Fluidized-bed technology for the production of iron products for steelmaking

by F.J. Plaul*, C. Böhm*, and J.L. Schenk†

Synopsis

The dominating technologies for steelmaking are the basic oxygen furnace (BOF or LD process, Linz-Donawitz) and the electric-arc furnace (EAF). The main iron input materials for both are liquid iron as hot metal, or solid iron as pig iron, DRI (direct reduced iron), HBI (hot briquetted iron) and scrap. Hot metal, pig iron (i.e., solidified hot metal) and DRI/HBI are virgin iron materials, which have to be produced from iron ore by so-called ironmaking technologies. The family of ironmaking technologies includes three process routes: blast furnace, smelting reduction and direct reduction.

Driven by steadily increasing costs of raw materials in the last two decades, the sector has seen a number of new developments in ironmaking technologies, developments based on fluidized-bed technology. The main advantage of a fluidized-bed technology is that fine iron ore can be directly charged to the process without prior treatment; it does away with agglomeration and its concomitant cost, a step practised in blast-furnace, COREX® and MIDREX® processes. With Posco of South Korea, Siemens VAI Metals Technologies has successfully developed the FINEX® process, a smelting reduction based on the direct use of iron ore fines to produce hot metal. The key technology is the four-stage, bubbling fluidized-bed-reactor system, in which fine iron ore is reduced to DRI fines in a countercurrent flow with a reducing gas generated by coal gasification.

Beside surveying the current state of the art, this paper discusses the technological principles of smelting-reduction and direct-reduction processes. The status of FINEX® and the outlook for further developments are described. Crucial to the successful development of the new ironmaking technologies for the direct use of fine ore was the scaling up of the fluidized-bed reactor system, which demonstrated new design features.

Process for ironmaking and process routes for steel production

The dominating technologies for steelmaking are the basic oxygen furnace (BOF) and the electric-arc furnace (EAF). Two-thirds of total annual steel production of approximately 1.4 bt of steel are processed via the BOF route. The EAF technology, which is the basis for long products, is applied where scrap is readily available and electric power is cheap. The main iron-input materials for both are liquid iron as hot metal (HM), or solid iron as pig iron, DRI (direct reduced iron), HBI (hot briquetted iron) and scrap.

Hot metal, pig iron (i.e., solidified hot metal) and DRI/HBI are virgin iron materials, which have to be produced from iron ore by so-called ironmaking technologies. The family of ironmaking technologies includes three process routes: blast furnace, smelting reduction (SR) and direct reduction (DR—see Figure 1).

Billions of dollars have been spent to find alternatives to replace the traditional blast-furnace route, which accounts for two-thirds of the raw materials for steel production (i.e., hot metal). However, only a few processes have ever reached industrial scale (Figure 2). The major drivers for such developments are

- The environment:
  - The reduction of emissions (e.g., SO_x, NO_x, dust and CO_2
- Flexibility in raw materials:
  - The use of fine ore
  - Independence from coke
  - The use of lower grade coal
  - Replacement of natural gas
  - The use of alternative raw materials (such as waste)
- Operational flexibility
- Capacity flexibility
- The search for low-cost alternatives to existing old plants.

Driven by the high cost of raw materials (i.e., lump ore) or the high cost of agglomeration (to form pellets or sinter) and the availability of fine ores (which account for about two-thirds of world iron-ore production), several developments based on fluidized-bed technology were started in the last two decades. The main advantage of this technology is that fine iron ore can be charged

* Siemens VAI Metals Technology GmbH & Co, Linz, Austria.

† Department of Metallurgy, Montanuniversität Leoben, Austria.

 This paper was first published in the Industrial Fluidization South Africa, Conference (IFSA 2008), proceedings book, 19–20 Nov. 2008.

