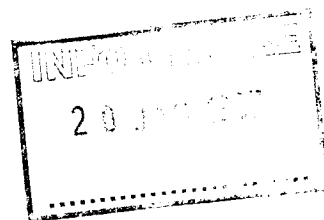


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PAPER 9917

J.C.VAN DEN BERG



FLUIDIZED-BED REDUCTION OF FINE IRON ORE
BY THE IN SITU COMBUSTION OF COAL.

BY J.C.VAN DEN BERG* AND R.J.DIPPENAAR†.

SYNOPSIS

This paper describes an investigation into the pre-reduction of hematite fines in a fluidized-bed reactor as a means by which they can be prepared for direct smelting in a transferred-arc plasma furnace. A single-stage fixed fluidized-bed reactor using *in situ* combustion of coal was employed.

It is shown that the hematite is reduced to magnetite at 1000°C, the degree of reduction being limited by the inherent shortcomings of a single-stage reactor in which both the combustion and reduction reactions have to occur. Methods by which the degree of reduction can be increased are suggested.

The combustion process is studied in some detail, and three different reducing agents are compared. The dominating effect of the Boudouard reaction on the behaviour of the fluidized bed is clearly illustrated. It is concluded that non-coking coals of high reactivity are best suited to this process, which would therefore complement the trend away from expensive coke as a metallurgical reducing agent.

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Van Den Berg J.C.

SAMEVATTING

Daar word verslag gedoen van 'n ondersoek na die voorreduksie van fynhematiet in 'n fluïedbedreaktor as 'n wyse om die erts voor te berei vir regstreekse uitsmelting in 'n oordraboogplasmaoond. 'n Vaste enkeltrapfluïedbedreaktor wat van die *in situ*-verbranding van steenkool gebruik maak, is vir die doel gebruik.

Hematiet word by 1000°C tot magnetiet gereduseer. Die mate van reduksie word egter beperk deur die inherente tekortkominge van 'n enkeltrapreaktor waarin sowel die verbrandings- as die reduksiereaksie moet plaasvind. Voorstelle word gemaak vir metodes wat aangewend kan word om die mate van reduksie te verhoog.

Die ontbranding van steenkool word in besonderhede bestudeer en drie verskillende reduseermiddels word vergelyk. Die bepalende invloed van die Bououard-reaksie op die gedrag van die fluïedbed word duidelik geïllustreer. Die belangrike gevolgtrekking is dat die mees geskikte reduseermiddel vir hierdie tipe fluïedbedreaktor 'n nie-kooksool met 'n hoë reaktiwiteit is. Die ontwikkeling van fluïedbedreaktortegnologie is dus 'n verdere stap in die vervanging van duur kooks met goedkoper laegraadse steenkool as metallurgiese reduseermiddel.

Introduction

Large quantities of hematite fines (smaller than 5 mm) are currently being stockpiled in South Africa because they cannot be processed economically as the feedstock for a blast furnace or a direct-reduction process. Although lumpy iron ore (larger than 5 mm) is expected to be available for another 30 years or more¹, there are several economic incentives for the development of a process that could use these fines as a feedstock. The mining costs of the fine material have already been recovered, and therefore the cost of the raw materials for a conversion process using these fines would be significantly reduced. Furthermore, the full production capacity of the hematite mines would be utilized, and stockpiling could be eliminated, should a conversion process be successfully developed.

An exciting prospect is the use of a fluidized-bed reactor for the pre-reduction of these fines, which could subsequently be charged hot to a transferred plasma-arc furnace for completion of the reduction process. Meihack *et al*² have shown that considerable savings in electrical energy can be achieved by the use of pre-reduced material as the feedstock to a plasma furnace.

The application of fluidized-bed technology in the pyrometallurgical industry is not new by any means. Examples of its application, are: the reduction of iron ore with hydrogen³, the production of titanium tetrachloride⁴, and the roasting of various sulphide ores³. The combination of a fluidized-bed pre-reduction unit with a plasma-arc furnace is not a new concept either. The ELRED process^{5,6}, which was proposed by ASEA of Sweden, comprises a recirculating lean-phase fluidized-bed reactor in which the combustion of coal provides the heat as well as the reducing gas required for the reduction of iron ore. This pre-reduction unit is coupled to a d.c. transferred plasma-arc furnace, which uses a hollow carbon electrode through which the product of the fluidized bed is fed to the furnace. The pre-

reduction stage has been successfully tested on the pilot-plant scale at a throughput of about 400 kg of pre-reduced material per hour. The final reduction stage has been tested in a 25 t plasma furnace at Domnarvet Steelworks, Sweden⁵.

The combustion of coal *in situ* as employed in the ELRED process offers a challenging opportunity of replacing expensive reducing gas with a cheap source of fuel. It further creates the possibility that the range of coals that can be used for iron-making can be enlarged. It is particularly important for the iron and steel industry in South Africa to move away from its dependence on coking coals, firstly because coking coals are expensive and secondly because high quality coking coal is in short supply⁷.

In the present investigation, a single-stage, fixed fluidized bed was chosen for evaluation as a potential pre-reduction unit, mainly because this type of fluidized bed is compact and therefore well suited to laboratory-scale investigations, but also because it is fairly easy to operate. However, a single-stage fixed fluidized-bed reactor, combusting coal *in situ*, would not be used as a self-contained pre-reduction unit on a production scale. A production plant should consist either of multistage units or a cascade of single stages. The emphasis in the present investigation was therefore not on the immediate development of a new process as such, but rather on an analysis of the principles involved in the *in situ* combustion of coal, the degree of reduction attainable in single stage pre-reduction, and the intricate interaction between combustion and reduction.

Apparatus

A schematic diagram of the fluidized-bed reactor used in the present investigation is shown in Fig. 1. The 'working part' of the reactor comprises an alumina tube with an inner diameter of 150 mm and a height of 540 mm. The fluidized-bed overflow is 267 mm above the distributor plate, leaving a freeboard height of approximately 275 mm. A thermocouple is located at each of the

following levels above the distributor plate: 30, 70, 170, 230, 330, and 515 mm. A multichannel digital thermometer displays one thermocouple reading at a time. The off-gas is sampled continuously and is analysed for oxygen, hydrogen, carbon monoxide, and carbon dioxide.

The feed materials are extracted from two sealed hoppers by screw feeders, and are gravity-fed into the reactor through the feed pipe. The product overflows through the product outlet into a sealed container. Air and liquified petroleum gas (LPG) are introduced via rotameters to the plenum chamber. LPG is combusted to pre-heat the reactor to a temperature at which coal combusts spontaneously (approximately 750°C). The off-gas passes through a cyclone, where the dust is collected, and then through a burner where, as a safety measure, any remaining combustible gases in the off-gas are fully combusted.

