

1 Introduction

1.1 Current status of the iron and steelmaking industry

Current world iron production comprises of 600 million tons per year (MTPY) of hot metal and pig iron, 37.1 MTPY of direct reduced iron (DRI) and hot briquetted iron (HBI), and approximately 2 MTPY of hot metal produced by direct smelting. Most hot metal is produced in blast furnaces, which are operated in conjunction with mining beneficiation plants, pelletizing plants, sinter plants, coke batteries, limestone plants, oxygen plants, fuel gas plants and power stations⁽¹⁾.

Virtually all the steel in the world is either produced in an oxygen steelmaking converter (such as a BOF, LD or OBM (Q-BOP)) or an electric arc furnace (EAF)⁽²⁾. Most of these steelmaking equipment was built or rebuilt between 1955 and 1975. The BOF and EAF were the best technologies available at that time to further process blast furnace hot metal and relatively inexpensive scrap, into steel.

During the last three decades, more efficient blast furnaces, oxygen steelmaking, continuous casting and hot metal- and ladle metallurgy practices were developed. However, technology drivers are currently changing. At present, the most important technology drivers are^(2,3,4):

- **Lower capital and fixed cost:** The capital cost to value added ratio for integrated steelmaking is the highest of any major industry. Existing facilities are therefore expanded and renewed to optimise their useable life⁽¹⁾. Both ore-based production and scrap-based production are accompanied by high fixed, labour and raw material cost. Producers therefore tend towards lower capital costs as well as lower and more flexible fixed costs.
- **Energy and environmental:** Environmental drivers are usually in response to national or international regulation, with reduction of greenhouse gasses and recycling of steelmaking waste materials the major drivers. The reduction of energy consumption goes hand in hand with reduction of CO₂ emissions. Although reduction of energy consumption may be limited (due to the laws of conservation of energy), CO₂ emissions can be reduced by using fossil fuels to replace electrical energy. Note that electrical energy is only about 30-40% effective when considering production and transmission.

- **Flexibility:** In order to be responsive to market conditions, steelmakers need flexibility regarding raw materials, energy and production. Flexibility regarding the use of scrap, hot metal, direct reduced iron (DRI), waste oxides and iron carbide, and the substitution of coke with coal⁽⁵⁾, will allow the producer to minimize input costs. The use of fossil fuel as well as electrical energy will optimise the process with respect to energy, cost and productivity. Finally, processes that can reduce or increase production economically will enable producers to respond to market conditions.
- **Competitive forces:** New technologies need to be competitive with existing technologies. The production cost of liquid steel therefore needs to be reduced continuously.

Industry's response to these technology drivers will probably result in incremental improvements in existing technologies as well as in major developments in certain areas (of which one is direct iron and steelmaking processes)⁽⁶⁾. During the next 20 years the blast furnace will continue to produce most of the iron requirements, while direct reduced iron (DRI) could represent 20% of the virgin iron units by 2015⁽³⁾. Direct smelting may be commercialised, initially for treatment of waste oxides and to supplement scrap or to increase hot metal in integrated plants⁽⁶⁾.

1.2 Direct reduction processes

Direct reduction processes are methods for reducing iron ore directly to metallic iron⁽⁷⁾. These methods bypass several of the steps currently used in conventional steelmaking. Direct reduction processes can be separated into two major categories: i.e. gas-based- and coal-based processes.

1.2.1 Gas-based DRI processes

Gas-based processes dominate the direct reduced iron (DRI) market, with **shaft furnace gas-based processes** accounting for 94% of world DRI production. From this, the Midrex process accounts for 70% (with 50 operational furnaces), the HYL processes accounts for 23% (with 29 operational furnaces) while the Arex accounts for approximately 1% (with 5 operational furnaces). The contribution of the Purofer furnace is negligible⁽¹⁾ while the Danarex process is still at pilot plant stage. The major differences between these processes are the way in which reducing gas for the

process is generated. The Midrex uses a natural gas reformer, the HYL uses a steam reformer, and the Arex is based on direct injection of natural gas into a reduction shaft. All of these processes require the use of high grade, sized iron ore lumps and/or pellets as feedstock. Typical process parameters for shaft furnace gas-based processes are shown in **Table 1**.

Table 1: Process parameters for shaft furnace gas-based processes ^(1,8).

Parameter	Unit	Midrex	HYL (shaft process)	HYL (self- reforming)	Arex	Danarex
Ore/pellets	t/t DRI	1.45	1.45	1.42	1.45	1.42
Natural gas	Gcal/t	2.42	2.42	2.23	2.2-2.4	2.4
Oxygen	Nm ³ /t			41		38
Pressure	atm	1	5		2	1
Metallization	%	92-95	92-95	92-95	92-95	91-94
%C in DRI	%	1.0-3.5	1.2-4.5	1.0-5.0	1.8-2.0	1.0-4.0
Capital cost	USD/t	125	170	140		

In addition to shaft furnace gas based processes are **fluidised bed gas based technologies** such as the Fior-, Finmet-, Iron carbide- and Circored processes. These processes were developed to use iron ore fines as feedstock and are mostly multi-stage processes.