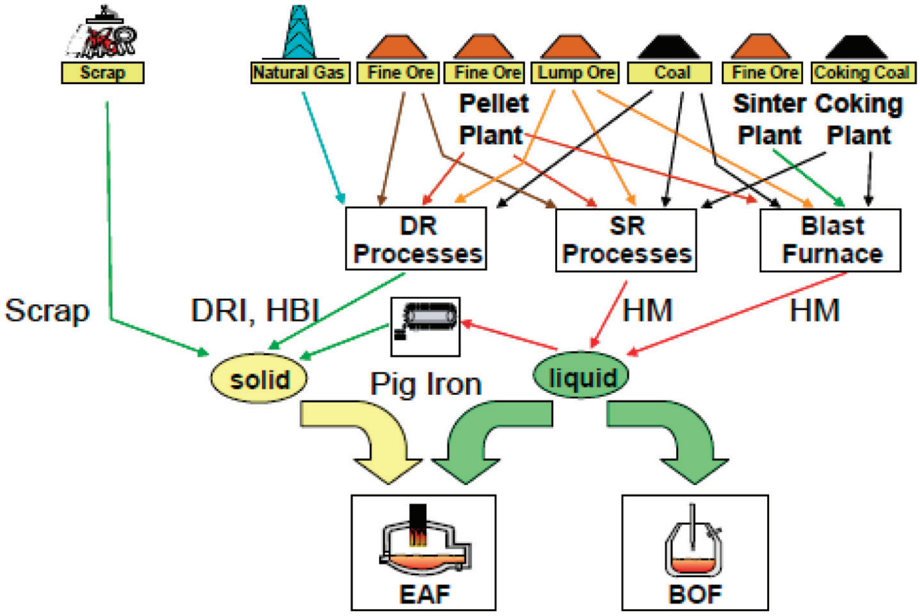

Figure 1—Basic flowchart for steel production

	Basic iron		Virgin iron units		
Product	Hot metal / Pig iron		DRI / HBI		Iron carbide
Reductant / Iron carriers	Coke	Coal	Natural gas	Coal	Natural gas
Lump Pellet Sinter	BF[3] Tecnored[4]	COREX®[3] Redsmelt[3] Oxicup[3] Fastmelt[2] Sidcomet[2]	Midrex®[3] HYL[3] Arex[2] Ghaem[2]	COREX®-DR[3] Fastmet[3] SLRN/DRC[3] ITmk3[3] Inmetco[2] Grate Car[2]	
Fines		FINEX® HIsmelt® HIsarna[1] CCF[2] DIOS[2] \Romelt[2] Ausmelt[2]	Finmet®[3] Fior[3] Circored[2] Spirex[2]	4Primus[4] Circofer[2] Comet[2]	Iron Carbide[2]

Figure 2—Processes for ironmaking, (1) under implementation, (2) stopped, (3) operated industrially, (4) tested at (semi-) industrial scale

directly without prior treatment to the process, treatment such as agglomeration, which is practised for blast furnace, COREX® and the MIDREX® processes. Figures 3 and 4 illustrate a classification of smelting and direct-reduction processes; processes using a fluidized-bed system are highlighted.

Siemens VAI Metals Technologies (SVAI) successfully developed two processes based on fluidized-bed systems: the FINEX® and FINMET® processes. The former process, which was jointly developed with POSCO, South Korea, is a smelting-reduction process for hot metal production based on the direct use of iron-ore fines and non-coking coals. The FINMET® process is a direct-reduction process based on the direct use of iron-ore fines and natural gas as reductant. The key technology for both processes is a four-stage, bubbling, fluidized-bed reactor system where fine iron ore is reduced to DRI fines in a countercurrent flow with a reducing gas that is generated by coal gasification or by natural-gas reforming. Although both processes look similar there are several distinct differences in their operation (e.g., pressure) and the targets for the DRI produced (e.g., metallization).

Process descriptions of FINEX® and FINMET®

In the 1990s Siemens VAI was at the forefront in developing new ironmaking technologies that directly process fine iron ore without prior treatment. The first technology to reach maturity on an industrial scale was FINMET®. It is a direct-reduction process that produces hot briquetted iron (HBI). FINMET® was developed jointly with Orinoco Iron of