The Combustion of Coal

The type of coal used for *in situ* combustion has a significant influence on the behaviour of a fluidized bed, since the characteristics of the coal determine the eventual temperature of the bed and the composition of the reducing gas. It is preferable to operate the fluidized bed at temperatures below 1000°C so that sintering of the iron ore and coal particles is avoided. On the other hand, a temperature much lower than 1000°C is detrimental to the kinetics of the reduction reactions. Furthermore, a ratio of carbon monoxide to carbon dioxide of at least 2,3 (at 1000°C) is necessary for iron oxide to be reduced to metallic iron (Fig. 2). It is therefore imperative that the rate of the reaction between carbon and oxygen is high enough for a sufficiently high temperature to be attained, while the Boudouard reaction ($\text{CO}_2 + \text{C} \rightarrow 2\text{CO}$) should proceed at such a rate that the required amount of reducing gas is produced. A further complicating factor in this mass and energy balance is that sufficient gas should flow through the reactor for proper fluidization to be accomplished.

The influence of the feed rate, reactivity, and volatile content of the coal on the behaviour of the fluidized bed was investigated. Three reducing agents were evaluated: Springbok no. 5 coal, Springbok no. 5 char, and Collie coal. The chemical analyses and certain relevant properties of these reducing agents are summarized in Table I. The coal-evaluation experiments were conducted using silica sand with a particle size of 0,8 to 1,8 mm instead of hematite ore. This procedure was adopted in order that the influence of the reduction of hematite on the temperature of the fluidized bed and the off-gas composition could be eliminated.

Fig. 3 illustrates the dependence of the bed temperature and the off-gas composition on the feed rate for Springbok no. 5 coal, while the dependence of the bed temperature and the ratio of carbon monoxide to carbon dioxide in the off-gas on the feed rates of the three reducing agents are shown in Fig. 4. Fig. 5 shows the temperature profiles through the reactor for the three reducing agents.

Effect of the Coal Feed Rate

Fig.3 reveals that a sharp rise in the partial pressure of carbon dioxide, accompanied by a simultaneous decrease in the partial pressure of oxygen, occurs with increasing feed rate. This indicates that the carbon-combustion reaction



dominates the process at coal feed rates lower than 3 kg/h. This is confirmed by the accompanying rise in temperature, indicating that the heat of combustion provided by reaction (1) overrides the endothermic effect of the release and decomposition of the volatile materials, as well as that of the Boudouard reaction



At coal feed rates between 3 and 5,5 kg/h, reaction (1) still proceeds at a high rate, as shown by the rapid depletion of oxygen in the system. However, in this regime the Boudouard reaction is gaining in importance as carbon dioxide is converted to carbon monoxide, causing the rate of temperature increase to diminish. However, the combustion of the volatile materials, which consumes oxygen and releases heat, makes it difficult to quantitatively assess the relative rates of these reactions.

At coal feed rates higher than 5,5 kg/h, the oxygen in the system is depleted, carbon dioxide is consumed (carbon monoxide being released concurrently), and the temperature drops. The endothermic Boudouard reaction therefore dominates this regime, although the combustion of the volatile components of the coal may also contribute to the increase in the carbon monoxide content of the off-gas. In this regime, the temperature is also influenced, but to a lesser degree, by the heat capacity of the coal.

The difference in temperature distribution in the reactor as a function of coal feed rate is clearly shown by a comparison of the two curves for different feed rates of Springbok no. 5 coal in Fig.5. At a feed rate of 1,72 kg/h, enough oxygen is available to facilitate combustion, even above the surface of the fluidized bed. Consequently, the temperature increases from the bottom to the top of the reactor. The combustion taking place within the fluidized bed is due mostly to the reaction of oxygen with fixed carbon, while that above the surface is attributable mainly to the reaction of oxygen with volatile material. At a feed rate of 5,27 kg/h, more carbon is combusted, and hence the overall temperature in the fluidized bed is higher. Also, all the oxygen is consumed within the fluidized bed, and the Boudouard reaction ensues, causing the shape of the two curves to differ considerably.

At a feed rate of 5,27 kg/h, a high-temperature zone develops close to the bottom of the fluidized bed, indicating that the exothermic combustion of carbon to carbon dioxide proceeds at a

high rate in this region. This is in agreement with the findings of Cooke and Robson ⁹, who observed that a zone with a temperature about 100°C higher than that of the bulk bed exists near the bottom of a fluidized-bed combustor. The high temperature and excess carbon provide a strong driving force for the conversion of carbon dioxide to carbon monoxide, and this endothermic reaction results in a drop in bed temperature immediately above the high-temperature oxidizing zone. At the top of the fluidized bed, the temperature drops as a result of pre-heating of the feed material, devolatilization of the coal and cracking of the volatile components of the coal. Above the surface of the bed, the temperature is determined by the cracking of volatile material and heat losses through the reactor containment.

Effect of Coal Reactivity

It is evident from Table I that the reactivity of Springbok no. 5 coal is lower than that of Collie coal. The reactivity relates specifically to the rate of the Boudouard reaction, and it is to be expected that this reaction will proceed at a much higher rate with Collie coal than with Springbok no. 5 coal, resulting in a higher rate of formation of carbon monoxide and a lower bed temperature. This is confirmed by the experimental findings reported in Fig.4. A maximum of 13,5 per cent carbon monoxide was released during the combustion of Collie coal, while only 7,5 per cent carbon monoxide was released during the combustion of Springbok no. 5 coal. Further evidence that the reactivity of the coal, and hence the Boudouard reaction, dominates the behaviour of the bed is provided by the fact that the maximum temperature of the bed, as well as the maximum release of carbon monoxide, occurs at lower feed rates for Collie coal, i.e. the Boudouard reaction proceeds at a higher rate at any given temperature for coal of higher reactivity (Fig.4).

Inspection of the temperature profiles (Fig. 5.) indicates that, for Collie coal and Springbok no. 5 coal at similar feed rates, the coal with the higher reactivity causes a larger drop in temperature immediately above the zone of highest temperature because the Boudouard reaction proceeds at a higher rate. This stresses the dominating influence of the endothermic Boudouard reaction. In summary, not only are the reducing conditions better with the higher-reactivity coal (Collie coal), but the bed temperatures are somewhat lower, but still high enough to ensure reduction of the hematite. Lower bed temperatures are advantageous because the softening of partially reduced iron ore will be less severe, reducing the possibility of clinker formation.

Effect of Volatile Content.