The **Finmet process** was derived from the Fior process (of which a plant is operational in Venezuela). Two Finmet plants are currently operational: one at Port Hedland, which was commissioned in 1999, and another that was commissioned at Orinoco Iron C.A in 2000. The Finmet is a 4-stage process, operating at a pressure between 11 and 13 atm, and temperatures between 550°C and 800°C. The main problems encountered with this process were difficulties in achieving high degrees of reduction due to temperature control as well as problems with briquetting of the product.

The **Iron carbide process**, which was developed by Hazen Research Institute, uses iron ore fines to produce 80% Fe₃C. The single vessel process is essentially a two-stage batch process. During the first stage the ore is reduced at temperatures between 570°C and 600°C with hydrogen (from a steam reformer), after which the metal is carburised with methane. Although the design capacity of the plant was 300000 tons per annum (tpa), the Trinidad plant had an actual capacity of 120000 tpa and was therefore shut down in 1999.

The **Circored process**, which was developed by Lurgi and commissioned in 1999, produces HBI from iron ore fines. For this, the process uses almost pure hydrogen, which is produced in a steam reformer with natural gas as heat source. The process comprises of two reduction stages, i.e. a circulating Fluidized bed as well as a fixed fluidised bed. The Fluidized bed operates at 630°C and a pressure of 4 atm to achieve between 92 and 93% metallisation. Due to the use of hydrogen as reductant the carbon content of the product is virtually zero. Although the process uses readily available ore fines, the operating cost of the process is relatively high.

1.2.2 Coal-based DRI processes

Coal-based DRI processes comprise the following:

- Rotary kiln based processes
- Rotary hearth based processes
- Fluidised bed based processes

The coal-based processes are less environmentally friendly than gas-based processes, due to higher CO₂ emissions. The production of fine ashes containing sulfur compounds, which requires treatment before disposal, is another potential problem of these processes⁽¹⁾.

Coal based DRI production is mainly accounted for by rotary kiln processes such as the SL/RN process (with commercial plants in South Africa, India and New Zealand), the Davy process (with commercial plants in South Africa and China), and the Accar process (with a commercial plant in Norway).

The SL/RN process is schematically shown in **Figure 1**

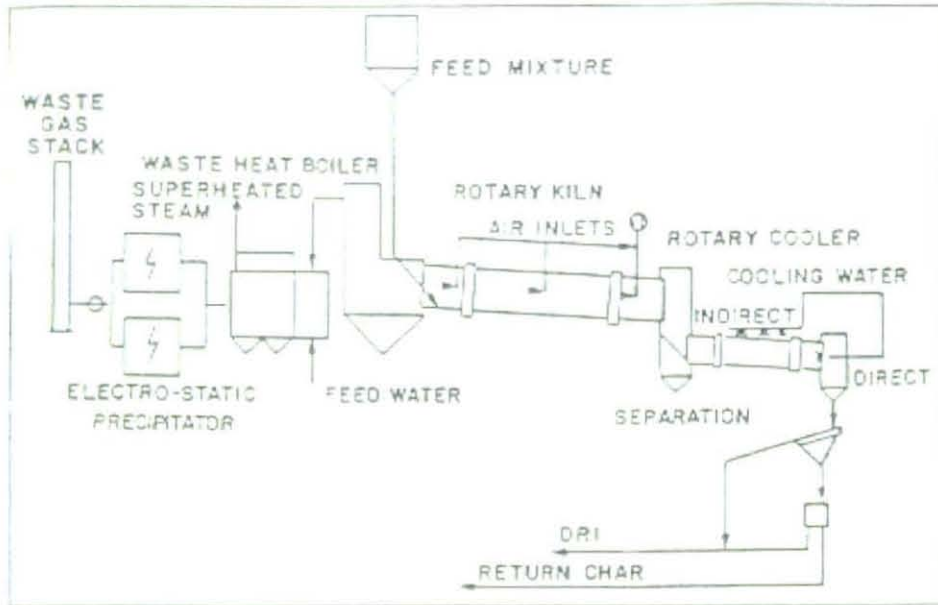


Figure 1: Schematic illustration of the SL/RN process⁽¹⁾

Rotary kilns (such as the SL/RN) typically have capacities ranging between 150000 and 200000 tpa. These processes charges lump ore, pellets and fines (1.42 t/t HBI), fine coal (0.85 t/t HBI) and limestone and dolomite (mainly for sulphur removal) into an inclined kiln that rotates at speeds less than 1rpm. The ore is dried, pre-heated and reduced as it moves along the length of the kiln. Between 92 and 93 % metallization of the iron ore is achieved within 14 hours, due to solid state reduction in the composite bed. The heat for reactions is provided by combustion of coal and part of the CO and H₂ that evolves from the reduction reactions, as well as from air-fuel burners. The process is operated at atmospheric pressure in the temperature range 1000°C to 1100°C. At the discharge end DRI is separated from char and ash to yield metal with a carbon content of 0.5% and sulphur content less than 0.02%. The major weaknesses of the process are the high capital cost, limited plant size, possible environmental impact, complex handling procedures at the exit end of the kiln and quality limitations of the DRI due to the presence of sulphur and gangue.

Rotary hearth coal-based processes include the Fastmet, Inmetco, Comet, Primus, IDI, Redsmelt and Itmk3 processes. The Fastmet process is schematically shown in **Figure 2**.