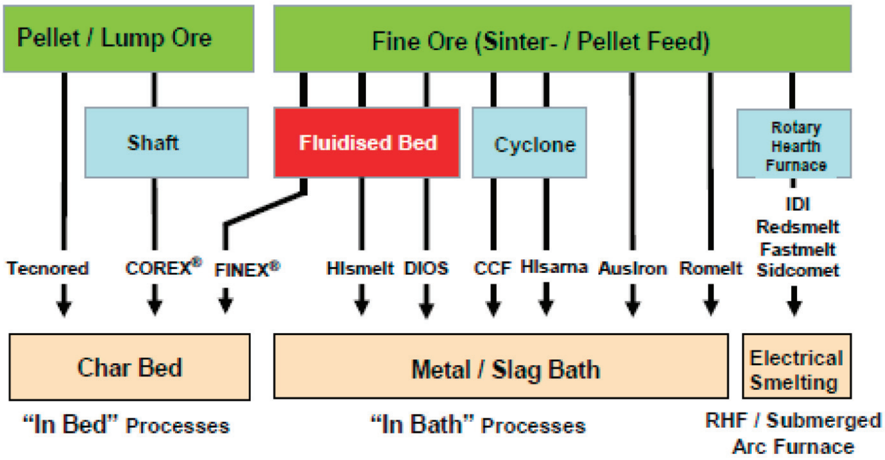

Figure 3—A classification of smelting-reduction processes

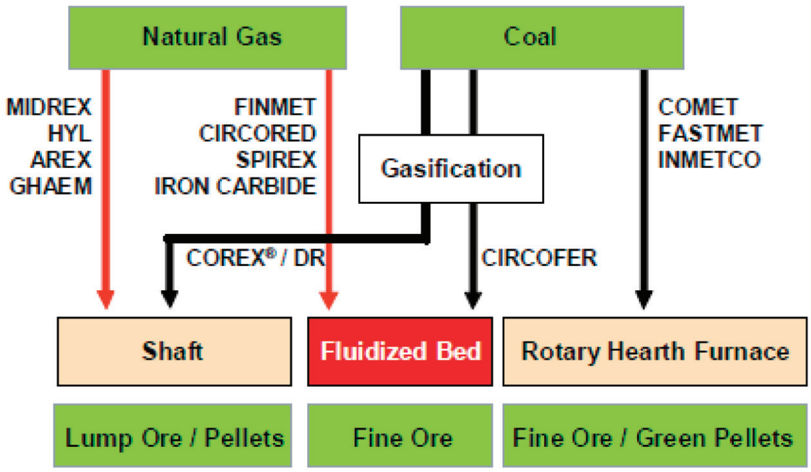

Figure 4—A classification of direct-reduction processes

Venezuela. Two plants, each with an annual capacity of 2 mt HBI, commenced operation, one in Australia, the other in Venezuela. The second technology that was successfully developed is the FINEX® process for the production of hot metal. The process was developed in cooperation with the South Korean steel producer POSCO. The first commercial plant with an annual capacity of 1.5 mt of hot metal started the operation in April 2007.

FINMET® process flow sheet

FINMET® is a direct-reduction process for producing HBI, which is used mainly as a scrap substitute for steelmaking in the electric-arc furnace or basic oxygen furnace. The process is based on natural gas as the energy source and steam-reforming technology is applied for the production of the reducing gas (Figure 5).

Four fluidized-bed reactors are interconnected with transfer lines for gas and solids. Ore fines are first dried in a fluidized-bed dryer and charged through a lock-hopper system to the top reactor, R40. The solid fines flow downward by gravity from the upper to the lowermost reactor, while H_2-rich reducing gas flows upwards in a counter-current fashion. The dried fine ore is heated in the first reactor (R40) by the partially spent reducing gas from the previous reactor. The solid fines are progressively reduced to highly metallized sponge-iron fines in the consecutive reactor stages. Each reactor is equipped with internal cyclones to separate and recycle, via a cyclone dipleg, the dust entrained in gas from the fluidized bed. In the final, lowermost reactor (R10) temperatures as high as 800 °C and pressures up to 14 barg prevail.

The sponge-iron fines are pneumatically conveyed by means of a riser to the hot compacting plant where the fines, metallized in excess of 90%, are hot-compacted to HBI in a double-roll briquetting press.

A mixture of recycled top gas and fresh gas generated in a steam reformer provides the gas required for reduction. The top gas exiting the uppermost reactor is first quenched and scrubbed in a wet scrubber. A small portion of the dedusted gas is removed to control the inert gas build-up in the system. This gas is mainly used as a fuel in the reducing gas furnace. The remaining recycle gas is returned via a recycle gas compressor to the process. The reformed gas stream and the recycle gas stream (or a portion thereof) is sent through a

CO_2 removal system. The gas is then preheated in the reducing gas furnace to ~850 °C before being sent to the reactors.

FINEX® process flow sheet

FINEX® produces hot metal with comparable quality to the conventional blast-furnace route (i.e., a coking plant, a sinter plant and a blast furnace). FINEX® can use non-coking coal and a fine ore that might otherwise serve as sinter feed. Therefore coke making and sintering of fine iron ore can be avoided, an option not open to the conventional blast-furnace route. (Figure 6.)

In FINEX® dried, fine iron ore is charged into a series of fluidized-bed reactors together with fluxes such as limestone or dolomite. The iron-ore fines pass in a downward direction through four reactors where they are heated and reduced to directly reduced iron (DRI) by means of a reducing gas—derived from the gasification of coal—that flows in a direction running countercurrent to the ore.

After exiting the final reactor, the DRI fines are hot-compacted to HCI (hot-compacted iron), transferred to a charging bin positioned above the melter-gasifier, and then charged by gravity into the melter-gasifier where smelting takes place. The tapped product, a hot liquid metal, is equivalent in quality to the hot metal produced in a blast furnace or Corex plant.