An important conclusion can be drawn from a comparison of the bed temperature and the off-gas composition for Springbok no. 5 coal and those for its devolatilized equivalent. Fig. 4 shows that the temperature of the fluidized bed is virtually independent of the volatile content of the coal, but the char produces less carbon monoxide. A comparison of the temperature curves shows clearly that the endothermic decomposition of volatile products does not dominate. However, at high feed rates of coal there is some indication that the release of volatile material does lower the temperature of the bed. The small difference in bed temperature that results from the use of standard, as opposed to devolatilized coal, is clear evidence of the dominant role played by the Boudouard reaction with respect to the temperature of the bed.

Coal Utilization

Because a fluidized-bed process using the *in situ* combustion of coal to produce reducing gas requires an excess of coal, it is to be expected that the coal will not be fully utilized,

particularly in a single-stage design like that used in the present study.

The utilization of fixed carbon, degree of devolatilization, and degree of combustion of volatile materials for Springbok no. 5 and Collie coal are compared in Fig. 6. At coal feed rates lower than 3 kg/h, the utilization of fixed carbon increases with increasing feed rate for Springbok no. 5 coal, whereas the opposite trend is observed at higher feed rates. This apparent anomaly can be resolved if it is recalled (Figs. 3 and 4) that there is a sharp rise in temperature in this regime. As the feed rate increases, the temperature of the bed increases markedly, causing the carbon-combustion reaction to accelerate. The sharp decline in the oxygen content of the off-gas (Fig. 3) is further evidence that the carbon is combusted at an increased rate at higher coal feed rates, provided that the feed rate is lower than 3 kg/h.

For the economic operation of a single-stage fluidized bed of the current design, it is clear that coal feed rates in excess of 4 kg/h should be avoided. The utilization of fixed carbon diminishes sharply at higher feed rates, with the result that unreacted coal forms a pronounced portion of the product stream. The sharp decline in the degree of combustion of volatile material provides further proof that the increased amount of volatile materials made available at higher coal feed rates do not provide proportionally more reducing gas. At the high temperatures prevailing in the fluidized bed, the volatile materials are effectively driven off, but are not utilized as reducing gas, probably because the higher hydrocarbons are not fully cracked.

The combustion of volatile material is more complete for Collie than for Springbok no. 5 coal. When heated, Springbok no. 5 coal swells to form a char with a bulk density of about 500kg/m^3 , whereas Collie coal does not swell, and produces a char with a bulk density of about 800 kg/m^3 . Particles with different masses

segregate to some extent in a fluidized bed ¹⁰, and it is therefore expected that Collie coal would mix better into the bed than Springbok no. 5 coal, so that its volatile materials are more likely to be combusted.

Although the reactivity of Collie coal is higher than that of Springbok no. 5 coal, its fixed carbon is utilized to a lesser extent. This may be due to the fact that the degree of combustion of the volatile components of Collie coal is higher, and that, as a result, less oxygen is available for the combustion of the fixed carbon.

Stability of the Fluidized Bed

The fluidized bed frequently destabilized as a result of the formation of agglomerates (clinkers) when Springbok no. 5 coal or char was used, but not when Collie coal was used. It is essential that the mechanism of clinker formation should be understood, because destabilization of the bed has to be avoided at all costs.

Topper *et al.*¹¹ postulated that clinker formation in the high-temperature zone of a fluidized bed is primarily due to the tendency of a coal to swell. They suggested that char particles stick together when passing through a regime of plastic flow at high temperature, and were able to relate this sticking behaviour to the swelling index. Should this postulate be correct, it is to be expected that Springbok no. 5 coal, with a relative swelling index of 3,5, should tend to form clinker, whereas Collie coal, with a relative swelling index of zero, should not have this tendency. This was found to be the case in the present investigation.

During the formation of clinkers, the temperature in the lower of zone the bed rose sharply to above 1300°C, and then fell to ambient temperature, while the temperature of the freeboard gas

rose to about 1100°C.

It is suggested that clinker formation starts when some char particles stick together in the high-temperature zone of the reactor. Owing to the relative stagnancy of the clinker, the heat generated by the combustion reaction in this area is dissipated less efficiently than in zones where small particles are readily mixed. The first observable effect of clinker formation is an increase in temperature in the hot zone. (Cooke and Robson⁹ suggested a similar reason for the overheating of the bottom part of the fluidized bed when coal particles are too large to be fluidized sufficiently.) The temperature in the vicinity of the clinker rises sharply, probably exceeding the fusion temperature of the coal ash. The clinker now becomes even stickier, and grows as particles of char and silica are attached to it until it may occlude the entire cross-section of the bed. Air forces its way through only a few channels and particulate material is blown up into the freeboard area. The rise in the temperature of the freeboard gas that was observed experimentally during clinker formation, indicated that the entrained stream of coal (char) particles combusted in accordance with the proposed mechanism.

Reduction of Hematite

Hematite fines from the Sishen's northern mine were reduced in the experimental reactor in a determination of the degree of reduction that is attainable in a single-stage fluidized-bed in which the reducing gas is supplied by the *in situ* combustion of coal.

The ratio of carbon monoxide to carbon dioxide in the off-gas from Springbok no. 5 coal that was combusted in the presence of silica was about 0,5 and that in the off-gas from Collie coal was approximately 1,6 (Fig 4). At a reaction temperature of 1000°C in the fluidized-bed, wüstite would be the only stable

iron oxide phase if either of these coals was used as the reductant (Fig 2).

Springbok no. 5 coal was used as the reducing agent for hematite. (This was done despite the superiority of Collie coal as a reducing agent, since insufficient quantities of Collie coal were available.) In experiments on the influence of retention time on reduction, the same iron ore was passed through the reactor three times in succession. LPG was always introduced into the reactor to maintain the temperature below 1000°C. During the third pass of the iron ore through the reactor, it was necessary to add nitrogen and to decrease the flow of air, because control of the temperature of the fluidized bed became increasingly difficult. Details of the experimental conditions are summarized in Table II.

The results of the reduction experiments are presented in Fig. 7. As the retention time was increased, the average reduction approached 11,1 per cent asymptotically. This is equivalent to the complete reduction of hematite to magnetite, and indicates that the oxygen potential in the fluidized bed is not low enough for the reduction of hematite to wüstite. This is in contrast to the equilibrium conditions suggested by the temperature and the ratio of carbon monoxide to carbon dioxide in the off-gas, which indicate that wüstite should form (Fig. 2). However, the ratio of carbon monoxide to carbon dioxide does not necessarily reflect the reducing conditions in the fluidized bed, firstly because the combustion of volatile material can cause carbon monoxide to form, even above the surface of the fluidized bed, and secondly because an oxidizing zone exists immediately above the distributor plate.