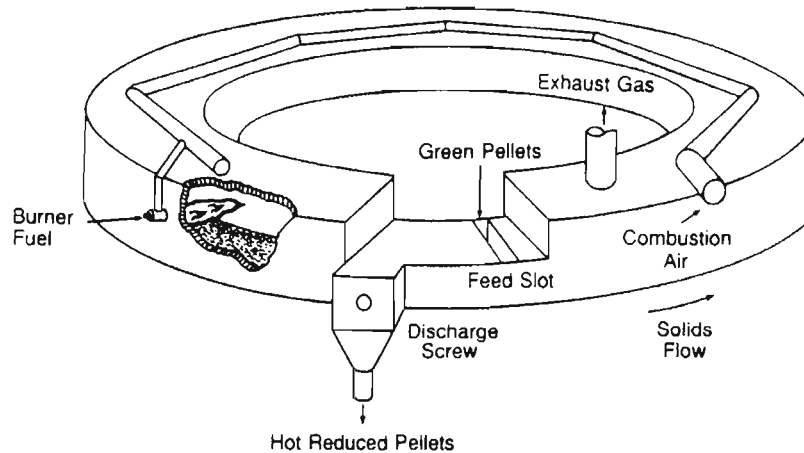


Figure 2: Schematic illustration of Midrex's Fastmet process⁽¹⁾.

In the Fastmet and Inmetco processes, pellets containing ore fines (1.34 t/t DRI) and coal fines (0.38 t/t DRI) are charged onto a rotary hearth where they are dried, pre-heated and reduced in the solid state. Carbon in the agglomerate is the reductant, with various air-fuel burners providing heat for the reactions. The process is operated at atmospheric pressure in the 1200°C to 1350°C range. 92% Metallization is achieved within 12 to 15 minutes to produce metal with a carbon content between 1.5 and 5%, and sulphur content between 0.12 and 0.2%. The design capacity regarding iron production is 450000 tpa. However, the two operational plants that were commissioned in 2001 at Kobe steel (for processing of waste oxides) have capacities of 50000 tpa.

The Comet process is similar to the Fastmet and Inmetco processes, but ore and coal fines are charged as discrete layers. Since the excess char and ash can be removed from the final product, the DRI produced has lower carbon (0.5 to 0.7%) and sulphur (0.02 to 0.06%) content.

The **fluidising bed coal-based Circofer process** (developed by Lurgi) is similar to the Circored process. The difference however is that instead of using natural gas, the process uses gas generated (at 1000°C in a gasifier) from coal. The main inputs

to the process consist of iron ore fines (1.42 t/t HBI), coal (0.8 t/t HBI) and oxygen (205 Nm³/t HBI). The iron ore fines (in the size range 0.03 to 1.00 mm) are pre-heated to between 800 and 900°C and pre-reduced during the first stage in a circulating fluidised bed, after which final reduction occurs in another fluidised bed. The process produces 92 % metallized HBI with carbon content about 2% and sulphur content less than 0.02%. The design capacity for this plant is 500000 tpa.

1.3 Direct Smelting processes

1.3.1 Two stage processes

Two stage direct smelting processes are processes such as the Corex, Finex, Hismelt, AISI, DIOS, CCF (which is similar to cleansmelt), IDI, Redsmelt, Fastmelt, Inmetco etc. These processes use an ore pre-reduction step followed by a smelting step.

Pre-reduction occurs either in shaft furnaces (Corex and AISI), fluidised beds (DIOS and Hismelt), rotary hearth furnaces (Redsmelt) or melting cyclones (CCF). In these processes, ore is charged to the pre-reduction furnace where off gas from the smelter unit is used for partial reduction of the ore. The partially reduced ore, coal, fluxes, oxygen and/or air are fed to the smelter unit, containing hot metal and slag. The furnace is operated at a pressure of 4 atm with the temperature of the pre-reduction shaft and smelter approximately 900°C and 1500°C respectively. Since the cleaned product gas from these processes has considerable value, the gas is either consumed as fuel for the plant, utilised in direct reduction plants, or used to produce electricity.

The Corex process (developed by Voest Alpine) is schematically shown in **Figure 3**. This is the only smelting reduction technology in commercial use, with four of the five plants currently operational.

