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The Processes

THE PRODUCTION OF MANGANESE FERRO-ALLOYS IN
TRANSFERRED-ARC PLASMA SYSTEMS

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The three basic processes that are applicable to the production and treatment of manganese ferro-alloys are: the smelting of the ore, the remelting of ferro-alloy fines or other physically unacceptable forms of the alloys, and the refining of the alloys to yield a product with a lower carbon or silicon content than that of the alloy produced initially.

In the present study, plasma technology was applied to the production of manganese ferro-alloys, and its suitability was evaluated in the context of these three processes.

Transferred-arc Plasma Systems

Two furnaces were used in the tests: a 1400 kVA furnace manufactured by Tetronics Research and Development Limited (TRD) and a 100 kVA furnace at Mintek. Both furnaces employ direct current (d.c.), and operate with a single electrode as the cathode and the molten bath as the anode. The molten pool of process material forms an integral part of the electrical circuit, and the furnaces used in the experiments can therefore be classified as d.c. transferred-arc plasma furnaces. In the 1400 kVA furnace, a water-cooled tungsten cathode (plasma gun) was used; in the 100 kVA furnace, graphite or water-cooled tungsten was used as the cathode material.

Introduction

Manganese ferro-alloys are usually made in submerged-arc electric smelting furnaces. These furnaces are of the three-phase type, employing three carbon or graphite electrodes. The electrodes project through the charge, which is choke-fed at the top of the furnace. The arc is buried or submerged in the charge material, and the off-gases escape through the porous burden. Although the submerged-arc furnace is a proved and efficient system for the production of ferro-alloys, it has some distinct disadvantages (1,2). For example, if the burden is to maintain a suitable degree of porosity, it is inadvisable for very finely sized material to be fed to a submerged-arc type of furnace. The presence of fines in the feed results in impermeability and the building-up of gas pressure within the burden, followed by an explosive release of this gas, commonly known as eruption (3). Also, it is extremely difficult, if at all possible, for the carbon electrode to be excluded from the reaction zone, which is desirable in refining processes for the production of alloys with a reduced carbon content. In the submerged-arc remelting of fines, the high electrical conductivity of the fines lowers the electrical resistance of the burden, and consequently limits the input of power to the furnace.

Plasma-arc technology provides an alternative method for the treatment of ferro-alloys, in which the above-mentioned disadvantages can be obviated to some extent (2,4).

For example, in most existing plasma systems, fine feed materials can be used direct, without prior briquetting or agglomeration. Also, a wider range of carbonaceous reducing agents can be used in plasma furnaces than in conventional furnaces. In South Africa, the Council for Mineral Technology (Mintek) realized the potential benefits of plasma technology some years ago. Test facilities rated between 50 kVA and 3.2 MVA have been built since so that assistance can be given to the ferro-alloy industry in the evaluation of thermal plasma.

The Mintek 100 kVA System

The furnace (Figure 1), which has been described previously, consists essentially of a 100 kVA d.c. power supply, and a refractory-lined steel shell of 600 mm diameter that contains the molten bath (6). A hollow graphite electrode of 50 mm diameter or a water-cooled plasma gun of 30 mm diameter is employed as the cathode. The single cathode is located centrally above the molten bath and enters the furnace through a water-cooled seal. Argon or nitrogen is used as the plasma gas at flowrates between 5 and 15 l/min, depending on the power level employed. Three steel anodes of 40 mm diameter project through the refractory hearth and are in direct contact with the frozen heel and molten bath. The roof has three apertures: a central entry port for the electrode, a feed port, and an off-gas duct. A vibratory feeder or a screw feeder is used to deliver material through the single feed port into the bath. Thermocouples are located at various positions in the refractory lining, the roof, and the anodes. The temperature recordings are used as a guide in the monitoring and reproduction of the operating conditions. Material is fed into the furnace at a controlled rate while the bath is maintained in a molten state by the utilization of a power level sufficient to balance the loss of heat from the furnace and the thermodynamic energy requirements for the process. The furnace capacity is about 50 kg of ferromanganese, and typical electrical operating characteristics are 90 V, 800 A, and about 70 kW at arc lengths of between 50 and

100 mm. A normal smelting campaign lasts for a few days, and the furnace is tapped every 1 to 2 hours.

For first-stage work, the 100 kVA furnace is operated on a somewhat smaller scale and at a lower power level of about 30 kW (Figure 2). Prebaked, high-magnesia crucibles with an inside diameter of 200 mm and a height of 400 mm are employed. The anodic connection is established with one steel rod that penetrates centrally through the bottom of the crucible. The crucible or refractory pot, with a working capacity of about 10 kg of ferromanganese, is replaced after each test run. Experiments carried out with this arrangement are referred to as "pot tests".

The TRD 1.4 MVA System

Large-scale tests were conducted on a 1.4 MVA system developed by TRD. That furnace, which is shown schematically in Figure 3, consists of a cylindrical steel shell with a dish-shaped bottom and a domed roof. For the present investigation, the walls were lined with magnesia-chrome bricks, the hearth was made of cast magnesia, and magnesia bricks were used for the roof. A water-cooled plasma gun was mounted centrally in the roof and precessed mechanically in a conical motion to facilitate the even distribution of the energy over a large area in the hearth of the furnace. The system had a single horizontal exhaust port, three feed ports spaced at equal intervals around the central plasma gun, and a central steel anode projecting through the bottom of the furnace. More-detailed descriptions of the TRD system are available in the literature (7-10).

The Remelting of Ferromanganese Fines

During the sizing and handling of ferroalloys, considerable amounts of fines smaller than 6 mm are generated. There is a limited market for these fines, and only a small quantity can be recycled to the submerged-arc furnace (11). Preliminary remelting tests were carried out in the Mintek 100 kVA furnace using a graphite electrode as the cathode. A total of 180 kg of high-carbon ferromanganese metal fines were remelted. The chemical analyses of the feed material and the average analyses of the ferromanganese produced are given in Table I. The metal fines contain a small percentage of slag, which is included in the analyses for manganese, iron, and silicon.

TABLE I

Remelting of FeMn fines in the Mintek 100 kVA furnace:
chemical analyses of the feed and the product (% by mass)

Material	Mn	Fe	Si	C	S	P
High-carbon ferromanganese < 6 mm	73.7	13.5	1.8	6.6	0.03	0.12
Metal product	75.3	17.1	0.5	5.8	<0.01	0.08

Further remelting tests were conducted in the TRD 1.4 MVA furnace. The furnace was operated at a power level of 450 kW (1400 A, 300 V), and about 4.5 t of metal was tapped continuously in two campaigns lasting a total of 8 hours. The specific energy consumption was 795 kW.h per ton of metal produced. The losses of manganese in the baghouse represented 0.65 per cent of the manganese fed to the furnace, and about 8 per cent of the feed reported to the slag. As a result of the relatively small scale of the furnace, the thermal efficiency was about 75 per cent compared with an expected value of over 90 per cent for operation on a larger scale, for which the specific energy consumption would approach more closely the theoretical value of 450 kW.h/t. The chemical composition of the consumed metal fines and the produced alloys are given in Table II.