A mineralogical investigation of the partly reduced particles revealed that the hematite ore originally contained both dense and porous particles, the latter constituting some 82 per cent of the total. The dense particles exhibited typical topochemical reduction behaviour (Fig. 8). The porous particles were reduced

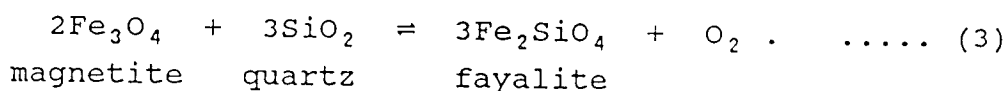
more homogeneously (Fig. 9), evidently because the reducing gas could enter the particles through the pores. After the second pass of the iron ore through the reactor, all the porous particles were fully reduced to magnetite. Although some of the dense particles were fully reduced to magnetite, others were only reduced to about 25 per cent magnetite.

Sporadic clinker formation occurred during the second and third successive passes of the iron ore through the reactor. These clinkers were very sticky at the operating temperature of the fluidized bed, and much more difficult to break than the silica-coal clinkers referred to earlier. The clinkers were examined mineralogically, and were found to possess the structure shown in Fig. 10. This photomicrograph shows lath-shaped iscorite crystals with fayalite inclusions penetrating wüstite grains, which have magnetite rims. The presence of iscorite ($5\text{FeO}\cdot\text{Fe}_2\text{O}_3\cdot\text{SiO}_2$) in the structure is interesting, because this phase appears to have been described only once in the literature - by Smuts *et al.* ¹², who found it at the bottom of a steel-reheating furnace, that had been kept at a temperature of about 1300°C.

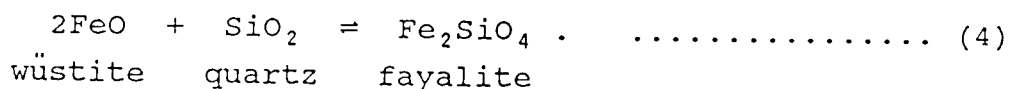
The following mechanism of clinker formation within the bed containing iron ore is proposed with reference to the phase diagram shown in Fig. 11.

Because of the coking properties of the coal used in the present investigation, some char particles tend to stick together initially to form a small clinker. This clinker then becomes overheated (according to the mechanism described earlier, i.e. the heat cannot be dissipated efficiently from the clinker because of its relative bulkiness), which causes the coal ash to soften and particles of magnetite to attach themselves to the clinker. This probably occurs just above the distributor plate, which, during normal operation, represents the hottest zone in the fluidized bed (Fig. 5). Although the clinker is contained in this relatively oxidizing zone just above the distributor plate,

a rise in temperature would cause the ratio of carbon monoxide to carbon dioxide inside the clinker to increase, because the clinker contains coal, and the formation of carbon monoxide from carbon and carbon dioxide is favoured at higher temperatures (Fig. 2). Fig. 11 indicates that a rise in temperature of the clinker and/or an increase in the ratio of carbon monoxide to carbon dioxide may eventually cause the magnetite in the clinker to become transformed to wüstite (A→B or A→C in Fig. 11). However, fayalite may also be formed in association with the quartz contained in the coal ash :



It is also thermodynamically feasible that fayalite may form by a reaction between wüstite and quartz, as follows:

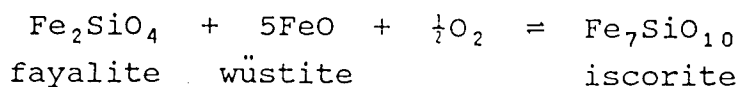


(Wüstite is represented by the simplified formula FeO.)

If the assumption that the softening of the coal ash contributes to clinker formation is valid, the implication is that the temperature within the clinker was higher than 1400°C (Table I). Also, since iscorite was observed mineralogically, and previous investigators¹² have shown that iscorite forms only at temperatures in the region of 1300°C, the temperature within the clinker must have been at least about 1300°C. It was evident from the mineralogical investigation of the clinker that fayalite formed in the fluidized bed (Fig. 10). Since the liquidus temperature of fayalite¹⁵ is only 1205°C, and the clinker clearly reached higher temperatures, the liquid fayalite must have contributed to the cementation of grains of iron ore, thereby promoting clinker formation.

It can be inferred from Fig. 11 that a decrease in temperature (B→A), probably accompanied by a decrease in the ratio of carbon

monoxide to carbon dioxide (C→A), results in the transformation of wüstite to magnetite, which would explain the presence of the magnetite rims that were observed on the wüstite grains (Fig. 10). Similarly, the formation of iscorite would be expected to be an oxidizing reaction and, because of the association of iscorite with fayalite and wüstite (Fig. 10), the following reaction for the formation of iscorite is envisaged:



Discussion.

In the course of the present study, it was found that the coking properties of a given coal contribute significantly to the formation of clinkers. Hence, it seems that only non-coking coals should be considered for *in situ* combustion in a fluidized-bed reduction process. The use of such a process could therefore benefit the South African iron and steel industry, which would naturally prefer to reduce its present dependence on expensive coking coal⁷.

A further prerequisite for the acceptance of coal in this process is that the ash-fusion temperature should be in excess of 1400°C so that melting or even excessive softening of the ash can be avoided. It was proposed, and observed, that fayalite may form by the reaction of silica with magnetite or wüstite. Nevertheless, the silica content of the coal ash is not considered to be of critical importance provided that the requirements with respect to coking properties and ash-fusion temperature are met. A reducing gas with a ratio of carbon monoxide to carbon dioxide of at least 2,3 must be produced, because this is the minimum ratio needed for the reduction of iron ore to metallic iron at 1000°C.

The present configuration of the fluidized-bed reactor and the coal used limited the degree of reduction of hematite that could

be attained to 11,1 per cent. This low degree of conversion can possibly be attributed to the following factors.

A gas of low reducing strength is produced in the fluidized bed. Apart from the properties of the coal that influence the production of reducing gas, two other factors may also be of importance: the short retention time of the gas in the fluidized bed (less than 0,2 seconds), which does not allow sufficient carbon monoxide to be produced, and insufficient utilization of the volatile materials. Also, because an oxidizing zone is present in the fluidized bed just above the distributor plate, reduced iron-ore particles may be re-oxidized.

Conclusions

Fine iron ore can be reduced with coal in a fluidized-bed reactor. However, modifications to the design of the reactor used in this study are needed to improve the efficiency of the process. For example: the retention time of the gas in the fluidized bed would increase if the bed was deeper; the utilization of the volatile materials would improve if provision was made for the coal to be fed into the bottom, rather than the top, of the fluidized bed; reduced particles of iron ore could be prevented from coming into contact with the oxidizing zone at the bottom of the reactor by dividing the fluidized bed into two compartments with the incorporation of a perforated horizontal baffle-plate. This in effect would transform the single-stage reactor into a two-stage co-current fluidized-bed reactor.