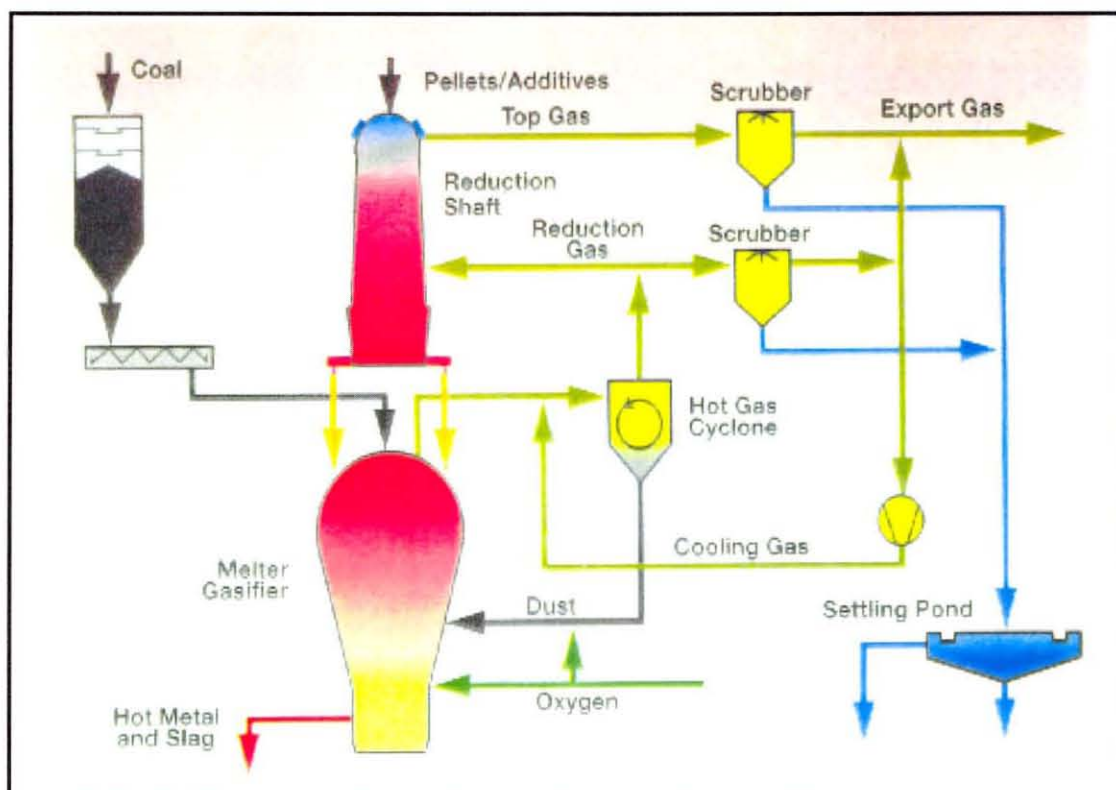


Figure 3: Schematic illustration of the Corex process⁽¹⁾.

Typical consumption rates for the Corex are as follows: lump ore and pellets: 1.48 t/t hot metal (HM), coal: 0.98 t/t HM (of which 10% is usually coke) and limestone: 0.242 t/t HM. The carbon content of the metal produced is typically 4 to 5% and the sulphur content between 0.05 and 0.1%. The slag typically has a CaO/SiO₂ ratio between 1 and 1.3, with a FeO content between 1 and 2. Typical production rates are between 600000tpa and 1.1 MTPY. The major weaknesses of the process are high capital cost, limited size compared to blast furnaces and the need to utilize off gas to be competitive.

1.3.2 One stage processes

One stage direct smelting processes are processes such as the Romelt (also Vanyukov), Technored, Ausmelt and Ifcon®. The Romelt process is schematically shown in **Figure 4**.

