the process technology and site conditions are not comparable with those of

the MS&A plant. The SwedeChrome plant is based on SKF non-transferred plasma-gas heaters. Chromium-ore fines, along with a blend of lime, silica, and coal, are fed into four tuyère zones in the front of the plasma heaters at the bottom of a coke-filled shaft, as shown in Figure 6²⁵. The SwedeChrome plant has a hybrid energy input of electricity, coal, and coke, producing not only ferrochromium and hot water for district heating, but large quantities of fuel gas. Based on the energy flow diagram (Figure 8), the heater efficiency is about 80 per cent, which is not uncommon for a non-transferred arc design. This represents a production of about 5 MW of relatively low-grade hot water. The process economics requires a use for this excess energy. A thermochemical model²⁶ indicated that the process was flexible, permitting many process variations that allowed the optimal selection of feed materials.

Ferromanganese

The high volatility of manganese (e.g., 174 mm Hg, 1762 °C) is a critical factor in the design of a furnace or process for the production of ferromanganese. In the conventional processes, the ferromanganese blast furnace and the submerged-arc furnace, the manganese vapours are captured by condensation on the burden charge of ore and coke.

SFPO, Boulogne sur Mer, France

The Societe du Ferromanganese de Paris-Outreau (SFPO) has three ferromanganese blast furnaces with a total capacity of 400 kt per year²⁷. The highly endothermic carbon reduction of MnO occurs at temperatures above 1250 °C in the lower part of the furnace, and results in a high consumption of coke with the production of an off-gas rich in carbon monoxide. Only one-third of this off-gas can be utilized in the hot-blast stoves; the remainder is used for the generation of electricity, which is a valuable byproduct during the winter when the electricity demand is high. During the rest of the year, the seasonal demand is low, and the relative value of electricity is also low. In 1984, SFPO installed three 1.5 MW Aerospatiale plasma-gas heaters to utilize the generated electricity on site during periods of low demand to further superheat the hot blast. For every 100 °C of additional blast temperature, the calculated coke savings were 52 kg per tonne of ferromanganese. The initial trials were successful, and in 1986 five additional plasma heaters were installed for a total of 8 of the 9 tuyères having a blast superheated by plasma heaters. The blast temperature has been increased from between 1150 and 1200 °C up to 1500 °C, with coke savings of about 170 kg per tonne of ferromanganese; the replacement rate, at 500 kWh per tonne of ferromanganese, is 3 kWh per kilogram of coke. Substantial improvements were required in the design of the plasma/hot-blast tuyères and adjacent refractories to accommodate the higher blast temperatures. Additional design improvements to the plasma heaters resulted in an increase of heater efficiency from 62 per cent in 1984 to 72 per cent by 1989. The lower coke rates, i.e. less shaft volume occupied by coke, resulted in an increase of 20 per cent in productivity and also a smoother operation with better furnace control.

This successful application of plasma technology to the ferromanganese blast furnace has not been repeated for electric-furnace hearth reactors. It is evident that, for an open-bath plasma system, there will be manganese losses to

the gas phase. A recent analysis²⁸ emphasized the need to recycle volatilized manganese vapours, e.g. with a molten-slag filter, and that existing transferred-arc reactors, however capable of reducing manganese ores, must be designed for condensation. Two suggested concepts are

- (1) the injection of manganese and coal fines into the tuyère level of a shaft furnace, which could be done in shafts of SFPO and SKF design equipped with non-transferred heaters;
- (2) a design of a non-transferred arc-gas heater with a falling film of manganese-rich slag that is eventually reduced to produce manganese, the manganese product being centrifuged to the inner layer on the reactor wall and, presumably, being protected from vapour loss by the outer slag/coke layer.

Voest-Alpine: Two-stage Smelter/Shaft Reactor

A burden-condensation furnace, shown in Figure 9, was proposed by Voest-Alpine²⁹. In experiments with an open-bath transferred-arc electrode, the manganese losses to the gas phase were 40 to 50 per cent. In the new design, the charge is prereduced in the shaft and then descends into the smelting zone. A water-cooled transferred-arc heater is equipped with oxygen ports for final smelting. The oxygen is provided to optimize the decarburization, and to control the melt temperature and therefore produce a medium-carbon ferromanganese. Ore fines could be injected into the smelting zone. It would appear that a hollow graphite-electrode system could also be used in this reactor, and any safety problems associated with potential torch failure and water leak explosions could be avoided. The initial objective for this reactor is to achieve a power level of 2.5 MW at a production rate of 800 kg per hour. No data are yet available on this operation.