Briquetted coal fines and/or lump coal are charged into the dome of the melter-gasifier, while pulverized coal is injected into the vessel together with oxygen. As coal is gasified a reducing gas is generated, one comprising mainly CO and H_2. After exiting the top of the melter-gasifier, this gas is ducted to the fluidized-bed reactor system to reduce the iron ore fines. A portion of the consumed reducing gas that exits from the top of the fluidized-bed reactor train is

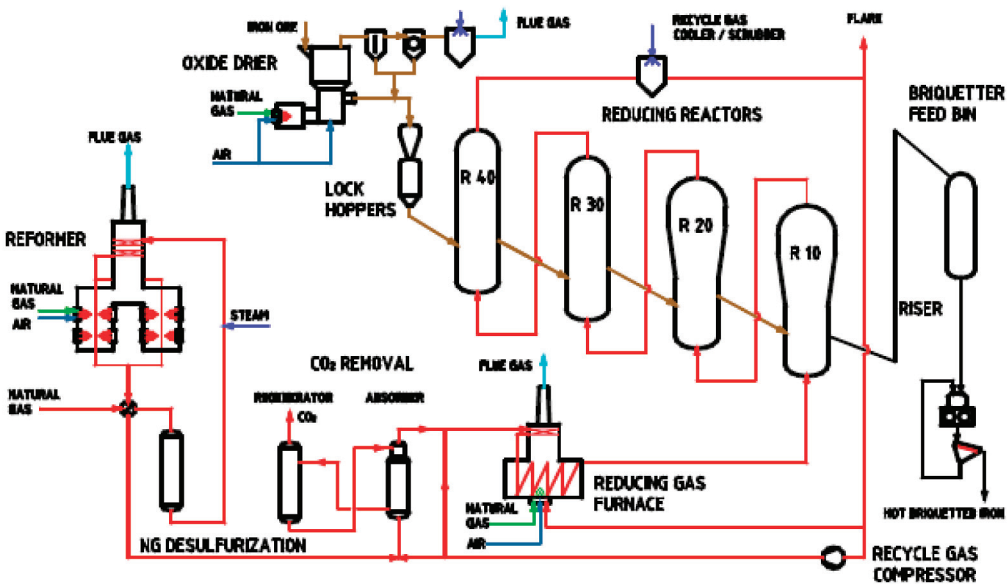

Figure 5—FINMET® process flow sheet

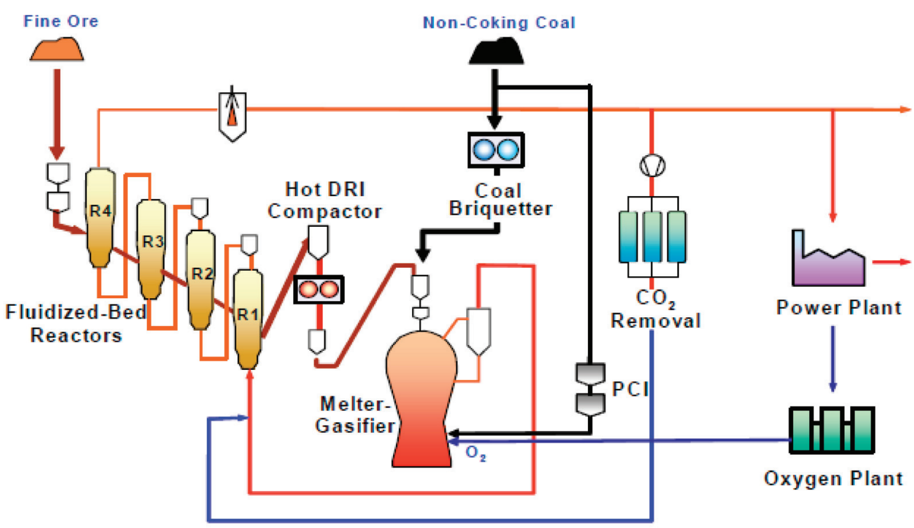

Figure 6—FINEX® process flow sheet

recycled back to the system after CO_2 removal in order to achieve a higher gas-utilization rate. The heat generated from the gasification of the coal with oxygen also serves as the energy source for the melting of the HCI to hot metal as well as for the formation of liquid slag. Both hot metal and slag are tapped exactly as in the standard blast-furnace procedure.

The export gas from the FINEX® process is a valuable by-product that can be used for a variety of industrial applications, such as heating within a steel plant, power generation, or additional production of DRI/HBI (hot-briquetted iron).

Process technology

A history of fluidized-bed-reactor developments at SVAI

The developments of FINMET® and FINEX® in the 1990s had as their main focus an optimum design for the fluidized-bed reactors. The test programme comprised the following steps:

- Laboratory-scale tests for the evaluation of the reduction behaviour of the fine ore
- Bench-scale tests for the evaluation of the fluid dynamics of alternative fluidized-bed designs

The following information on the results of laboratory- and bench-scale tests refers to the development of FINEX®. Information on FINMET® is published elsewhere[1].