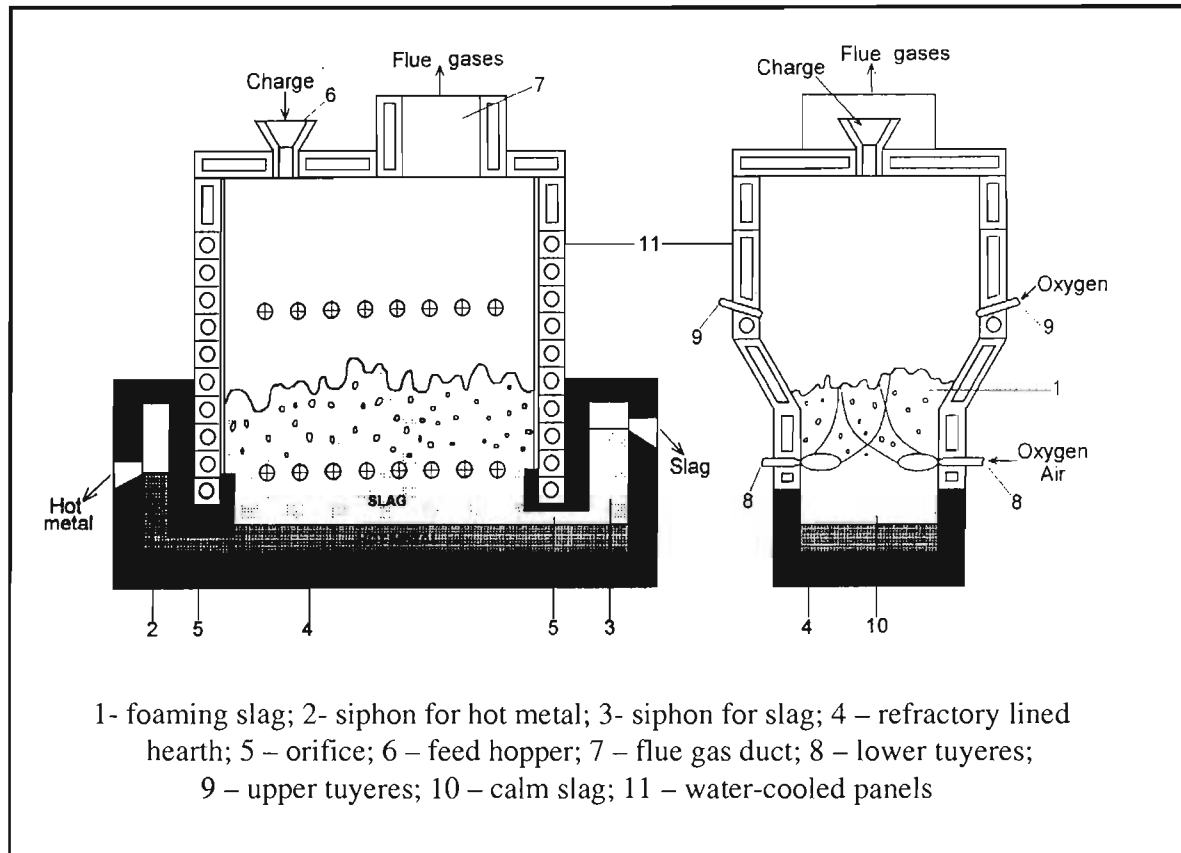


Figure 4: Schematic illustration of the Romelt process⁽¹⁾.

In **Romelt** and **Ausmelt** processes, lump or fine ore, coal and fluxes are charged directly into the smelter containing hot metal and slag. The Romelt process uses tuyeres located in the vessel sidewalls for air/oxygen injection, while the Ausmelt (which was developed for non ferrous metals) uses a top lance system. Fine coal is also injected through the lance in the Ausmelt process.

The Romelt process consumes 1.5 to 2.0 tons of iron ore fines, 0.8 to 1.1 tons of coal, 0.1 tons of limestone, 850 to 1100 Nm³ of oxygen and 450 to 700 Nm³ of air to produce a ton of hot metal. The hot metal contains 4 to 5 % carbon and 0.025 to 0.05 % sulphur, while the slag produced has a CaO/SiO₂ ratio between 1 and 1.3, with a FeO content between 1.5% and 3%.

The **Technored** process (which is shown schematically in **Figure 5**) uses unfired green pellets (1.5 to 1.6 t/t HM) and coal (0.74 t/t HM) to produce hot metal with carbon contents between 3.5% and 4.5%, and sulphur contents between 0.05% and

0.1%. The slag produced has a CaO/SiO₂ ratio between 1 and 1.3, and a FeO content of approximately 0.5%.

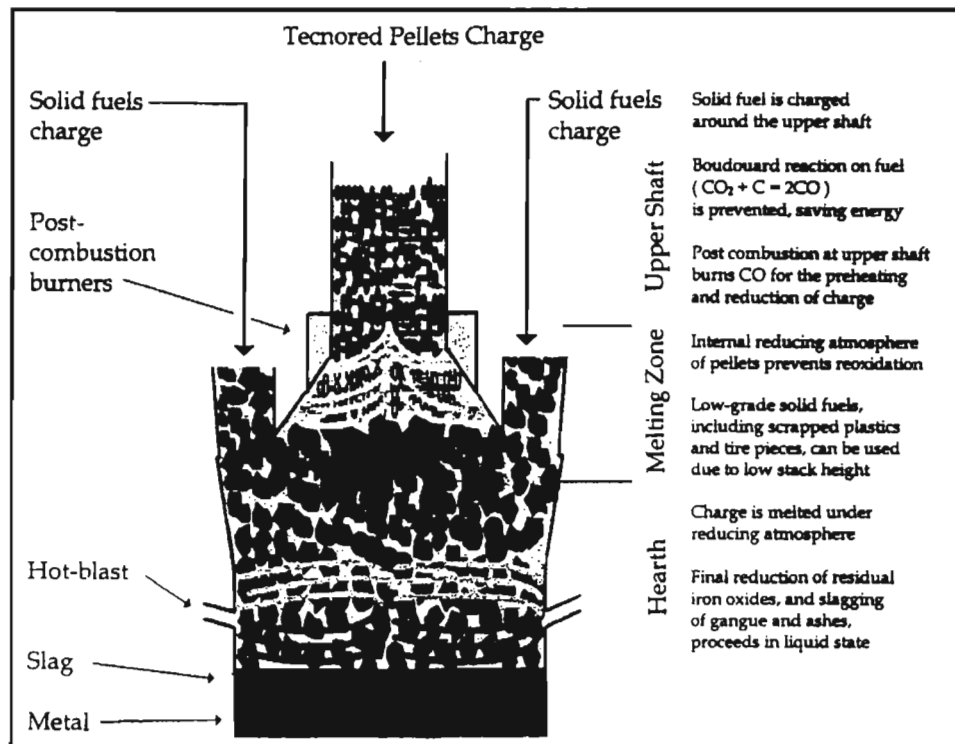


Figure 5: Schematic illustration of the Technored process⁽¹⁾.

While other direct smelting processes produce either hot metal or high carbon steel, the **Ifcon**[®] process⁽⁹⁾ produces liquid crude steel with carbon content $\pm 0.05\%$, and phosphorus content $\pm 0.007\%$. Other advantages of the process is that it uses ore fines, non-coking coal, and unburnt fluxes (dolomite and limestone) as feed materials. Energy for the process is supplied as a combination of fossil fuel and electrical energy, thereby reducing the electrical energy consumption significantly. The disadvantages of the process are the relatively slow production rate, and high sulphur content $\pm 0.1\%$ combined with high oxygen content of the bath. Although the original plant was a horizontal cylindrical vessel, the current reactor is a vertical cylindrical vessel, as shown schematically in **Figure 6**.