The remelting operations resulted in some refining, in that, in each instance, the silicon content of the produced metal was markedly lower than that of the original ferromanganese. The carbon level, on the other hand, was reduced only marginally. The remelting was also characterized by a decrease in the manganese-to-iron ratio of the alloy, caused mainly by the removal of the entrained slag, which has a very high manganese-to-iron ratio.

The Co-melting of Ferromanganese and Silicon Fines

High-carbon ferromanganese and silicon fines were remelted simultaneously in an attempt to produce a valuable low-carbon silicomanganese from off-grade metal fines. It should be noted that Mintek has successfully remelted ferromanganese and silicon fines separately in a transfer-arc plasma furnace (12,13). The co-melting tests were carried out in the Mintek 100 kVA furnace using a graphite electrode as the cathode. Initially, a heel of mild steel was established, after which 440 kg of metal fines, divided into 12 batches, were fed to the furnace. The furnace was tapped after the remelting of each batch of material. The 12 melts consisted of three series of four melts each. The silicon-to-ferromanganese ratio was increased in steps, from 0.18:1 for the first series of four batches to 0.38:1 for the next series and to 0.67:1 for the last series. Different ratios were employed in the three successive groups of runs to yield alloys with variable silicon contents. The composition of the feed materials and the average analyses of each series of melts are given in Table III.

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TABLE II

Remelting of FeMn fines in the TRD 1.4 MVA furnace:
chemical analyses of the feed and the product (% by mass)

Material	Mn	Fe	Si	C	S	P
High-carbon ferromanganese < 6 mm	75.5	14.5	0.7	7.0	<0.01	0.07
Metal product (campaign 1)	74.0	17.9	0.2	6.0	<0.01	0.09
Metal product (campaign 2)	76.2	15.8	0.1	6.8	<0.01	0.09

TABLE III

Co-melting of FeMn and Si fines in the Mintek 100 kVA furnace:
chemical analyses of the feed and the products (% by mass)

Material	Mn	Fe	Si	C	S	P
High-carbon ferromanganese < 6 mm	73.8	13.4	0.8	6.6	0.014	0.08
Silicon < 6 mm	<0.1	1.3	93.0	0.2	<0.01	<0.01
Metal product (Series 1)	63.1	21.9	11.3	2.8	<0.01	0.08
Metal product (Series 2)	60.8	13.5	23.6	0.8	<0.01	0.08
Metal product (Series 3)	54.6	11.8	32.8	0.1	<0.01	0.07

It can be seen from Table III that satisfactory alloys were obtained and that the carbon content decreased substantially relative to that contained in the ferromanganese feed material. A significant advantage is that the removal or exsolution of carbon took place almost as soon as the reactants became molten and that, accordingly, prolonged heating was not required. In some instances the carbon content of the product was even lower than its initial level in the silicon, indicating that the conditions for the displacement of carbon in the plasma system were very favourable.

The average recoveries of manganese and silicon were 97 and 82 per cent respectively. It should be noted that the original fines contained some slag, and that this was not taken into account in the calculation of the above-mentioned recovery values. The somewhat lower manganese contents and the relatively high iron contents obtained for the alloys produced can be attributed to the use of steel anodes and the establishment of a steel heel in the hearth of the furnace at the start of the melting campaign. This dilution effect would disappear after a few taps in a continuous operation.

The Refining of Ferromanganese

Refined or medium- to low-carbon ferromanganese is usually made by the reaction of silicomanganese with an ore-lime melt, which removes the silicon from the low-carbon alloy, or by the decarburization with oxygen of high-carbon ferromanganese in a blowing vessel (14, 15). The carbon content of high-carbon ferromanganese can

also be reduced by remelting of the alloy with an excess of manganese ore. The latter is not common practice in conventional furnaces because sufficiently low levels of carbon can be reached only at the cost of considerable losses of manganese.

This is not necessarily true in a plasma system. Encouraging results were obtained during the remelting of high-carbon ferromanganese fines, in that, even without the use of extra ore, some refining took place. The lowering of the carbon and silicon contents during the remelting process might, to a great extent, have been governed by the refining action of a small amount of entrained slag. At higher temperatures, the manganese carbides in high-carbon ferromanganese react with the metal oxides in the slag to yield manganese metal and carbon monoxide. Further refining experiments were therefore carried out in the Mintek 100 kVA furnace. Synthetic manganese ores (prepared previously) of different basicities were reacted with high-carbon ferromanganese, a metal-to-ore ratio of 2:1 being utilized each time. A wide range of basicities was selected so that the influence of ore basicity on the degree of refining could be studied. The refining tests were conducted as pot tests or small-scale plasma tests, a graphite electrode being used as the cathode. During each experiment, about 10 kg of charge material (composed of high-carbon ferromanganese and one of the synthetic ores) was fed to the furnace. The average run time was about 1 hour and the arc power was kept around 30 kW (500 A, 60 V). The bath temperatures, measured with an optical pyrometer towards the end of the tests, varied in the narrow range between 1580 and 1620°C. The chemical composition of

TABLE IV

Refining of FeMn fines in the Mintek 100 kVA furnace:
chemical analyses of the metal feed (% by mass)

Material	Mn	Fe	Si	C	S	P
High-carbon ferromanganese < 6 mm	73.8	13.4	0.83	6.6	0.014	0.08

TABLE V

Refining of FeMn fines in the Mintek 100 kVA furnace.
chemical analyses of the ore feed (% by mass)

Synthetic ore no.	MnO	FeO	CaO	MgO	Al ₂ O ₃	SiO ₂
1	45.0	18.5	5.0	0.8	7.3	19.7
2	42.8	12.9	8.5	2.2	4.5	27.3
3	54.2	13.7	10.7	4.2	0.8	10.8
4	52.1	12.2	17.5	3.6	0.9	8.9
5	50.3	10.5	21.4	6.2	0.7	7.3

the feed materials are given in Tables IV and V.