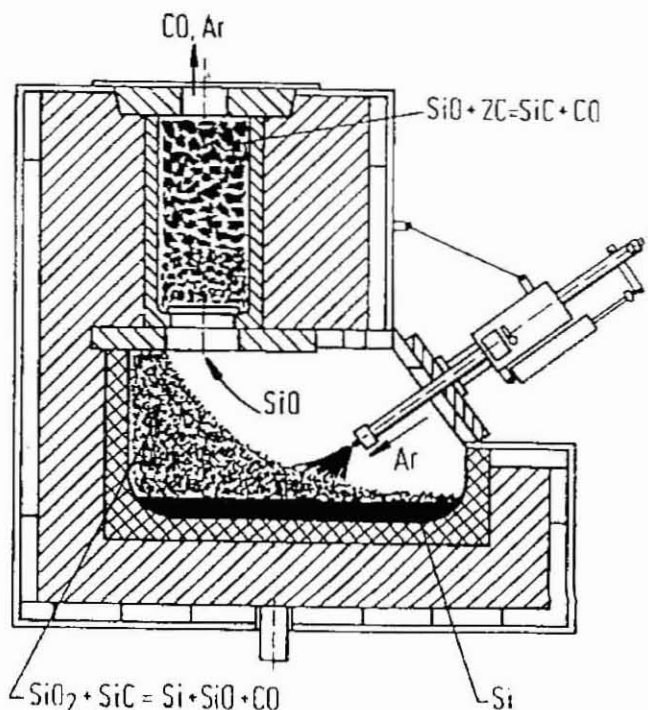


FIGURE 9. Voest-Alpine 'shaft-hearth' 100 kW plasma furnace using water-cooled tungsten-cathode arc heaters for the production of ferro-silicon and silicon metal³³

Remelting of Ferromanganese-metal Fines

The plasma remelting of ferromanganese fines started in June 1983 at the Samancor Metalloys plant³⁰. The transferred-arc heater is limited in voltage capability owing to the conductive manganese vapour. At the full current capability of 10 000 A for the tungsten cathode, the power input is only 3 to 4 MW.

Davy McKee has described a 5 MW plasma furnace³¹ based on the operation of a 350 kW pilot plant for the melting of ferromanganese fines. The proprietary design features a cylindrical sleeve that surrounds a d.c. transferred arc 1 m in length. The fines are fed onto the sleeve, where melting occurs, and the melted material then falls off onto the bulk melt. The 5 MW heater was commissioned for Plasma Arc Limited, Melbourne, Australia. No production data for this operation have been published.

The current limitations of the Voest-Alpine and Davy McKee plasma heaters (both with water-cooled tungsten electrodes), the complexity of the sleeve reactor, and the potential for water leaks suggests that the basic hollow graphite electrode should be used for the melting of ferromanganese fines.

Ferrosilicon and Silicon

Each ferroalloy system has its characteristic complexity: the chromite system requires high temperatures, high heat fluxes, and a complex slag chemistry; manganese alloys have a vapour pressure highly dependent on the alloy component and concentration; the ferrosilicon reaction system, Si-O-C-Fe, has complex low- and high-temperature reaction sequences involving gaseous intermediates. The sili-

con reaction sequence involves the countercurrent flow of solid carbon and silicon dioxide, and gaseous CO and SiO. Silicon carbide, formed by the reaction of the carbon and SiO gases, reacts with silicon dioxide through an SiO intermediate reaction to form silicon metal. SiO side reactions form excess silicon carbide and also dissociate to form deposits of silicon and silicon dioxide, which tend to plug the furnace. In conventional submerged-arc furnaces, it is necessary to physically break up the charge to allow the furnaces' gases to escape. As a result, it is necessary to use a burden of carefully sized quartz and coke to optimize the permeability of the burden. A reactor system capable of processing fines, in this case inexpensive silicon dioxide as sand, is an attractive application for plasma reactors.