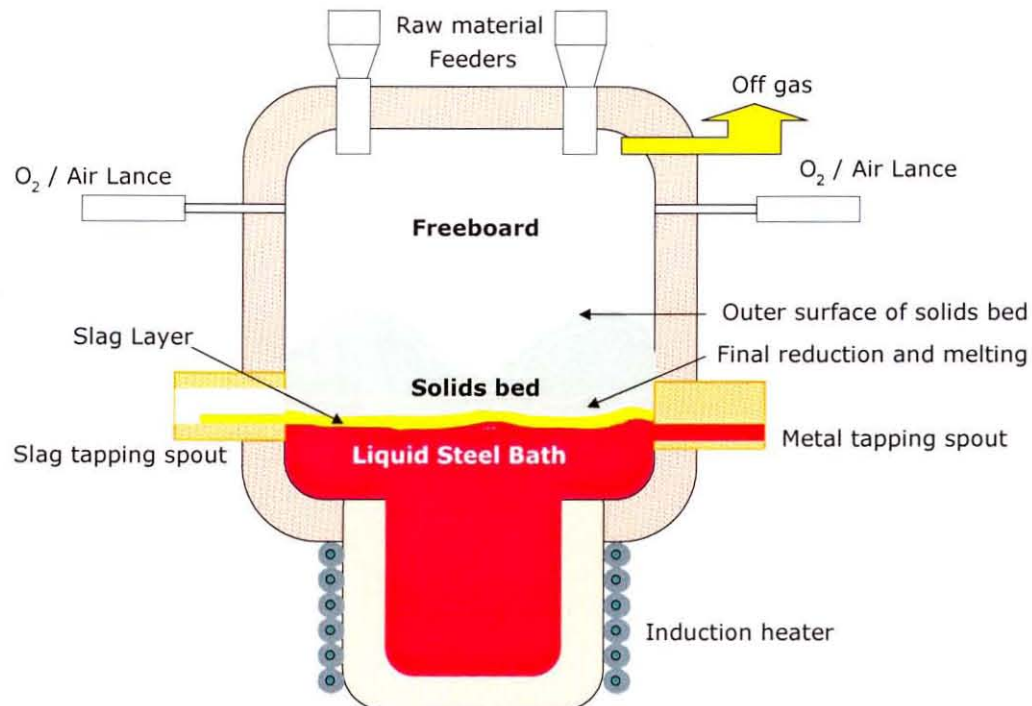


Figure 6: Schematic representation of the current configuration of the Ifcon[®] furnace.

1.4 Process description of the Ifcon[®] process

The feed material is a composite mixture of iron ore fines, coal, dolomite and limestone. The material mixture is fed from the top of the furnace, through the freeboard, onto a solids bed. The solids bed, which floats on top of the metal bath, covers most of the planar surface of the bath.

The bath is heated from below with induction heaters. Molten metal and slag are tapped intermittently through tapping spouts, by tilting the vessel.

Combustible gasses (such as CO and H₂)⁽¹⁰⁾ are released into the freeboard, from the solids bed. Additional heat for the process is provided by post-combustion of these gasses with oxygen enriched air.

The amounts of ore and coal fed into the furnace, is controlled in such a way that there is always a slight excess of iron oxide in the slag. This means that the burden

at the bottom of bed is almost depleted of carbon. This results in the production of low carbon crude steel.

The Ifcon[®] process can be divided into three characteristic horizontal zones: the freeboard, the solids bed and the liquid bath, which are schematically shown in **Figure 7**. The main material and energy flows are also indicated in the figure.