Reduction tests at laboratory scale

In these tests we examined the effect of temperature, residence time and specific gas composition on degree of reduction for different ore types and particle size. As an example of test results, Figure 7 shows the reduction degree as a function of the specific gas consumption. These tests

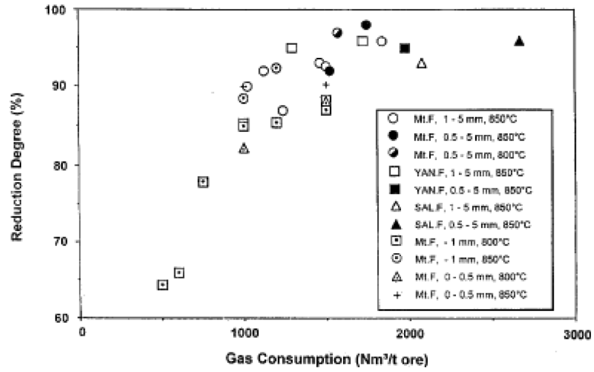

Figure 7—An example of results of laboratory-scale reduction tests

were carried out with particle-size fractions up to 5 mm. For different types of ore (fines from Mount Newman, Yandi and Saldoca) 90% reduction can be reached with a specific gas consumption of 1000 to 1200 Nm³/t ore and reasonable reduction-gas temperatures.

Fluid-dynamic tests

Several types of fluidized-bed systems were evaluated for FINEX® in cold bench-scale tests. A challenge was the selection of the optimum reactor sytem for one reduction stage, which can process sinter feed ore with the typical broad particle-size distribution. Figure 8 outlines the principal types of system that were investigated. Three twin-type systems (A to C) and one single-vessel system (D) were evaluated. The background to the twin-type systems was the separation of material into coarse and fine fractions that could be reduced under specific optimal conditions in separate reactors.

All twin-type reactors have a common design feature,

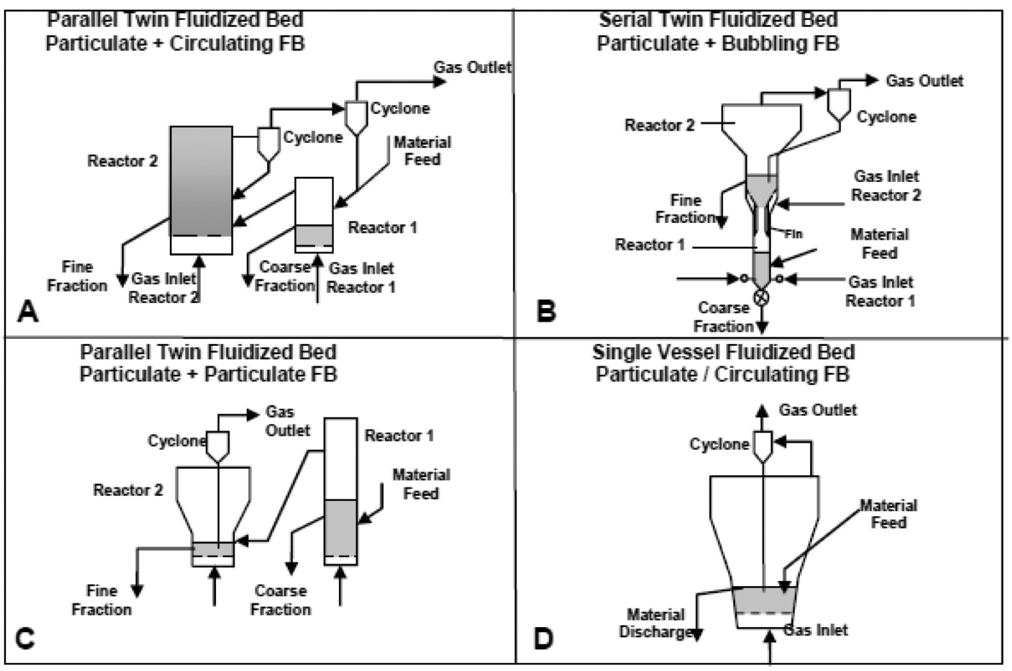

Figure 8—Comparison of fluidized-bed systems

namely, that feed is introduced into the reactor for coarse material and the fine fraction is separated by entrainment in reducing gas from this reactor. In the single-vessel system the entire fraction is fed and treated in one reactor vessel. Owing to entrainment of large amounts of fine particles from the fluidized bed, a high-efficiency cyclone is required to recycling these fines to the bed.

Exercising the criteria for selecting the most suitable type of fluidized bed—criteria such as specific gas consumption; solids elutriation, entrainment and separation; bed geometry; the flexibility and simplicity of the systems—led to the choice of single-vessel fluidized bed. The subsequent development of FINEX® confirmed the advantage of this choice.