Hollow Graphite Electrode Plasma Reactor

The capability of producing ferrosilicon from a charge of silica and carbon fed through a hollow graphite electrode was demonstrated on a 2 MVA furnace operating continuously over a three-week period³⁰. A decrease in the total energy required was attributed to the 100 per cent conversion of the silica fed through the hollow electrode, which was 20 per cent of the charge. The remainder of the charge was a conventional burden.

Voest-Alpine/Dow Corning Project

An extensive development of a plasma-reactor design, similar to Figure 9, by Voest-Alpine and Dow Corning^{33,34} demonstrated the production of silicon metal from quartz and sand, and ferrosilicon from taconite fines, at 100 kW. The reactor operated with the production of silicon carbide

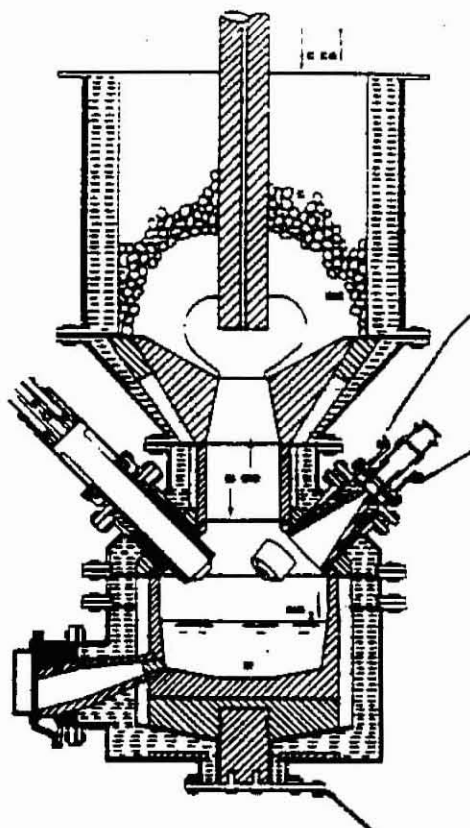
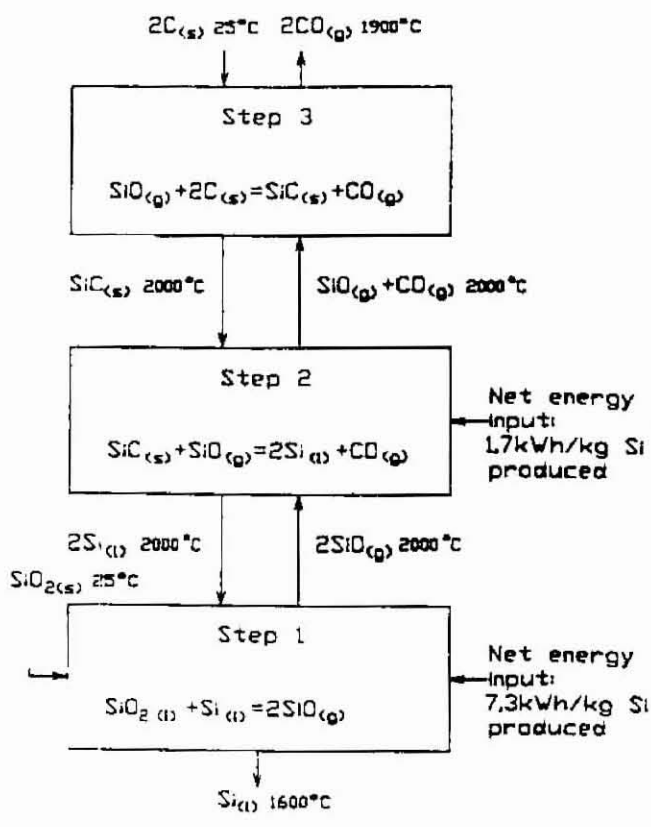


FIGURE 10. NTH/SINTEF reaction sequence and reactor concept for the production of silicon metal—hearth heating with a water-cooled tungsten-cathode transferred arc, and shaft heating with a graphite electrode³⁸

by the reaction of coke with SiO gas in the shaft. The silicon carbide was periodically pushed down into the plasma smelting zone to react with quartz to produce silicon metal and to regenerate the SiO gas. The torch reliability and life were found to be the prime operational limitations during these trials, which used a Voest-Alpine water-cooled transferred-arc torch. The scale-up of this process would require a practical design for the continuous transfer of silicon carbide from the shaft into the smelter zone.