A coal selected as a fuel and a reductant in a fluidized-bed reactor should be non-coking, and have a high ash-fusion temperature as well as a high reactivity. The use of the fluidized-bed process would complement the trend away from the use of expensive coke as metallurgical reducing agent.

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- Fig.4. Effect of feed rate on the bed temperature (70 mm above the distribution plate) and the ratio of carbon monoxide to carbon dioxide in the off-gas for three reducing agents
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- Fig.6. Comparison of Springbok no. 5 coal and Collie coal in terms of utilization of fixed carbon, degree of devolatilization, and degree of combustion of volatiles
- Fig.7. Reduction of hematite
- Fig.8. Topochemical reduction of a solid particle of hematite (H) to magnetite (M)
- Fig.9. Porous particle of hematite fully reduced to magnetite
- Fig.10. Lath-shaped iscorite crystals (I) with fayalite inclusions (F) penetrating magnetite-rimmed (M) wüstite grains (W)
- Fig.11. Equilibrium diagram for the iron-silicon-oxygen system (after Eugster *et al.*¹³. The ordinate on the right-hand side was constructed from data presented by Muan and Osborn¹⁴)

TABLE I
COMPOSITION AND PROPERTIES OF REDUCING AGENTS TESTED

Reducing agent	Springbok no. 5 coal	Springbok no. 5 char	Collie coal
Comments	A slightly coking Transvaal coal	The carbonaceous product from the reduction experiments	A non-coking Western Australian coal
Particle size, mm	1,0 to 1,9	Made from coal 1,0 to 1,9	1,0 to 1,9
CO ₂ reactivity (Iscor standard)	2,06	*ND (should be the same as for Springbok no. 5 coal)	3,70
Ash-fusion temp., °C	>1400	ND (should be the same as for Springbok no. 5 coal)	>1400
Swelling index	About 3,5	-	0
Composition, %			
Fixed C	55,6	61,2	50,9
**VM	31,0	2,6	31,7
Ash	10,3	34,9	3,8
Moisture	3,1	1,3	13,6
Ash composition, %			
TiO ₂	1,13	ND (should be about the same as that of Springbok no. 5 coal)	2,07
MgO	1,98		1,70
Al ₂ O ₃	22,61		32,5
SiO ₂	59,12		37,7
CaO	3,85		1,47
Cr ₂ O ₃	0,93		-
MnO	0,13		-
Fe ₂ O ₃	3,79		20,9
P ₂ O ₅	-		1,1
K ₂ O	0,145		0,27
Na ₂ O	0,038		1,06
Balance	6,3		1,2

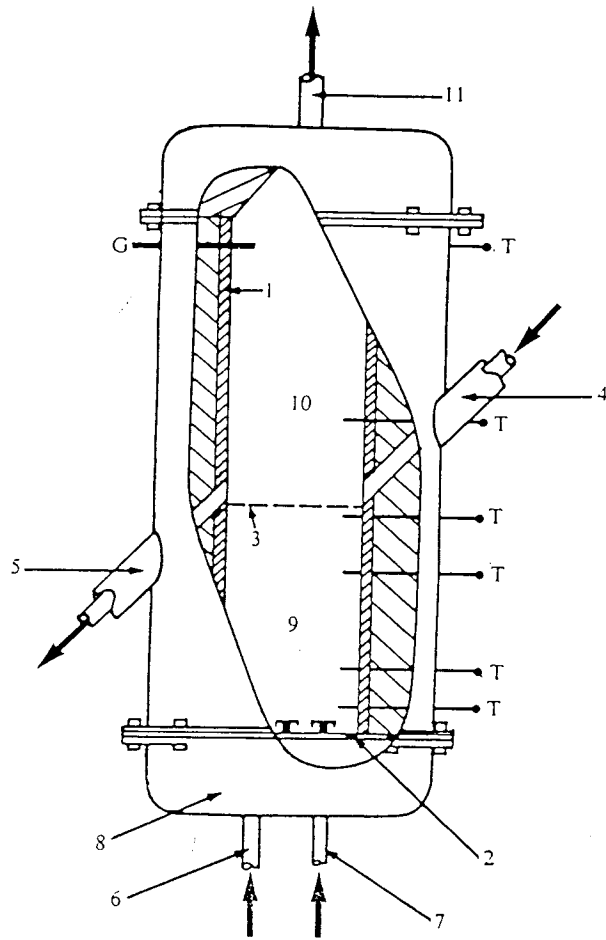
* ND Not determined

** VM Volatile material

TABLE II
CONDITIONS FOR THE REDUCTION OF HEMATITE

Pass no.	1	2	3
Iron-ore feed	Hematite	Magnetic product from 1	Magnetic product from 2
Particle size, mm	0,5 to 1,0		
Feed rate, kg/h	14,90	12,88	12,31
Fe, %	65,8		
SiO ₂ , %	3,22		
Al ₂ O ₃ , %	1,17		
Iron retention time, min	11	12	13
Coal	Springbok no. 5	Springbok no. 5	Springbok no. 5
Particle size, mm	1,0 to 1,9	1,0 to 1,9	1,0 to 1,9
Feed rate, kg/h	5,27	5,27	5,27
Fixed C, %	55,6		
*VM, %	31,1		
Moisture, %	3,1		
Ash, %	10,3		
Feed rate of LPG, kg/h (Nℓ/min)	1,87 (16,0)	1,87 (16,0)	2,80 (24,0)
Flowrate of nitrogen, kg/h (Nℓ/min)	-	-	9,2 (121)
Flowrate of air, kg/h (Nℓ/min)	21,7 (279)	21,7 (279)	14,5 (187)
Temperature, °C	950 to 1000	950	950
Approx. composition of off-gas			
CO, %	7,5	4,5	3,5
CO ₂ , %	11,3	10,4	7,0
CO:CO ₂	0,66	0,43	0,50
H ₂ , %	**ND	5,0	3,8

* VM Volatile material
** ND Not determined



- 1 Alumina tube
- 2 Distributor plate with bubble caps
- 3 Level of fluidized-bed surface
- 4 Feed pipe
- 5 Product outlet
- 6 Air inlet
- 7 Liquefied petroleum gas (LPG) inlet
- 8 Plenum chamber
- 9 Fluidized-bed area (below dotted line)
- 10 Freeboard area (above dotted line)
- 11 Gas off-take
- T Thermocouple
- G Gas-sampling probe