Reduction metallurgy

The prevailing chemical reactions for the process design of FB systems in SR and DR plants are those of three iron oxides—Fe_2O_3 (hematite), $Fe_{1-x}O$ (wüstite) and Fe_3O_4 (magnetite)—with CO and H_2. The reactions are all heterogeneous:

Hematite (Fe_2O_3) reduction to Fe_3O_4 (magnetite)

$3\,Fe_2O_3 + CO = 2\,Fe_3O_4 + CO_2 \quad +\Delta H$ [1]

$3\,Fe_2O_3 + H_2 = 2\,Fe_3O_4 + H_2O \quad -\Delta H$ [2]

Fe_3O_4 (magnetite) reduction to $Fe_{1-x}O$ (wüstite)

$Fe_3O_4 + CO = 3\,FeO + CO_2 \quad +\Delta H$ [3]

$Fe_3O_4 + H_2 = 3\,FeO + H_2O \quad +\Delta H$ [4]

$Fe_{1-x}O$ (wüstite) reduction to metallic iron

$FeO + CO = Fe + CO_2 \quad -\Delta H$ [5]

$FeO + H_2 = Fe + H_2O \quad +\Delta H$ [6]

Below 570 °C the wüstite phase is unstable and magnetite reduces directly to metallic iron:

$Fe_3O_4 + 4CO = 3\,Fe + 4\,CO_2 \quad +\Delta H$ [7]

$Fe_3O_4 + H_2 = 3\,Fe + 4\,H_2O \quad -\Delta H$ [8]

The equilibria in the hydrogen- and carbon monoxide-reduction reactions are shown as functions of temperature in the Baur-Glaessner diagram. (Figure 9.)

The activities of H_2 and CO are coupled by water-gas reduction, which can take place heterogeneously (Equations [9] and [10]) or homogeneously (Equation [11]):

$C + H_2O = H_2 + CO \quad +\Delta H$ [9]

$C + 2\,H_2O = 2\,H_2 + CO_2 \quad +\Delta H$ [10]

$CO + H_2O = H_2 + CO_2 \quad -\Delta H$ [11]

The Boudouard reaction has an equally important impact on the reduction on the reduction of the iron oxides reaction (Equation [12]):

$CO_2 + C = 2\,CO \quad +\Delta H$ [12]

As in the water-gas reactions, the Boudouard reaction is dependent on temperature. At low temperatures carbon monoxide tends to form carbon exothermically.

Because gas generation differs for the fluidized-bed operation in FINEX® (coal gasification) from that in FINMET® (steam reforming), the gas composition varies markedly (see Table I).

The fluidized-bed-reactor systems in FINMET® and FINEX® are four stage in order to overcome the metallurgical and thermodynamically limitations of a one-stage system. The investment cost of a four-stage system is higher than that of a single-stage system, but the advantages of a multi-stage system are patent, as the Rist[3]) and Baur-Glaessner diagrams demonstrate (see Figure 10). The equilibrium between iron and wüsite determines the gas composition, which is equal to the outlet composition because of ideal

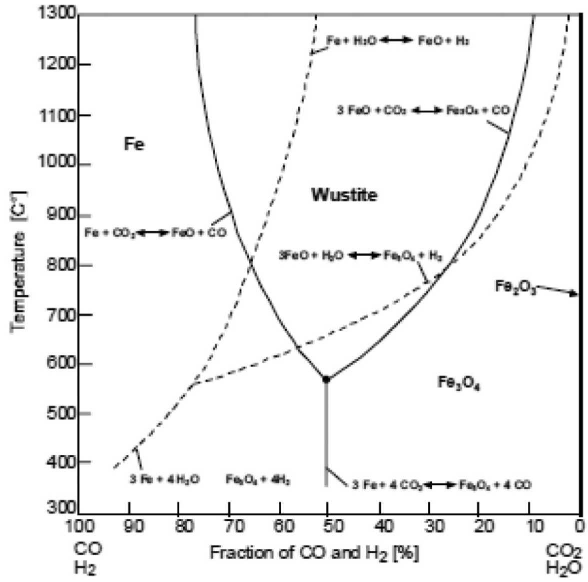

Figure 9—Combination of the Baur-Glaessner diagrams for H_2-H_2O and CO-CO_2 atmospheres[2]

back-mixing in a fluidized bed. The slope of the operating line in the Rist diagram represents the consumption of reducing gas. The minimum gas consumption can be achieved with the theoretical operating line, but in practice the constraints of reaction kinetics have to be considered. In the bed the gas composition is at equilibrium, and the bed temperature is too low because there is insufficient sensible heat in the gas for heating the ore and the properties of materials of construction limit the inlet temperature to below 900°C. Accordingly the amount of reducing gas has to be increased (i.e., a steeper slope for the practical operating line) and consequently the operation becomes inefficient owing to high reducing-gas consumption, low gas utilization and high off-gas temperatures.