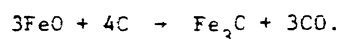
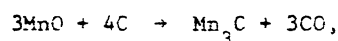
South African Mamatwan and Wessels ores were employed in the preparation of the synthetic ores, and the basicity was regulated by the use of quartz or a mixture of limestone and dolomite during the melting of the ores. It should be noted that the stoichiometric amounts of ore needed for the complete removal of carbon are reached at metal-to-ore ratios between 1.4:1 and 1.7:1, depending on the type of ore.

The chemical composition of the manganese ferro-alloys produced are given in Table VI, from which it can be seen that refining was achieved, in that the carbon content of the metal was reduced from 6.6 per cent to between 1.7 and 5.8 per cent, and that the silicon content decreased from 0.83 per cent to between 0.08 and 0.32 per cent. In experiments 2 and 3, in which the greatest degree of refining took place, an overall manganese recovery of 86 per cent was obtained. In both instances, the amount of manganese recovered in the refined alloy was about the same as the amount of manganese introduced by the high-carbon ferromanganese fines (i.e. the recovery of manganese as metal was about 100 per cent). The somewhat lower manganese content of the refined metal (about 70 per cent manganese) was caused by a combination of factors, as follows: the low manganese content of the starting ferromanganese (73.8 per cent manganese), the losses of manganese due to evaporation, the high iron contents of the synthetic ores and the preferential reduction of iron over manganese oxide, and the dilution of iron from the steel anode. It is noteworthy that, in similar plasma experiments performed elsewhere in an "extended-arc flash factor" and without the application of steel anodes, the manganese content of the refined metal was significantly higher than that of the original ferromanganese fines (16).

One further refining experiment was carried out on a somewhat larger scale in the Mintek 100 kVA furnace. In this test, a water-cooled plasma gun was used instead of a graphite electrode, and the furnace was tapped at the end of the run. Ferro-manganese metal fines and Mamatwan manganese ore were used at a ratio of 2:1, and a little dolomite flux was added (at a ratio of dolomite-to-manganese ore of 0.2:1) to produce a slag with an estimated basicity of 1.8. The furnace was operated at an average power of 60 kW, and heated to a bath temperature of about 1850°C. Considerable refining was achieved, in that the carbon content of the metal was reduced from 6.6 to 0.8 per cent, and the silicon content from 1.3 to 0.4 per cent.

The Smelting of Ferromanganese

The first series of smelting tests were carried out as batch-smelting operations or pot tests, in much the same way as were the small-scale refining experiments. The feed mixture consisted each time of 10 kg of one of the five synthetic ores (smaller than 10 mm) prepared previously, and the stoichiometric amount of metallurgical coke (smaller than 3 mm) was calculated on the basis of the following reduction reaction:



The analyses of the synthetic ores are given in Table V and the composition of the coke is shown in Table VII.

The processing conditions for the different experiments were substantially the same, except

TABLE VI

Refining of FeMn fines in the Mintek 100 kVA furnace:
chemical composition of the metal produced (% by mass)

Run no.	Feed		Metal analysis*				
	Ore no.†	Basicity‡	Mn	Si	C	S	P
1	2	0.4	67.5	0.32	5.8	<0.005	0.09
2	3	1.4	70.6	0.16	1.7	<0.005	0.08
3	4	2.4	70.4	0.12	1.8	<0.005	0.08
4	5	3.8	68.8	0.08	3.2	<0.005	0.09

*The balance is Fe

†See Table V

‡Basicity = $(\% \text{ CaO} + \% \text{ MgO}) / \% \text{ SiO}_2$

TABLE VII

Smelting of FeMn in the Mintek 100 kVA furnace.
composition of the coke reducing agent used

C	Volatile material	CaO	MgO	Al ₂ O ₃	SiO ₂	FeO	P ₂ O ₅	SO ₃
83.1	0.8	0.4	0.1	4.1	8.6	1.0	0.05	0.25

for the basicity of the ore, which was varied so that its effect on the smelting of ferromanganese could be established. The average run time was about 1 hour, and the arc power was kept around 30 kW (500 A, 60 V). The bath temperatures were measured towards the end of the tests, and varied between 1500 and 1600°C. Nitrogen was used as the plasma gas, and a flowrate of 5 l/min was maintained.

It should be noted that the basicities of the residual slags, although similar to those of the synthetic ores used, deviate from the latter due to erosion of the refractory (magnesia) crucibles and the intake of ash from the reducing agent. It can be seen from Table VIII that the manganese content of the alloys produced was rather low. In the experiments with synthetic ores of low basicity (i.e. with basicities of 0.3 and 0.4), the overall recovery of manganese exceeded 90 per cent, so that the low manganese content was associated with a low degree of reduction and, accordingly, with high levels of manganese in the slags produced. The failure for satisfactory alloys to be produced at higher basicities was related mainly to increasing losses of manganese with increasing basicities. (Other factors that affected the manganese grade adversely were: the high iron contents of the synthetic ores and the dilution of iron from the steel anodes.) The manganese oxide content of the slag, on the other hand, decreased markedly with increasing basicity, and dropped below 5 per cent at basicities greater than 2. Maximum manganese extraction occurred at a basicity of 1.6 in the residual slag. About 60 per cent of the manganese passed from the ore into the alloy, 10 per cent remained

in the slag, and 30 per cent was lost as a result of vaporization and entrainment.

A second series of smelting tests was carried out on a somewhat larger scale on the Mintek 100 kVA furnace. The smelting campaign consisted of 12 smelting and tapping operations, which were performed during a continuous operating period exceeding 24 hours and yielding a total of about 250 kg of product. A standard South African smelting recipe was employed, in which coal was used as the reducing agent with a self-fluxing blend of Mamatwan and Wessels manganese ores to produce a slag with a basicity of approximately 1.3. On average, the alloy produced contained 72 per cent manganese, 6.7 per cent carbon, and 0.50 per cent silicon. This time the distribution of manganese among the smelting products (in percentage by mass of the quantity contained in the charged ore) was approximately as follows: 63 per cent of the manganese passed into the metal, 20 per cent remained in the slag, and 17 per cent was lost. As can be expected, the metallurgical efficiency improves when smelting is carried out on a larger scale, i.e. when the arc-attachment area occupies a smaller fraction of the molten-bath area (and the localized vaporization in this high-temperature zone decreases as a proportion of the throughput).