Fig. 1—The experimental fluidized-bed reactor

VO 5.1g

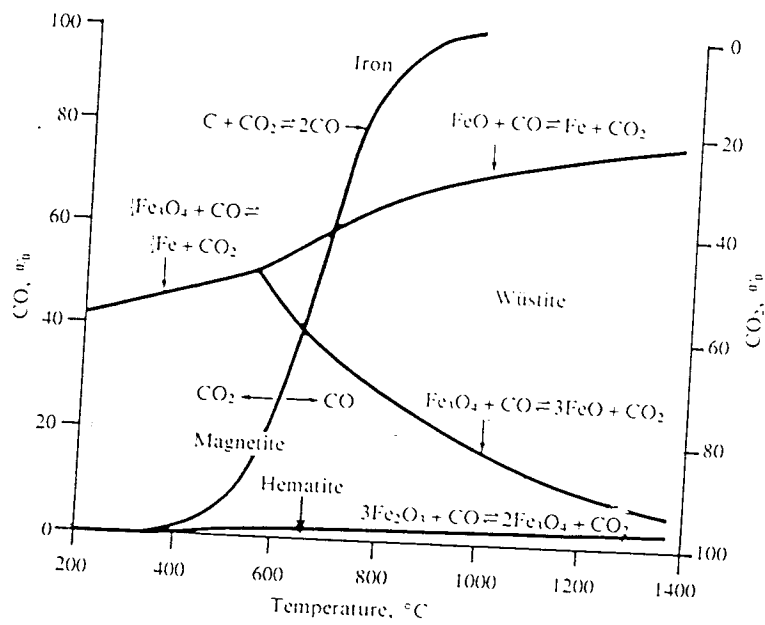


Fig. 2—Equilibrium diagram for the iron-carbon-oxygen system (after Stephenson⁸)

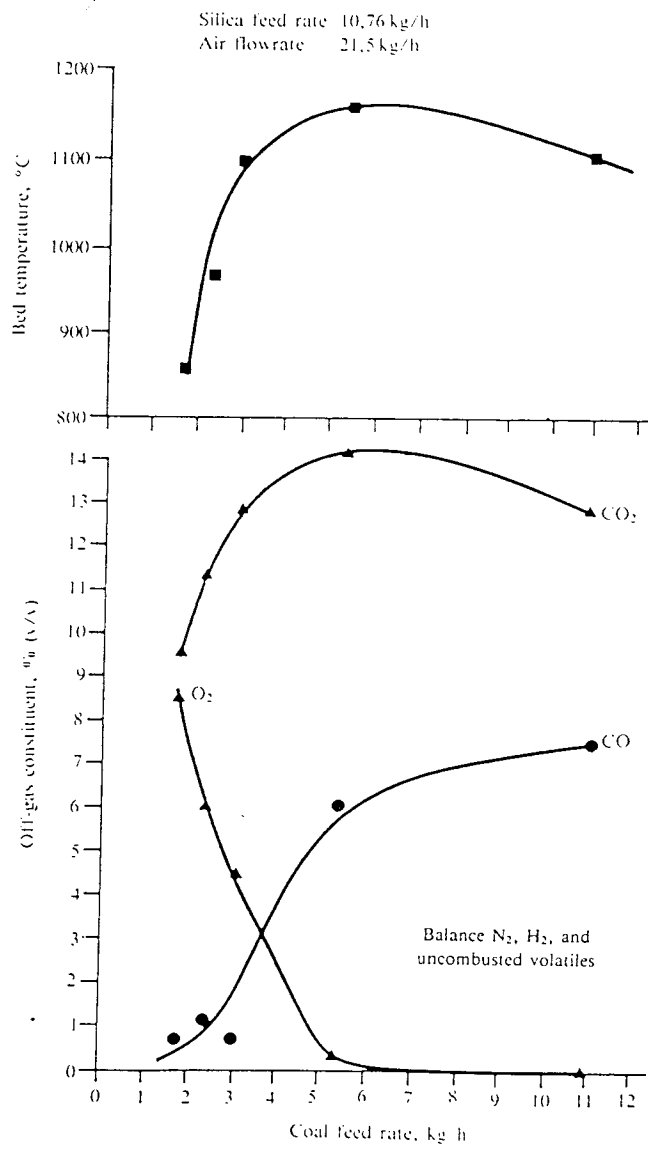


Fig. 3—Effect of the feed rate of Springbok no. 5 coal on bed temperature (70 mm above the distributor plate) and on off-gas composition

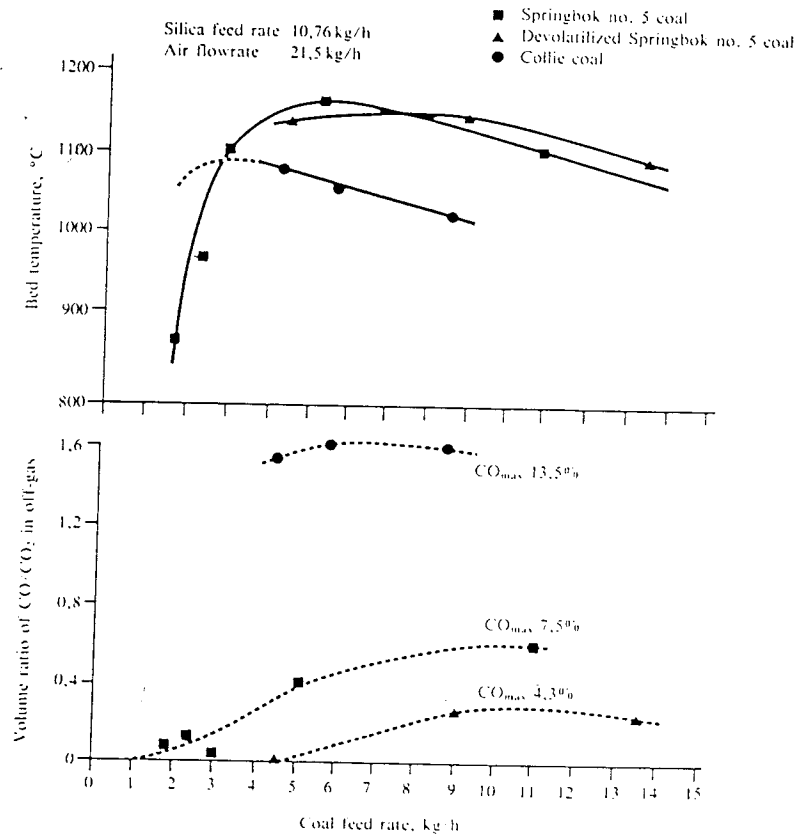


Fig. 4—Effect of feed rate on the bed temperature (70 mm above the distribution plate) and the ratio of carbon monoxide to carbon dioxide in the off-gas for three reducing agents