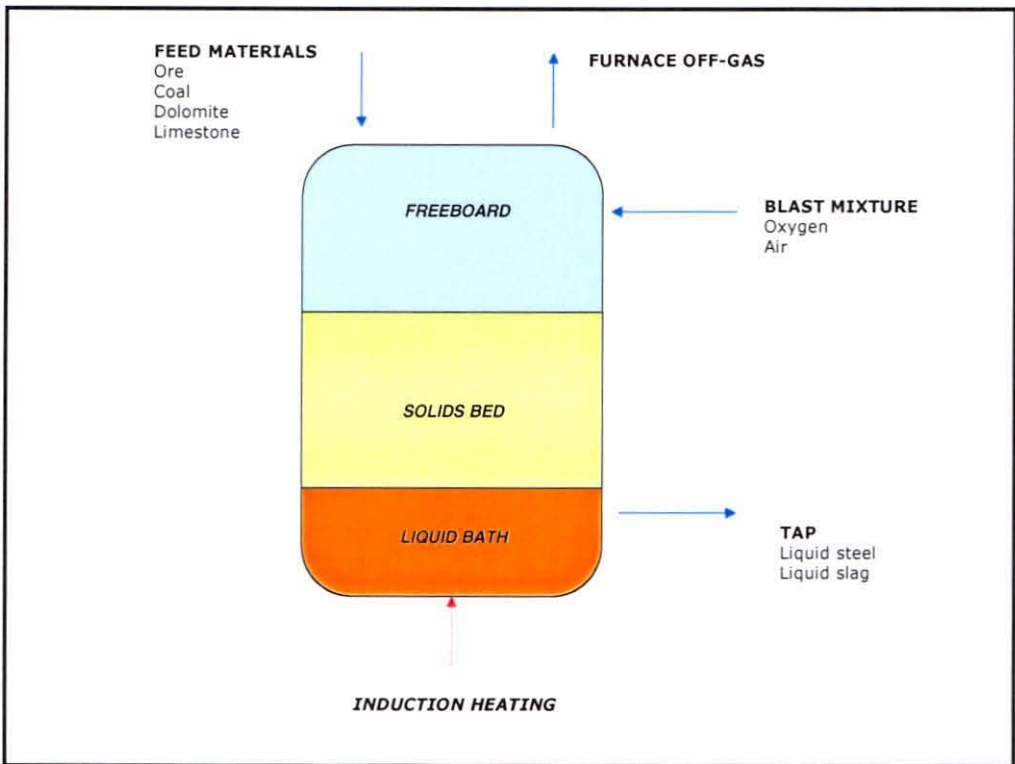


Figure 7: Schematic representation of the Ifcon[®] process, indicating the most significant mass and energy input and output streams.

1.4.1 The Freeboard

The main purpose of the freeboard is to generate heat by post-combustion of process gasses and other combustibles. This is achieved with oxygen-enriched air.

The heat generated is transferred to the upper part of the solids bed, where it is used to drive the overall endothermic reduction reactions.

The rate at which heat is generated for a specific air oxygen mixture is mainly determined by the rate at which combustible gasses evolve from the solids bed and the degree of post-combustion achieved in the freeboard^(11,12,13).

1.4.2 The solids bed

The heat generated in the freeboard of the furnace is transferred to the upper part of the solids bed, mainly by radiation. This heat is used for heating material at the top of the bed. As this material reaches temperatures in excess of 700°C, the carbon gasification (or Boudouard) reaction sets in, and reduction of the iron oxides commences⁽¹⁴⁾. During heat-up, several other endothermic reactions occur, such as drying, devolatilization, and calcination of dolomite and limestone.

The temperature in the upper part of the solids bed is determined by the rate at which heat is transferred to (and into) the bed, as well as the rate at which heat is used to drive the endothermic reactions in the bed⁽¹²⁾.

Since bulk melting does not occur in the top part of the bed^(15,16), reduction in this area occurs mainly as solid-state reduction. (Solid-state reduction implies solid metal oxide being reduced with solid carbon, but with CO as intermediate gas.) The area is therefore referred to as the "solid-state reduction I" zone. The amount of liquid in the top part of the bed should be low enough, not to influence the solid-state reduction kinetics significantly^(15,16).

The atmosphere inside the solids bed is reducing, as opposed to the freeboard gas, which is oxidizing⁽¹⁶⁾.

Under steady state conditions, the bottom layer of the solids bed is continuously melted. Since material is fed to the top of the solids bed with the simultaneous melting of the bottom layer, the thickness of the solids bed remains constant. This implies that the process is operated with material continuously descending through the bed. As the original top layer of material descends through the solids bed, the material cools as a result of the endothermic reactions. This eventually results in the ceasing of reactions, hence creating a "dead" zone in the bed. In this area, the temperature gradient through the bed is negligible and reaction rates are very slow⁽¹⁶⁾.

Below the dead zone, the temperature of the solids bed gradually increases, due to heat transfer from the bath below the bed. In this area, the endothermic calcination, Boudouard, and reduction reactions recommence. At temperatures below the temperature where bulk melting of the feed mixture occurs, reduction occurs as

solid-state reduction. This area is therefore referred to as the “solid-state reduction II” zone.

This study will investigate reduction occurring in the solids bed.

1.4.3 The molten bath

As the material at the bottom of the solids bed is heated to a temperature exceeding the liquidus of the slag, bulk melting of the material (as well as dissolution of solids into the slag) occurs. It is therefore expected that reduction, in this area, will occur as liquid-solid-state reduction. (Liquid-solid-state reduction implies reduction of molten metal oxide (which is dissolved in a slag) with carbon, which is either solid or dissolved in the metal, with CO as intermediate gas.) The mixing reaction regarding slag formation, as well as the reactions between metal and slag, is also expected to occur in this zone⁽¹⁶⁾. This is where final reduction and melting of bed material occurs and is referred to as the “final reduction and melting” zone.

Electrical energy input to the bottom of the furnace is required to supply energy for the reduction reactions occurring in the “solid-state reduction II” and “final reduction and melting” zones. Electrical energy is also required for melting of the slag and metal produced. The metal bath acts as a transport medium for this energy⁽¹³⁾. The bath also serves as a reservoir for the produced metal and slag.

The slag chemistry of the process is controlled by changing the feed mixture. Slag-metal equilibrium is however not achieved⁽¹⁷⁾.

By considering the discussion above, the process can be re-divided into six zones, as shown in **Figure 8**.