The last series of smelting tests were conducted in the TRD 1.4 MVA furnace using a water-cooled plasma gun. The feed consisted solely of fine materials (< 6 mm), i.e. Mamatwan and Wessels manganese-ore fines, coal fines, and coke fines. The furnace was operated at power levels up to 550 kW, and fed at an average rate of about 300 kg/h. The chemical analyses of the raw materials

TABLE VIII

Smelting of FeMn in the Mintek 100 kVA furnace:
chemical composition of the metal and slag produced (% by mass)

Run no.	Feed		Metal*					Slag	
	Ore no.†	Basicity‡	Mn	Si	C	S	P	Basicity‡	MnO
1	1	0.3	30.7	0.48	5.0	<0.01	0.10	0.5	46.9
2	2	0.4	43.1	0.40	6.1	<0.01	0.10	0.9	29.6
3	3	1.4	61.0	0.31	6.0	<0.01	0.08	1.6	15.2
4	4	2.4	55.4	0.21	6.2	<0.01	0.09	2.2	3.8
5	5	3.8	52.5	0.14	5.7	<0.01	0.09	2.7	2.5

*The balance is Fe

†See Table V

‡Basicity = $(\% \text{ CaO} + \% \text{ MgO}) / \% \text{ SiO}_2$

TABLE IX

Smelting of FeMn in the TRD 1.4 MVA furnace:
composition of the raw materials (% by mass)

Material	Mn	Fe	SiO ₂	CaO	MgO	Al ₂ O ₃	S	P
Mamatwan ore	34.9	4.35	5.4	16.7	3.0	0.2	0.06	0.03
Wessels ore	47.4	11.2	7.5	6.3	1.3	0.1	0.12	0.04
Quartz		0.3	98.7			0.1		

Material	C	Volatile material	MnO	FeO	SiO ₂	CaO	MgO	Al ₂ O ₃	SO ₃	P ₂ O ₅
Coal	55.8	27.5	0.1	0.3	6.4	1.2	0.4	4.2	1.8	0.14
Coke	83.8	1.0	0.1	0.7	6.3	0.8	0.3	4.2	0.4	0.09

TABLE X

Smelting of FeMn in the TRD 1.4 MVA furnace:
mass of feed materials (kg per ton of ore)

Test no.	Mamatwan	Wessels	Coke	Coal	Quartz
1	701	299	265	-	36
2	703	297	255	108	21
3	702	298	101	430	51
4	702	298	102	431	178

are given in Table IX, the feed composition in Table X, and the analyses of the produced metal, slag, and dust in Table XI.

It appears from Table XI that the attainment of on-grade metal by the use of coal fines is feasible in a transferred-arc plasma furnace. The manganese oxide content of the slag under normal operating conditions reached a value of 10 to 12 per cent. In test 4, which was conducted with excessive reducing agent and in which extensive heating was applied after completion of the feeding, the possibility that slags containing as little as 2.6 per cent manganese oxide could be

produced, was demonstrated, but this was associated with a high silicon level (1.75 per cent silicon) in the alloy. The total loss of manganese to the dust stream constituted 11 per cent of the input manganese. The overall energy consumption was 1420 kW.h/t of feed compared to the theoretical value of 720 kW.h/t. The determination of significant figures for energy consumption, however, was not possible because of the intermittent nature of the runs and, hence, the disproportionately high heat losses.

TABLE XI

Smelting of FeMn in the TRD 1.4 MVA furnace:
chemical analyses of products (% by mass)

Metal no.	Mn*	Fe	Si	C	S	P
1	77.0	14.9	0.33	6.6	0.008	0.11
2	75.8	14.7	0.50	6.8	0.008	0.11
3	77.5	15.2	0.56	6.1	0.008	0.10
4	77.0	14.4	1.75	5.3	0.008	0.11

Slag no.	MnO	FeO	SiO ₂	CaO	MgO	Al ₂ O ₃
1	10.7	0.2	32.5	36.5	11.0	7.5
2	10.4	0.4	29.6	38.1	9.9	10.0
3	12.6	1.3	33.3	35.3	7.9	8.1
4	2.6	0.3	31.1	36.0	14.6	13.8

Dust no.	Mn	Fe	SiO ₂	CaO	MgO	Al ₂ O ₃
1	44.0	4.1	12.2	4.9	12.8	0.9
2	36.4	1.9	12.8	7.2	13.0	1.6
3	38.7	3.0	13.0	-8.7	-13.9	3.4
4	37.5	3.0	14.2	8.1	12.2	0.5

*Corrected for iron dilution from previous testwork

Interpretation of the Smelting Data.

An inherent feature of the transferred-arc plasma systems that were employed is the absence of a burden of charge material, which, in a submerged-arc furnace, enables substances that are volatile at elevated temperatures to be condensed and recycled. The open-bath configuration, together with the controllability of the furnace atmosphere, can be beneficial in a refining process in which impurities are to be removed via the gaseous phase. A major area of concern, in view of the relatively high vapour pressure of manganese metal, was the possibility that the losses of manganese to the dust stream would be high during smelting. For small-scale pot tests (a bath diameter of 200 mm), the manganese losses (due to vaporization and the entrainment of fine ore particles) were determined as the difference between the total manganese input and the manganese recovered in the metal and the slag. Figure 4 shows the manganese distribution between the metal, the slag, and the dust as a function of the basicity of the slag. The manganese losses to the dust increased with increasing slag basicity; the proportion of manganese recovered in

the alloy reached a maximum at a basicity of about 1.6, and the amount of manganese reporting to the slag phase decreased gradually as a function of slag basicity. However, it should be noted that the losses of manganese decreased substantially as the unit size of operation was increased. In the tests on the Mintek 100 kVA furnace with a bath diameter of 400 mm, the manganese losses were 17 per cent at a slag basicity of 1.3, whereas, in the trials on the TRD 1.4 MVA furnace with a bath diameter of 1100 mm, the manganese losses to the dust were reduced to 11 per cent of the input manganese at a higher average slag basicity of 1.5. The values obtained indicate that, on a large scale of operation (10 to 20 MW) and with a slag of somewhat lower basicity (1.1 to 1.3), the loss of manganese to the dust stream could be expected to be below 10 per cent. Industrial losses to the dust of around 6 per cent have been reported for submerged-arc furnaces when the discard-slag practice (of high-basicity slag) was employed, as in the experiments in the TRD furnace (17,18). Somewhat higher losses of manganese to the dust stream could be tolerated in a plasma operation, provided that a lower loss of manganese to the slag could be achieved. The manganese oxide content of the slag obtained during the smelting experiments in the TRD plasma furnace was around 10 per cent, which is very low in comparison with the industrial results for submerged-arc furnaces. It is convenient for equilibrium conditions associated

with the production of manganese ferro-alloys to be expressed by the use of an apparent equilibrium constant $k_{\text{Mn,Si}}$ (14,19). This is expressed as

$$k_{\text{Mn,Si}} = \frac{(\text{MnO})[\text{Si}]^{\frac{1}{2}}}{[\text{Mn}]}$$

where (MnO) is the mass fraction in the slag phase and [Mn] and [Si] are mass fractions in the alloy phase. In Figure 5, the smelting results and an equilibrium line from Heynert *et al.* are plotted as a relation between the logarithm of the apparent equilibrium constant and the slag basicity (19). Using graphite crucibles in their laboratory investigation, Heynert *et al.* established a linear relation between the logarithm of the apparent equilibrium constant and the manganese oxide content of manganese slags of different basicities in equilibrium with high-carbon ferromanganese alloys:

$$\log k_{\text{Mn,Si}} = -0.88(\% \text{CaO} + \% \text{MgO})/\% \text{SiO}_2 - 0.05.$$