Since 1988, Dow Corning has been developing a single-electrode, 200 kVA submerged-arc furnace to operate under totally sealed conditions using quartz with charcoal and coal reductants³⁵. This operation is now being scaled up to 6 MW.

Mintek: Melting and Refining of Silicon Fines

Silicon-metal fines have been successfully remelted in a 100 kVA transferred-arc plasma furnace under an argon atmosphere³⁶. Remelting resulted in upgraded quality from 0.45 per cent Al and 0.17 per cent Ca to 0.19 per cent Al and 0.01 per cent Ca.

NTH/SINTEF: Silicon-fines Melter and Silicon-reduction Reactor

The Norwegian Plasma Technology Group of NTH/SINTEF has proposed a three-step plasma reactor³⁸ (Figure 10) to produce silicon metal from quartz and coke. The lower part of the reactor has been operated under argon to remelt silicon-metal fines³⁷. The reactor has three water-cooled, tungsten-cathode heaters with a total power capability of 200 kW. In silicon smelting, silicon carbide forms at the top of the reactor by the exothermic reaction of SiO gas with the carbon charge. The upper reactor is to be heated by a graphite electrode, where the silicon carbide plus SiO gas form molten silicon. Silica is fed to the bottom reactor to react with the silicon metal to form the SiO gas. The bottom reactor will require about five times the energy input as the upper reactor. No information on the progress of this reactor is available.

Kawasaki Steel: High-purity Silicon by Carbothermic Reduction of Silica

The reactor-reaction scheme outlined by NTH/SINTEF was also followed in the Kawasaki Steel 150 kVA arc furnace³⁸, shown in Figure 11. Pure silica was injected with argon through silica-injection tubes into the arc space between the single-phase a.c. graphite electrodes, as shown in the cross-section view of the hearth region. It was possible to produce high-purity silicon at 2 kg per hour with a yield of 83 per cent. After decarburization, the silicon was of solar grade.

Other Ferroalloy Studies: FeMo, FeNb, Carbides

The promise of plasma technology to lead to new processing routes and improved reactor concepts, and the use of alternative charge materials, continue to foster developmental efforts and feasibility studies for ferroalloys. Recent developments have included the use of a 30 kW falling-film sleeve reactor to produce FeNbC⁴⁵ and NbC⁴⁶. Fly ash has been used as a charge material to produce ferrosilicon³⁹. Feasibility studies continue to be made on the production of ferromolybdenum from molybdenum disulphide^{41,42}.

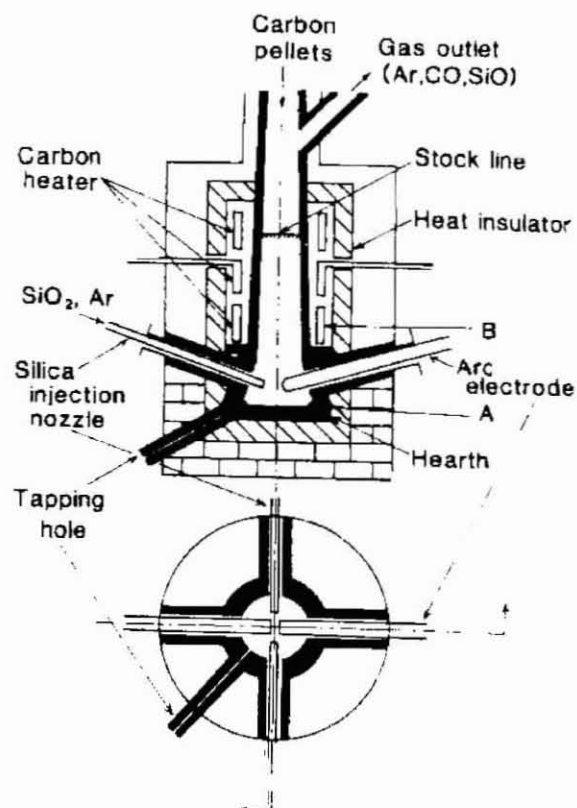


FIGURE 11. Kawasaki steel reactor for the production of silicon metal—hearth heating with a 150 kVA non-transferred graphite-electrode a.c. arc, and shaft heating with 180 kVA carbon resistance elements³⁸