In order to achieve low reducing-gas consumption and better overall efficiency the reduction by FB reactors has to be performed in a multi-stage reactor system. Figure 10(b) shows the theoretical operating line for a two-stage system. The reducing gas consumption is determined by the equilibrium-gas composition for reduction of wüstite to iron in the first stage. The off-gas of the first stage is used for the pre-reduction of hematite to wüstite and preheating of the material in the second stage. Even for an ideal two-stage system constraints by reduction kinetics prevail because the gas in the first stage is at chemical equilibrium and the

Table I

Typical reducing-gas composition before the fluidized-bed system (without inerts, CH_4 and higher hydrocarbons)

	H_2	H_2O	CO	CO_2
FINEX®	22.2	2.3	65.3	10.2
FINMET®	80.6	1.9	12.8	4.7

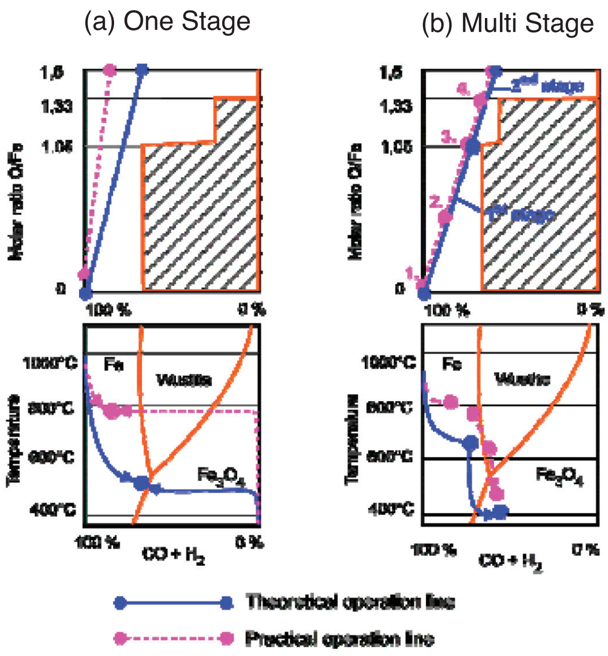

Figure 10—Phase-stability diagrams for one- and multi-stage FB-reactor systems

temperatures in both stages are still too low.

The operating line for a four-stage system, as in FINMET® and FINEX®, represents a practical approach to meeting the requirements that the consumption of reducing gas be at a minimum and that conditions suit the best reduction kinetics.

Fluid dynamics

A significant characteristic of the fine ores available as feed for FINEX® and FINMET® is the broad particle-size distribution. More the 95% of the total mass is in the size range of 50 μm to 8 mm, and the mean diameter, d50 (i.e., particle size at 50% on the cumulative mass-fraction curve), can vary from 200 μm to 1 mm.

Figure shows the Reh diagram, which illustrates fluid-dynamic states for various gas-solid reactor systems. The classification scheme is based on Reynolds number (Re_p), drag coefficient (C_D), Archimedes number (Ar), and a non-dimensional number, M. These numbers are defined in the following equations:

$$Re_p = \frac{u \cdot d_p}{v} \quad [13]$$

$$\frac{1}{C_D} = \frac{3}{4} \cdot \frac{u^2}{g \cdot d_p} \cdot \frac{\rho_G}{\rho_s - \rho_G} \quad [14]$$

$$Ar = \frac{g \cdot d_p^3}{v^2} \cdot \frac{\rho_s - \rho_G}{\rho_G} \quad [15]$$

$$M = \frac{u^3}{g \cdot v} \cdot \frac{\rho_G}{\rho_s - \rho_G} \quad [16]$$

u denotes superficial gas velocity; d_P, particle diameter; ρ_S, solid density; ρ_G, gas density; v, kinematic viscosity of the gas; and ϵ, voidage of the bed+.

The operating field, R, for the FB-reactor system is indicated in Figure 11. It is circumscribed by the following conditions:

- Particle diameters of the fine ores, d_P, in the range of 50 μm to 8 mm
- Particle densities of the ore and reduced ore, ρ_P, lie between 3 500 and 2 200 kg/m³
- Gas density, ρ_G, and viscosity, υ, for H_2, CO and mixtures of these two components at temperatures

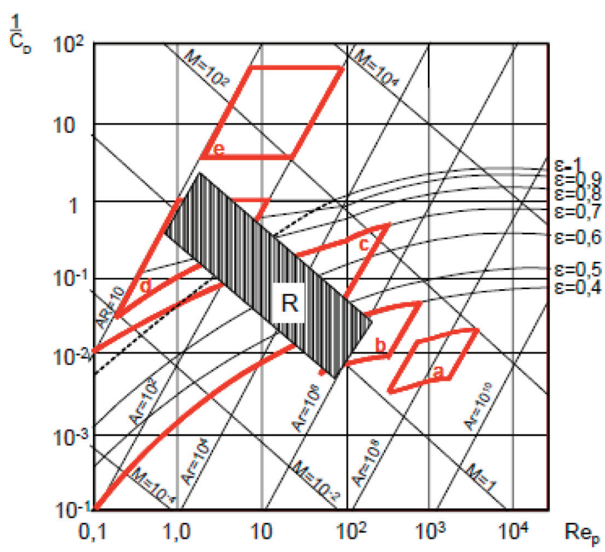

Figure 11—Reh diagram, (a) Shaft furnace, (b) Moving bed, (c) Particulate and bubbling FB, (d) Circulating FB, (e)Transport reactor, (R) Operation field for reduction processes