The decreasing values for $k_{\text{Mn,Si}}$ with increasing basicity implies that higher basicities lead to lower manganese oxide contents in the slag at equal silicon contents in the metal. (Usually, the manganese oxide and silicon contents are both reduced with increasing basicities.) During the small-scale plasma tests (30 kW), the slag basicity was varied over a wide range so that its influence on the manganese-extraction process could be established. The slope of the line obtained in these experiments is similar to that of the equilibrium line obtained by Heynert *et al.* (19). These equilibrium values are lower than the results obtained during the plasma experiments, which indicates that the reaction between the silicon in the metal and the manganese oxide in the slag was not completed to the equilibrium values obtained by Heynert *et al.* (19).

A practical means for the comparison of the smelting results with industrial data is the use of a plot of the manganese oxide content of the slag as a function of slag basicity (Figure 6). Because silicon contents of about 0.5 per cent were obtained in the plasma experiments on the TRD furnace, the equilibrium relation of Heynert *et al.* has been converted, for analytical purposes, into a relation between manganese oxide and basicity, at fixed manganese and silicon contents in the alloy of 80 and 0.5 per cent respectively (19). It appears from Figure 6 that, in plasma experiments, values for the manganese oxide content of the slag can be obtained that are substantially lower than those attainable in industrial submerged-arc furnaces (17,18,20-24). If these low values for manganese oxide can be reproduced consistently, accompanied by the required low silicon levels in the metal, the recovery of manganese into a regular-grade metal should be around 85 per cent, with dust losses of about 10 per cent. The South African ores that were employed in the experiments are ideally suited to the discard-slag practice so that, as a rule, the losses of manganese to the slag should be minimized. The dust could eventually be recycled or used as a source of high-grade manganese oxide.

High-carbon ferromanganese fines were successfully remelted in the Mintek 100 kVA and the TRD 1.4 MVA furnaces. The TRD furnace was operated at a power level of 450 kW, and about 4.5 t of metal was tapped continuously over a period of 8 hours. The specific energy consumption was 795 kW.h per ton of metal produced, and the losses of manganese in the baghouse represented less than 1 per cent of the manganese in the feed.

Silicomanganese was produced in the Mintek 100 kVA furnace by the simultaneous remelting of high-carbon ferromanganese and silicon fines. A sufficiently low level of carbon could be reached to meet the chemical requirements of a regular-grade silicomanganese, and the recoveries of manganese and silicon were 97 and 82 per cent respectively. In some instances, the carbon content of the product was even lower than its initial level in the silicon fines, indicating that the conditions for the removal of the carbon in the plasma system are very favourable.

Experiments in the Mintek 100 kVA furnace demonstrated that, when high-carbon ferromanganese is refined by manganese ore at temperatures around 1600°C, ferromanganese containing about 2 per cent carbon and 0.1 per cent silicon can be produced. Satisfactory results were obtained on synthetic ores with basicities of 1.4 and 2.4 at metal-to-ore ratios of 2:1. The overall losses of manganese were between 10 and 15 per cent.

High-carbon ferromanganese was produced from manganese-ore fines in the Mintek 100 kVA and the TRD 1.4 MVA furnaces. The manganese oxide contents of the resulting slags were significantly lower than those reported for submerged-arc furnaces. The losses of manganese to the dust stream, however, were substantial and, at the least, about 10 per cent of the manganese in the feed was lost by evaporation and entrainment. The relatively small scale of operation and the use of finely sized feed materials probably enhanced the losses of manganese, which were substantially higher than in conventional submerged-arc furnaces. It would appear that, because of the open-bath configuration and the absence of a burden of charge material, the areas over which the feed materials and power are conveyed to the reaction zone should be optimized and controlled more carefully if the recoveries obtained by industry are to be attained. Further work is required so that losses to the dust can be reduced and the benefits that would result from the utilization of finely sized manganese ores and reducing agents can be realized. This is especially important to the possible future production of upgraded ore fines with high manganese-to-iron ratios from relatively low-grade ore deposits, and because fine reducing agents will be available from coal deposits where the beneficiation process necessitates reduction of the coal ore to fine particles.