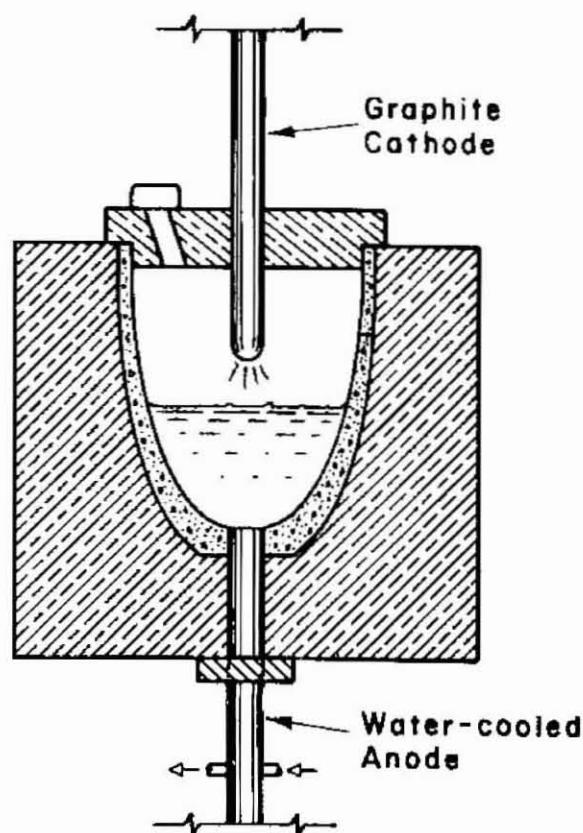


FIGURE 12. Siemens vertical open-bath graphite-electrode d.c. transferred-arc furnace from 1878¹¹

TABLE III
INDUSTRIAL PLASMA INSTALLATIONS FOR THE MELTING OF METALS AND ALLOYS

Process	Feed	Product	System	Power capacity	Start-up	Plant location	Reference
Melting/refining	Alloy scrap	Alloy steel	Freital	20 MW, 30-ton melt 10 MW, 10 ton	1973 1982	VEB, 8 May 1945, Freital,	51
			Mannesman Demag (Krupp)	3 MW, 10-ton melt 30-ton ladle	1986	FRG	52
			Freital/ Voest–Alpine	4 x 3 MW, 45 ton (decommissioned in 1987)	1983	Voest–Alpine, Linz, Austria	53
	Ti scrap/ sponge	Ti ingot	Retech	2 x 300 kW	1988	Pratt & Whitney, East Hartford, CT	58
			Retech	2,1 MW	1988	Wyman-Gordon, Worcester, MA	59
			Retech	2,25 MW	1989	Teledyne-Allvac, Monroe, NC	60
	Stainless scrap	Ingot slabs (4 t)	ULVAC	6 x 0,4 MW	1986	Nippon Stainless Steel	61
Ti scrap	Ingot	PEC/Leybold	3 x 400 kW	1990	TiMet, Henderson, NV	62	
Scrap consolidation	Ti scrap / sponge	Ti electrodes 14/22/28" dia	Retech	0,8 MW	1984	Oregon Metallurgical Corp., Albany, OR	57
Plasma blast cupola melting	Foundry-iron chips, borings	Fe	Westinghouse	6 x 1,5 MW	1989	General Motors, Central Foundry Div., Defiance, Ohio	77
			Aerospatiale	4 MW	1989	Peugeot, Sept-Fons	78