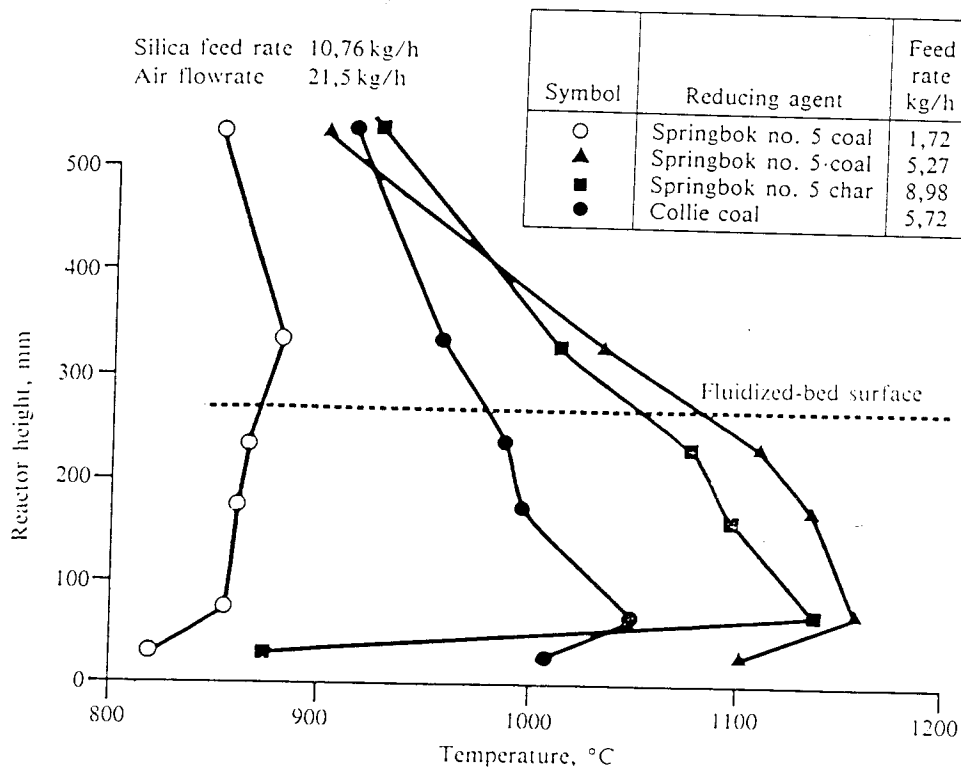


Fig. 5—Temperature profiles through the fluidized-bed reactor

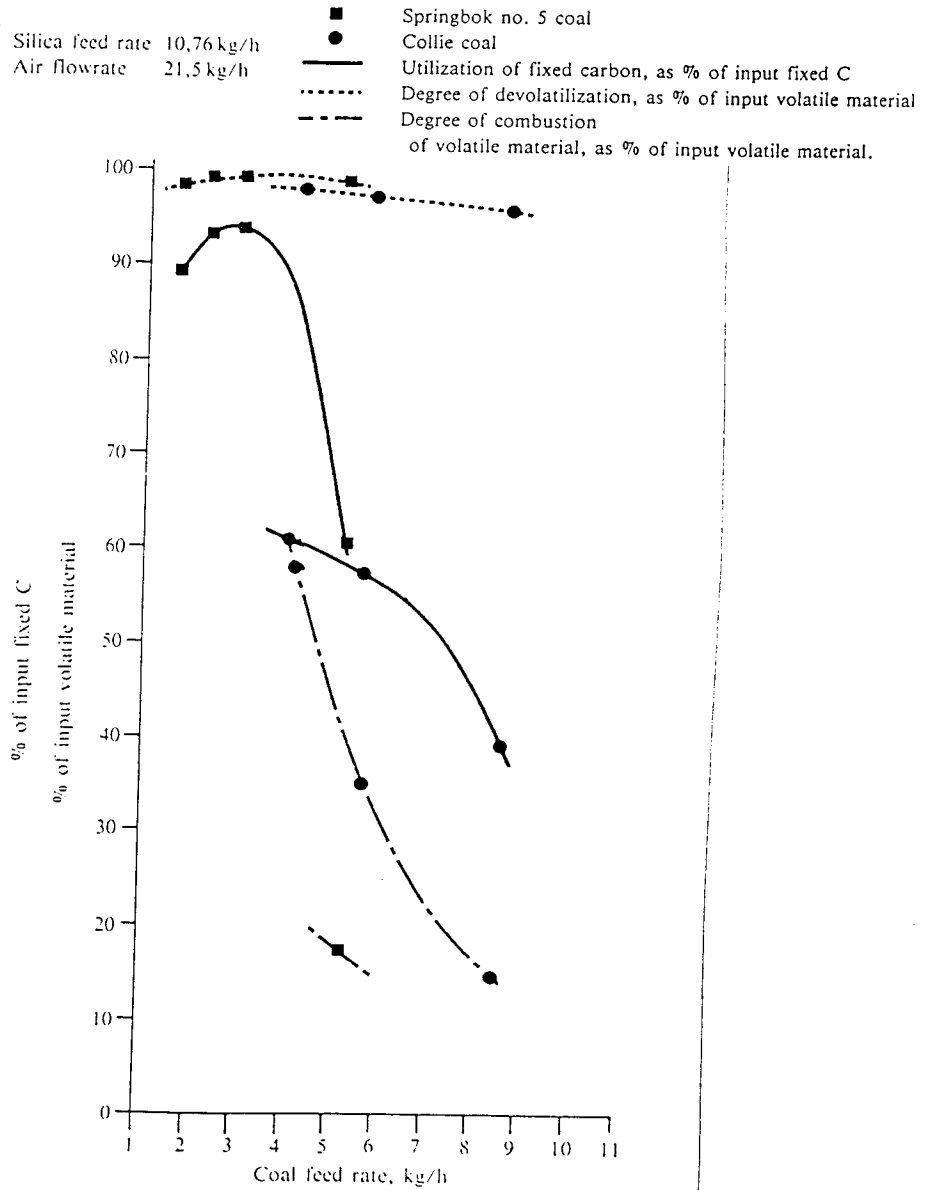


Fig. 6—Comparison of Springbok no. 5 coal and Collie coal in terms of utilization of fixed carbon, degree of devolatilization, and degree of combustion of volatiles