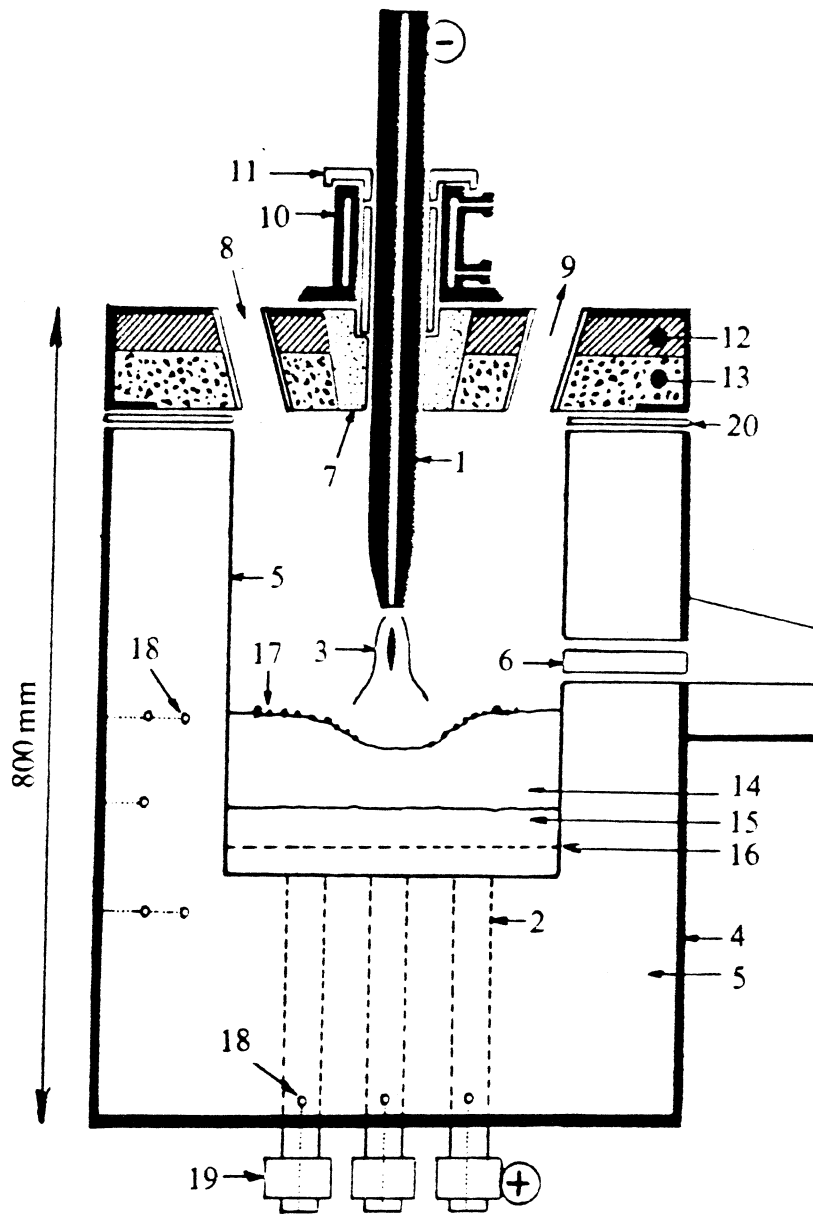
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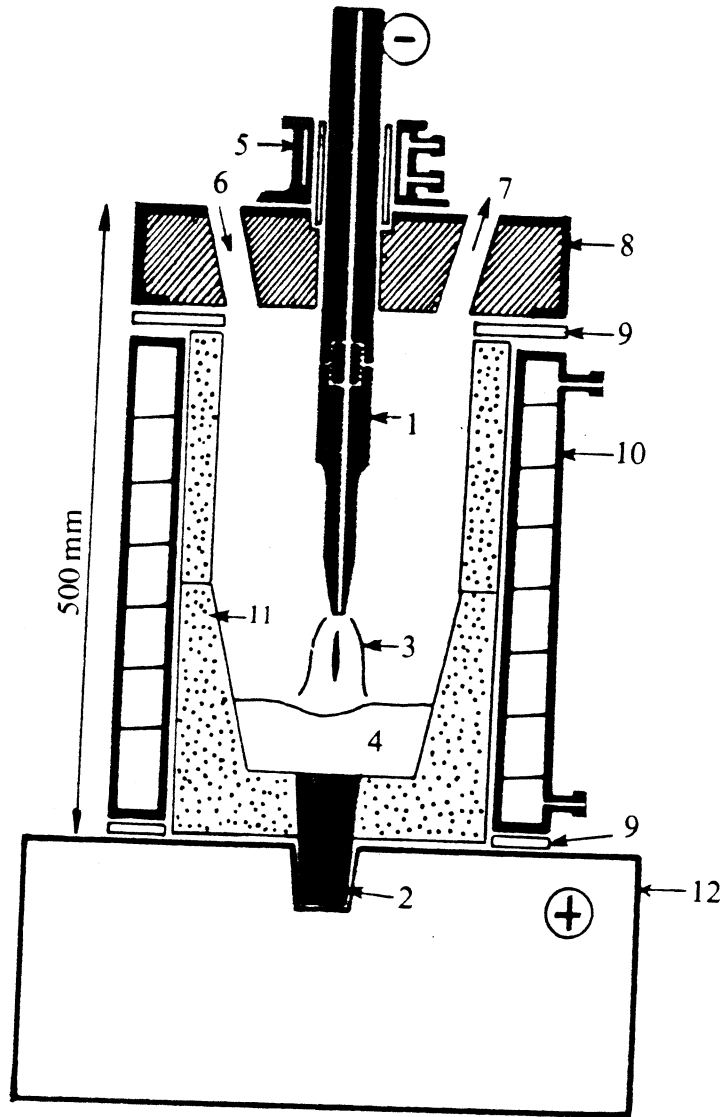
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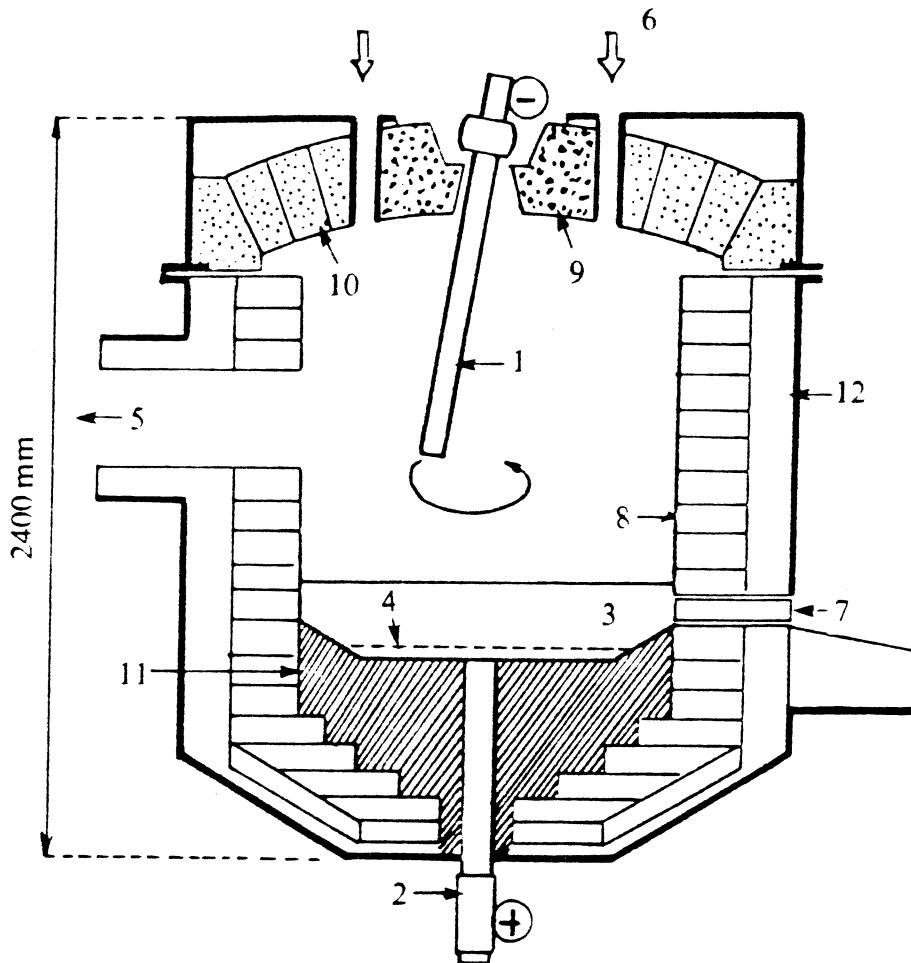
- 1 = Central hollow graphite cathode. 2 = Steel anode. 3 = Plasma zone. 4 = Steel shell.
 5 = Magnesia refractory lining. 6 = Refractory plug for taphole. 7 = Refractory plug for electrode port.
 8 = Feed port. 9 = Gas off-take. 10 = Water-cooled electrode seal. 11 = Refractory ring.
 12 = Magnesia refractory lining. 13 = Carbon lining. 14 = Slag layer. 15 = Metal. 16 = Hypothetical freeze line.
 17 = Unreacted feed. 18 = Thermocouples. 19 = Anode clamp. 20 = Refractory blanket.