TABLE IV
INDUSTRIAL PLASMA INSTALLATIONS FOR THE HEATING OF METALS AND ALLOYS

Process	Feed	Product	System	Power capacity	Start-up	Plant location	Reference
Ladle heating/ refining	Steel melt	Heated melt	Hollow graphite electrodes	16,8 MVA 3 phase a.c.	1988	CFI Steel Corp., Pueblo, Colorado	83
	Ferroalloys	FeSi	SINTEF	1 MW	1982	Holla Smeltverk, Norway	85
	Alloy steels		Mannesman Demag (Krupp)	6 MW 3 phase a.c.	1989	Krupp Siegen Steelworks	86
	Carbon steels		Advent Process Engineering	Hollow graphite electrode, 1 MW, 5 ton (demo)	1992	Maynard Steel Casting Co., Milwaukee, Wisconsin	84
Tundish heating	Steel melt	Heated melt	Tetronics R&D	1 MW, 14-ton melt	1987	Nippon Steel, Hirohata Works	88
			Tetronics R&D	350 kW, 5 ton	1988	Aichi Steel	89
			Tetronics R&D	1,1 MW, 40 ton	1989	NKK Keihin no. 3	90
			Tetronics R&D	1,1 MW, 40 ton	1989	NKK Keihin no. 4	90
			Tetronics R&D	1,1 MW, 40 ton	1990	NKK Keihin no. 1	89
			Tetronics R&D	1,1 MW, 50 ton	1990	NKK Keihin no. 5	89
			Tetronics R&D	1,1 MW, 17 ton	1990	NKK Fukuyama	89
			Tetronics R&D	0,8 MW, 6 ton	1990	Anval Nyby Powder AB	89
			Mannesmann Demag (Krupp)	2 MW, 20 ton	1988	Deltasidar (Italy), Aosta Works,	91
			Mannesman Demag (Krupp)	2,4 MW, 80 ton	1989	Kobe, Kakogawa Works	92
			Plasma Energy Corporation	4 MW, 27 ton	1988	Chaparral, Midlothian, Texas	93
			Plasma Energy Corporation	1,5 MW	1990	First Miss (Stoney Creek) Steel, Hollsopple, PA	94
Plasma reforming: Production of reduction gas	Iron oxide pellets/ore	Fe _x O/Fe prereduced product	SKF Plasma- Red	3 x 2 MW	1981 (decommis- sioned in 1985)	Hofors, Sweden	79
	Iron oxide pellets/ore	Fe _x O/Fe prereduced product	Huls USCO		1986 (mothballed in 1988)	Union Steel Corp., S.A.	80

Final Word on Plasma Ferroalloy Reactors

As the result of the last twenty years of development, a strong preference has been expressed for the use of hollow graphite electrodes for the plasma production of ferroalloys by carbothermic reduction of a particulate feed. An uncritical view might equate this reactor system to submerged-arc systems with solid carbon electrodes or even to the furnace setup¹¹ described by Siemens in 1878, shown in Figure 12. The development of these plasma reactors has required a critical re-examination of the fundamentals of the reaction kinetics, mass and heat transfer, slag chemistry and gas-phase behaviour of ferroalloy production⁷. The development of plasma-reactor systems for the production of ferroalloys is not complete, but will continue with the improved understanding of these systems⁸. Inevitably, the plasma-reactor concepts, most notably the feeding of fines through hollow electrodes^{9,10}, will be included in submerged-arc systems with the emergence of improved ferroalloy-production technology.

Conclusions

For the smelting of ferroalloys, the past twenty years of plasma-technology development has resulted in relatively few industrial installations. For the complex smelting of ferroalloys, the most appropriate system is the least complex, i.e. the d.c. transferred-arc hollow carbon electrode reactor.

As shown in Tables II to IV, applications of plasma technology other than ferroalloy smelting grew significantly during the 1980s. This growth occurred mainly for relatively simple systems such as the remelting of metal and the control of melt temperature (shown in Tables III and IV). These systems, particularly for reactive metals, use argon atmospheres and water-cooled systems to minimize trace contamination of the metal. It now appears that the complex heaters being used for melting and heating applications will be the next candidates for redesign.

In conclusion, the quest for simplicity of torch design and wider applications of plasma technology continues.

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