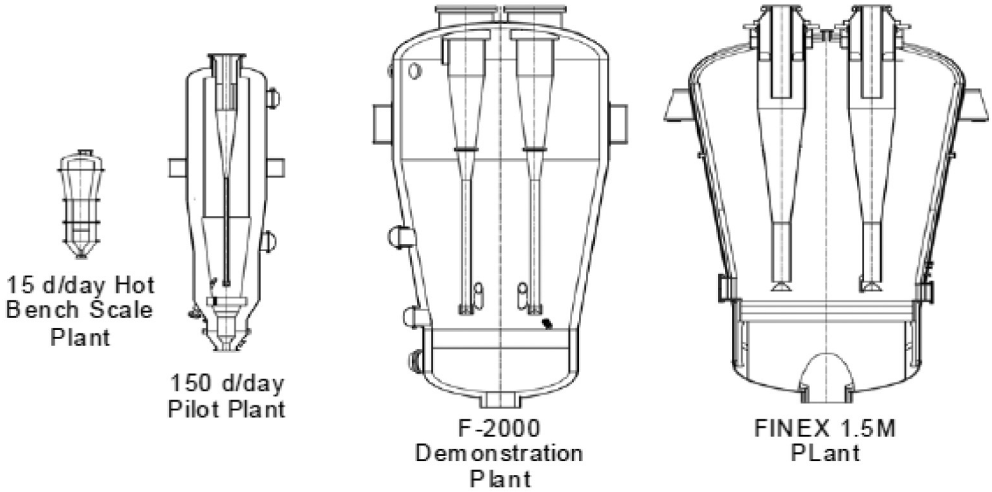

Figure 12—A comparison of fluidized-bed reactors at different phases in the development of FINEX®

from 400 to 800°C and pressures of 1 to 12 barg
- Superficial gas velocities, *u*, between 1 and 4 m/s

The operating field R ranges from the state of a moving bed for the coarse-particle fraction to a bubbling FB for the medium-sized particles, and ends as a circulating fluidized bed for the fine particles. However, the state diagram applies to beds of uniformly sized particles. In the FINEX® and FINMET® reactors the broad particle-size distribution of the ore has a buoyancy effect on the coarse particles in the bed. Consequently the actual operating field is in the area of bubbling and circulating fluidized beds. The design of the fluidized-bed reactors in FINEX® and FINMET® considers these circumstances well.

Scale-up of the FINEX® fluidized-bed reduction system

After the success of reduction tests in the laboratory and cold and hot bench-scale trials for into the fluid dynamics of fluidized-bed systems, Siemens VAI decided to build at Posco Pohang works, South Korea, a pilot plant with a three-stage, fluidized-bed reduction system for an ore-feed capacity of 150 t/d. The plant ran successfully under industrial conditions from 1999 to 2002, which led to a decision to build the first F2000 demonstration plant with a daily production capacity of 2 000 tonnes of hot metal in 2003.

In the operational campaign the design parameters of the plant were confirmed; it was even demonstrated that the plant performed better than expected once the operation had been optimized and newly designed components installed. Because the F2000 demonstration plant performed outstandingly, Posco decided to construct the first commercial plant for an annual hot-metal capacity of 1.5 mt in Pohang. The success of these developments depended upon the successful scaling up of the fluidized-bed reactors (see Figure 12).

Summary and outlook

Siemens VAI has developed a new ironmaking process based on fluidized-bed technology for reducing iron ore to DRI. It utilizes the advantage of lower costs for fine ores—i.e., lower than those for lump ore or agglomerated fine ore, which conventional technology requires. A consideration of the thermodynamics and chemical kinetics of the reduction of iron oxide to metallic iron by reducing gases (CO and H_2) led to a condition that two or more reduction stages be designed to meet the target of low reducing-gas consumption and good heat utilization. Crucial to the successful development of the new ironmaking technologies for the direct use of fine ore was the scaling up of the fluidized-bed reactor system, which demonstrated new design features. In FINMET® and FINEX® Siemens VAI and its development partners realized the commercialization of two technologies for the ironmaking industry. The focus of future developments will be the further scaling up of the processes and an improved design to guarantee economic and environmentally friendly production of directly reduced iron and hot metal.

References

1. Zeller S., Reidetschläger, J. Ofner H.P. and Peer G. Update on FINMET technology, Product information, Siemens VAI. 2003.
2. Bogdandy, L. von and Engell, H.-J. *Die Reduktion der Eisenerze: Wissenschaftliche Grundlagen und technische Durchführung*. Berlin: Springer Verlag; Düsseldorf: Verlag Stahleisen. 1967.
3. Rist, A. *J.Met*, vol. 19, 1967, pp. 50–59. ◆