Fig. 1. Arrangement of the Mintek 100kVA furnace for continuous operation



- 1 = Central hollow graphite electrode. 2 = Steel anode. 3 = Plasma zone. 4 = Molten bath.
 5 = Water-cooled electrode seal. 6 = Feed port. 7 = Gas off-take. 8 = Steel roof with magnesia lining.
 9 = Insulation blanket (ceramic fibre). 10 = Water-jacket. 11 = Refractory crucible.
 12 = Graphite block.

Fig. 2. Arrangement of the Mintek 100kVA furnace for 'pot tests'



1 = Plasma gun. 2 = Anode connection. 3 = Molten bath. 4 = Hypothetical freeze line.
 5 = Gas off-take. 6 = Feed port. 7 = Refractory plug for taphole. 8 = Magnesia-chromium bricks.
 9 = Alumina plug. 10 = Magnesia bricks. 11 = Cast magnesia. 12 = Steel shell.

Fig. 3. Arrangement of the TRD 1.4 MVA furnace

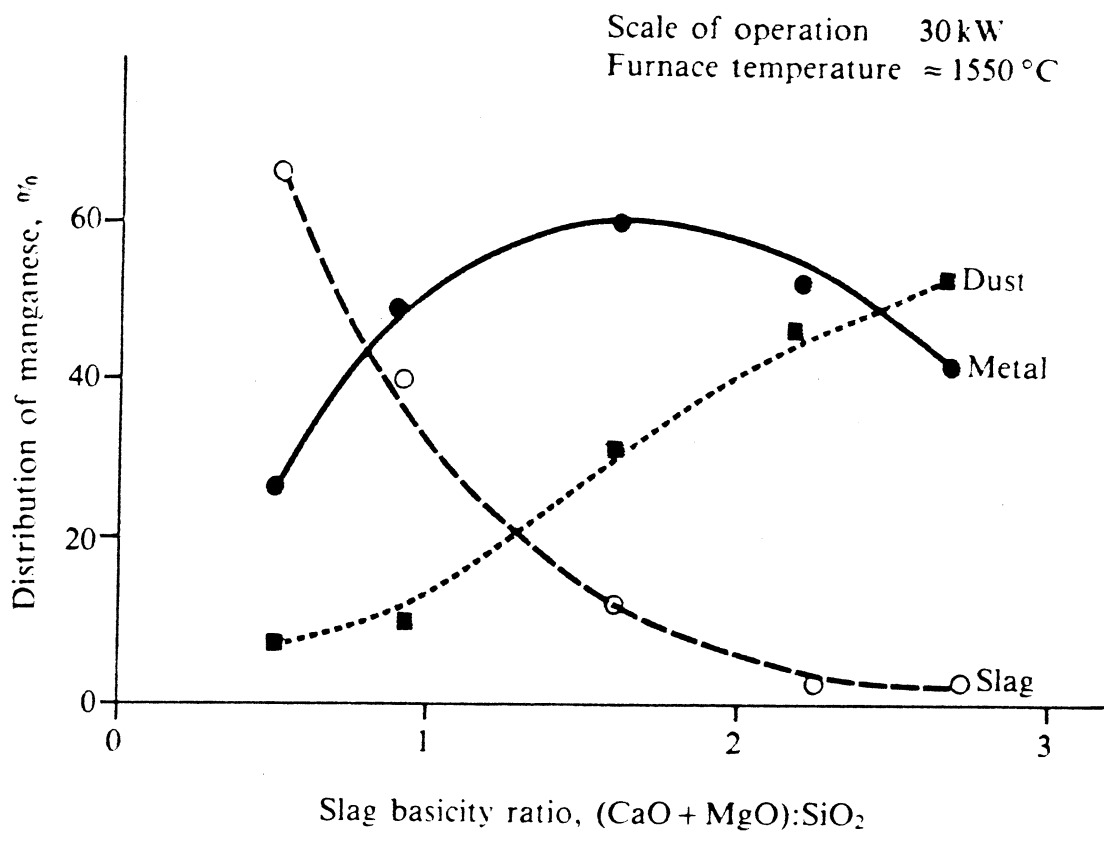


Fig. 4. Distribution of manganese between metal, slag, and dust at various slag basicities