Temperature 950 to 1000 °C
CO:CO₂ in off-gas Approx. 0,5

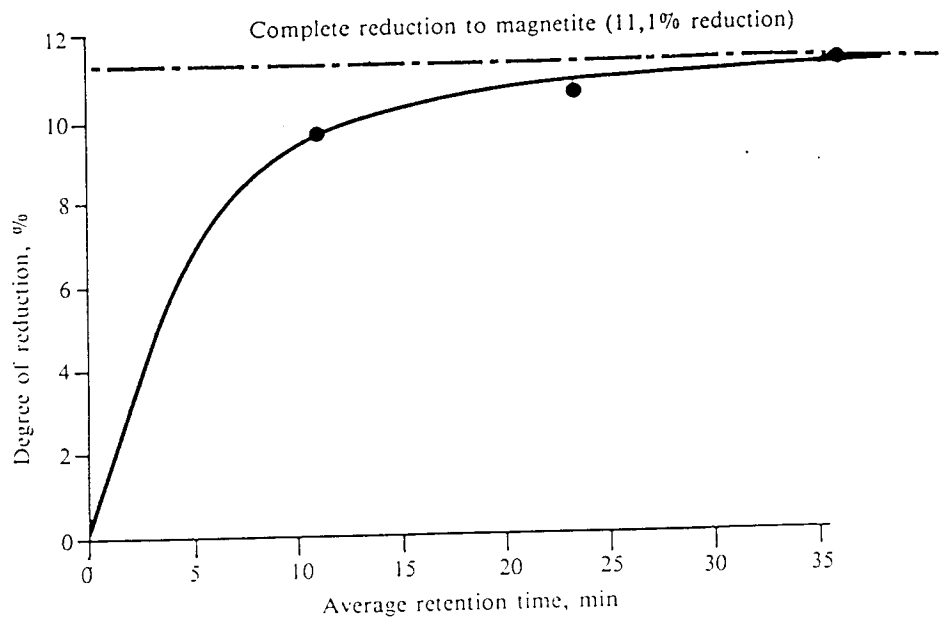


Fig. 7—Reduction of hematite

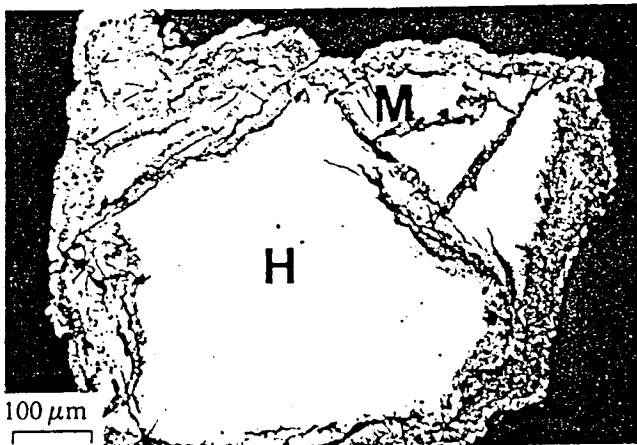


Fig. 8—Topochemical reduction of a solid particle of hematite (H) to magnetite (M)

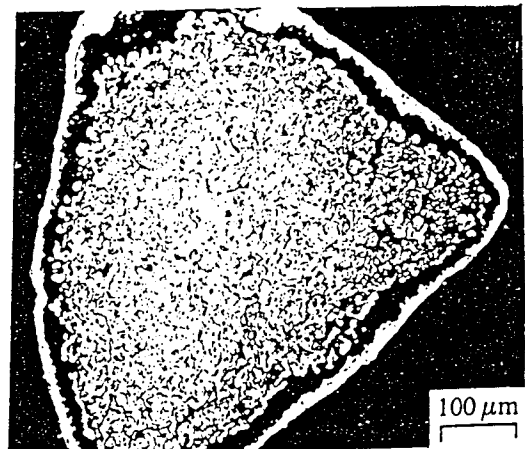


Fig. 9—Porous particle of hematite fully reduced to magnetite

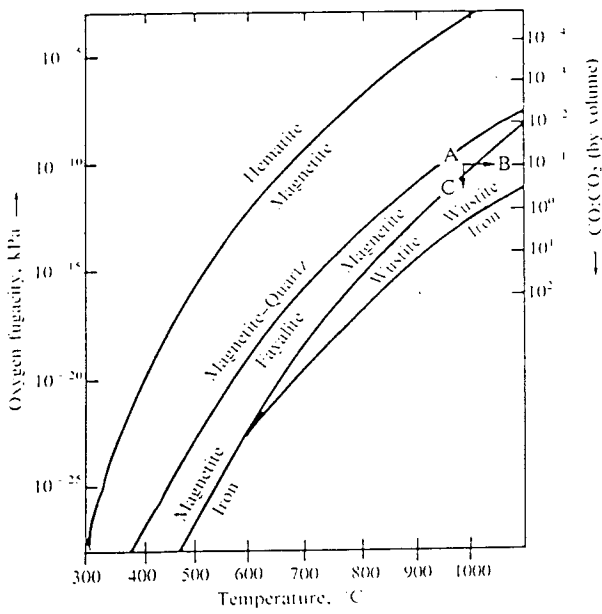


Fig. 11—Equilibrium diagram for the iron-silicon-oxygen system (after Eugster *et al.*¹³. The ordinate on the right-hand side was constructed from data presented by Muan and Osborn¹⁴)

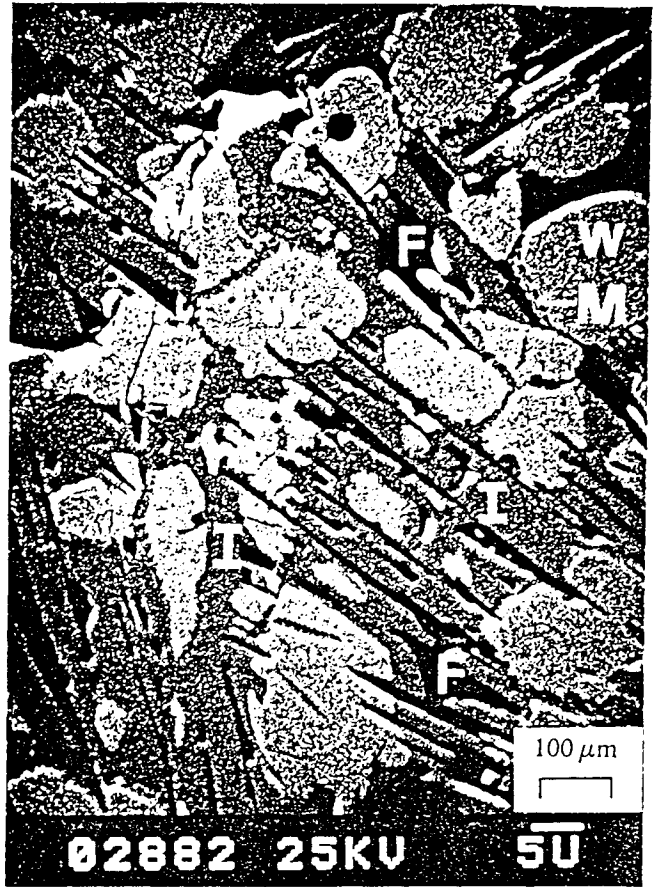


Fig. 10—Lath-shaped iscorite crystals (I) with fayalite inclusions (F) penetrating magnetite-rimmed (M) wüstite grains (W)