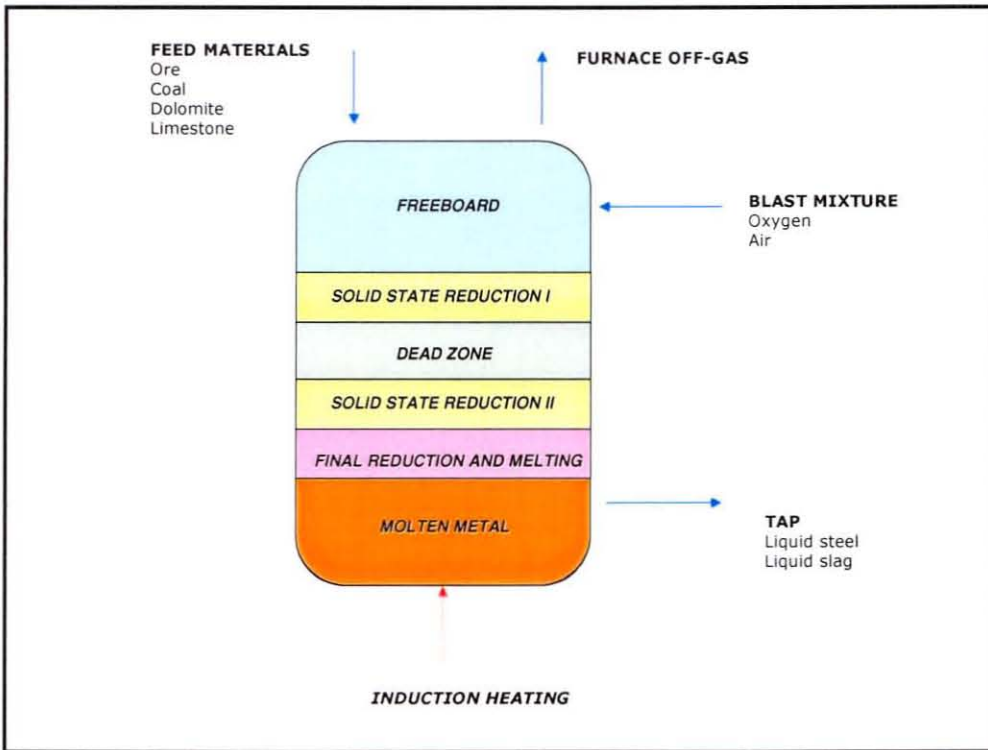


Figure 8: Schematic representation of the IFCON process, indicating the most significant mass and energy input and output streams

1.5 Hypothesis statement

During the first Ifcon test work⁽¹⁸⁾ 80% reduction was achieved in the upper part of the solids bed, at a feed rate of $135 \text{ Fe/m}^2/\text{h}$ (which corresponds with a production rate of $56 \text{ kg Fe/m}^2/\text{h}$). During pilot plant trails, crude steel was produced at a rate of $100 \text{ kg Fe per m}^2$ (scaled to the planar surface area of the bath). Additional investigations^(10,12,19) showed that approximately 30% reduction was achieved (as solid state reduction) in the "solid state reduction I" zone of the solids bed. At the time it was assumed that the rate of reduction was controlled by a combination of the rate of heat transfer from the freeboard to the solids bed and the rate of the gasification reaction. It was also assumed that volatiles did not contribute to the reduction reaction in the solids bed⁽¹⁵⁾.

Regarding the bottom of the solids bed, it was assumed that final reduction (up to 80% reduction) was achieved as solid-state reduction. The reduced burden was then melted, to form slag and liquid metal.

1.5.1 Objective of this study

This study aimed to test the assumptions stated above, by investigating the following:

- Is the rate of reduction in the solids bed influenced by the rate of heat transfer to the solids bed ?
- Is the rate of reduction in the solids bed influenced by the reactivity of the coal ?
- Is the rate of reduction in the solids bed influenced by the reducibility of the ore ?
- Does volatiles contribute to the rate of reduction in the solids bed ?
- Is final reduction (up to 80%) achieved as solid-state reduction at the bottom of the solids bed, when producing at a rate of 100 kg Fe per m² of planar bath surface area, per hour ?
- If final reduction is not achieved as solid-state reduction, at a rate of 100 kg Fe/m²/h, what is the extent of reduction achieved as solid-state reduction ?

Ifcon[®] is a very complex and integrated process, which cannot be duplicated in a single laboratory experiment. The investigation was therefore done in two phases.

1.5.1.1 Phase 1: Rate determining step investigation

The main aim of the first phase of this investigation was to determine the optimum feed materials (and criteria for the selection of optimum feed material) for the "Solid-state Reduction I" zone. From literature, it was not clear what the rate-determining steps are during reduction in a solids bed (comprising of ore coal and fluxes). The influence of changes to specific material characteristics and process parameters on the extent of reduction achieved in a mixed solids bed was therefore determined experimentally.

Process parameters that were varied included:

- Ore type (to achieve changes to the reduction rate constant).
- Coal type (to achieve changes to the Boudouard rate constant).
- The temperature to which the material mixture was exposed.

A modelling approach combined with experimental results was used to do the investigation.

Note that the accent of this study was to confirm whether specific process parameters influenced the rate of solid-state reduction of a composite material mixture, and therefore results were more of a qualitative, than quantitative nature.

1.5.1.2 Phase 2: production rate investigation

The second phase of the investigation focussed on solid-state reduction at the bottom of the solids bed. The main objective of this phase of the study was to investigate the extent to which final reduction occurred as solid-state reduction at the bottom of the solids bed. Secondary objectives were to back calculate the heat transfer coefficient in the solids bed and to determine the rate at which final reduction can be achieved as solid-state reduction (in the solids bed of the Ifcon® process). For this, a modelling approach combined with experimental results was also used.