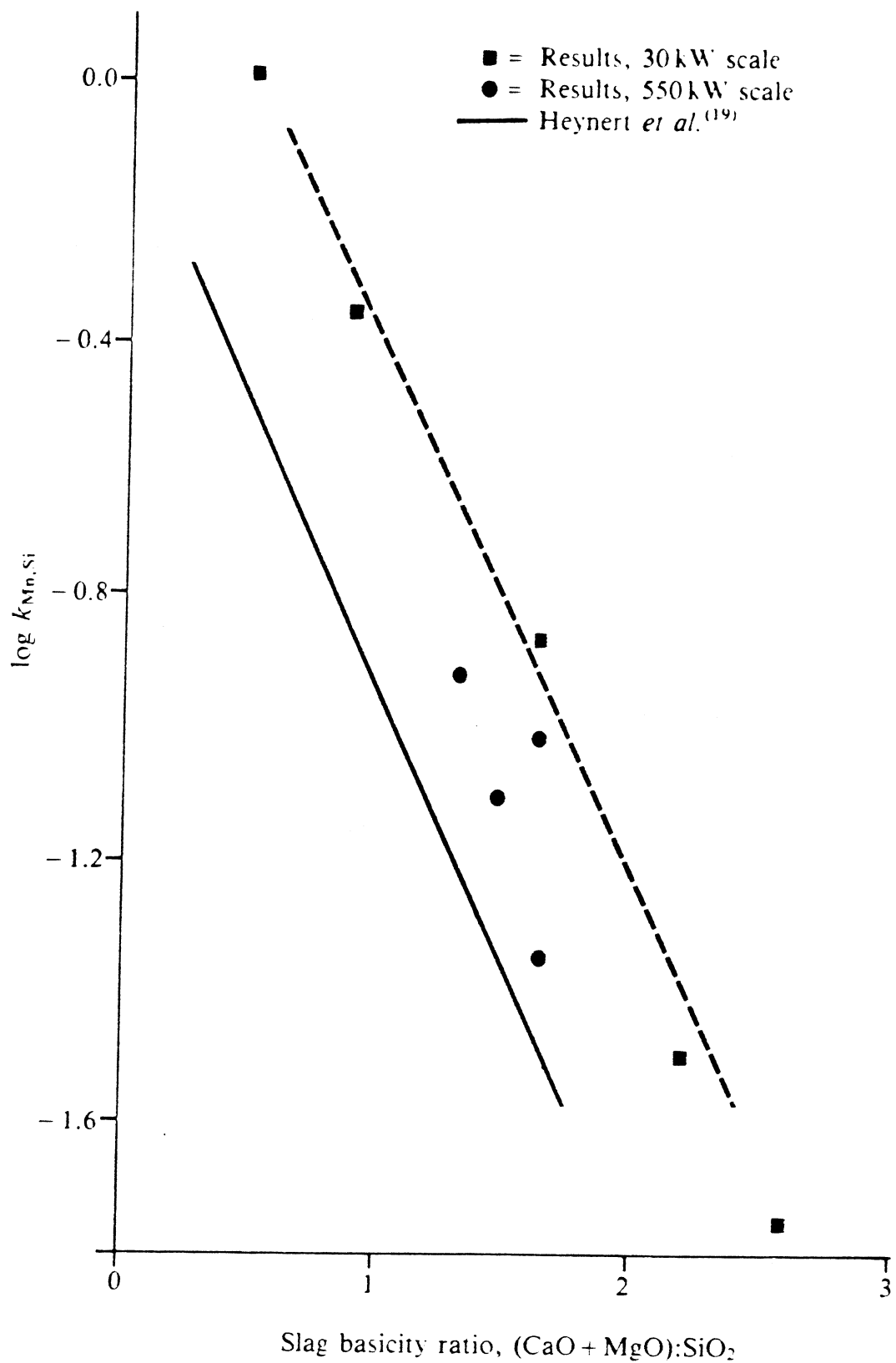


Fig. 5. The logarithm of the apparent equilibrium constant, $k_{Mn,Si}$, at various slag basicities

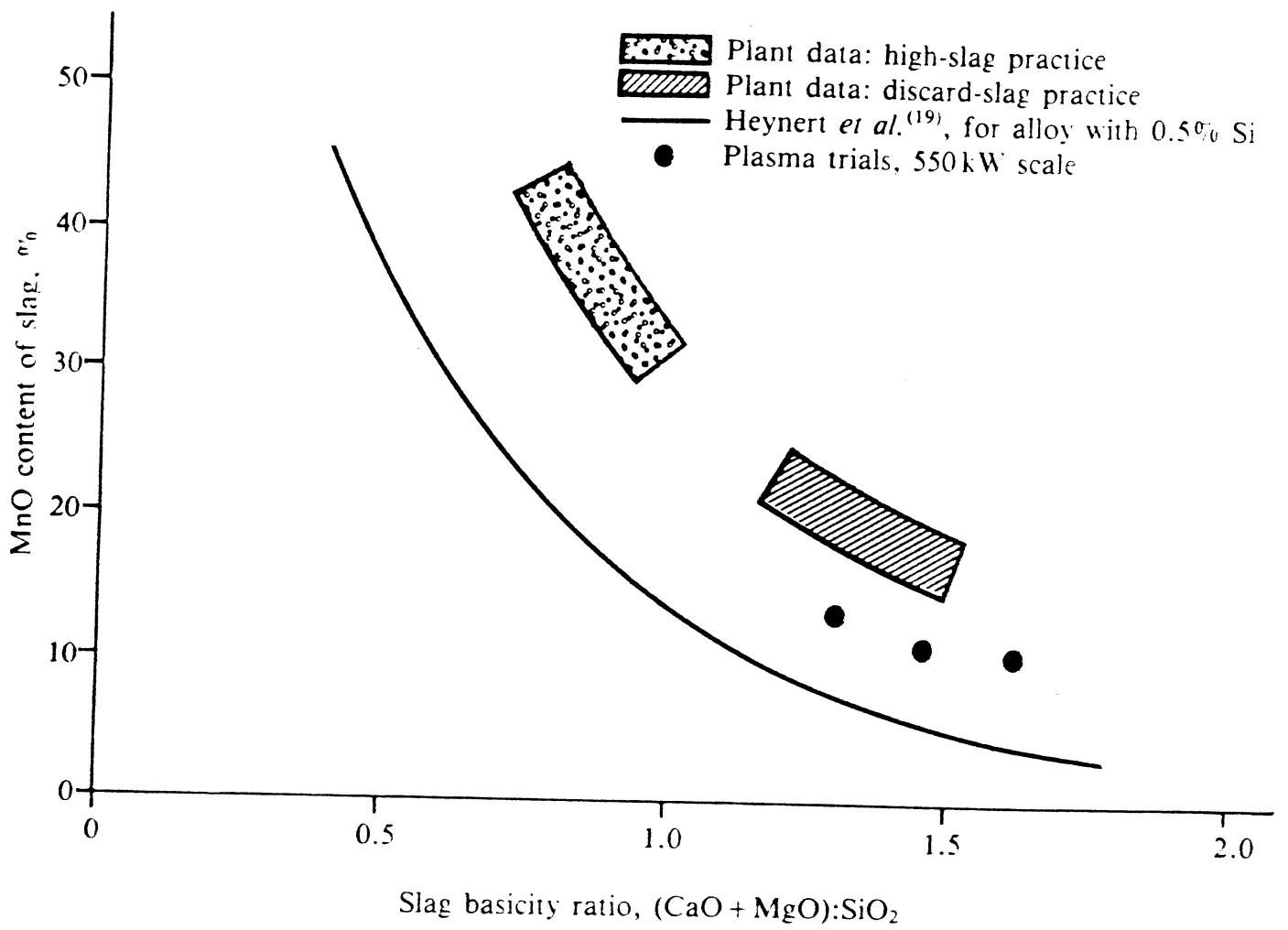


Fig. 6. The manganese oxide content of the slag as a function of slag basicity in the production of high-carbon ferromanganese and in plasma trials