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THE DIRECT PRODUCTION OF IRON AND ALTERNATIVES TO THE BLAST FURNACE IN IRON METALLURGY FOR THE 21st CENTURY

I. F. Kurunov

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The rapid development of gas-based (Midrex, HYL, ENERGIRON) and coal-based (DRyIron, Iron Dynamics, Fastmet, Fastmelt, Itmk3) technologies for the direct production of iron and blast-furnace-less iron metallurgy (COREX, FINEX, Hismelt, ROMELT) in the second half of the 20th Century failed to lessen the dominant role of blast-furnace smelting in extractive iron metallurgy. The blast furnace is expected to maintain this dominance in the 21st Century based on its popularity, economic benefits, and energy advantages. Direct ironmaking technologies that produce a solid metallized product which can be used to make pig iron and steel are also not true alternatives to blast-furnace smelting, but they can play an important role as sources of a clean metallic charge material for electric steelmaking or as processes which can recycle iron-bearing waste products at integrated metallurgical plants. Commercial processes in iron metallurgy that do not employ a blast furnace are inferior to blast-furnace smelting in terms of productivity, the amount of energy consumed, and technical and technological reliability.

Key words: *iron, direction production, metallized product, pig iron, blast-furnace smelting, blast-furnace-less iron metallurgy, energy consumption.*

Over the last century, the production of steel grew by a factor of 29.5 – from 28.5 million tons in 1900 to 843 million tons in 2000. The most rapid increase in steel production (from 200 to 700 million tons) took place from the mid-1950s to the mid-1970s, and it has again grown rapidly from the end of the 1990s to the present (see Fig. 1) [1].

Most steel is made by the basic-oxygen process and will continue to be for the foreseeable future, despite the gains made in electric steelmaking in a number of countries that have a large supply of scrap metal.

The annual increase in steel production is expected to slow in the second decade of the 21st Century, but by that decade's end steel production will exceed 2 billion tons and the output of iron will top 1.3 billion tons. In the same period, worldwide the ratio of steel production to iron production will decrease from 0.74 to 0.65–0.70 [1].

Thus, liquid pig iron is still the main component in the metallic part of the charge used for making steel, and its production increases in accordance with the growth of steelmaking. The percentage of total iron production that is accounted for by liquid pig iron remains stable, and ore and coal continue to be the main raw materials used in extractive iron metallurgy.

Over the last two decades, the production of iron by direct methods (metallized pellets or sponge iron – SI; hot-briquetted iron – HBI) has increased at the same rate as the output of pig iron. However, there has been almost no change in the percentage contribution of direct-produced iron to the total output of primary iron (5–6%). Sponge iron is made mainly by gas-based (Midrex, HYL, ENERGIRON) and coal-based technologies (in rotary tubular furnaces and annular reverberatory furnaces with a rotary hearth – RHF). The progress being made in these technologies is not impacting the dominant position of blast-furnace smelting in extractive iron metallurgy, mainly because solid metallic charge materials – including SI and HBI – are still used only on a limited scale in steelmaking (Table 1).

Novolipetsk Metallurgical Plant (NLMK), Lipetsk, Russia; e-mail: kurunov_if@nlmk.ru. Translated from Metallurg, No. 6, pp. 27–32, June, 2010. Original article submitted May 21, 2010.

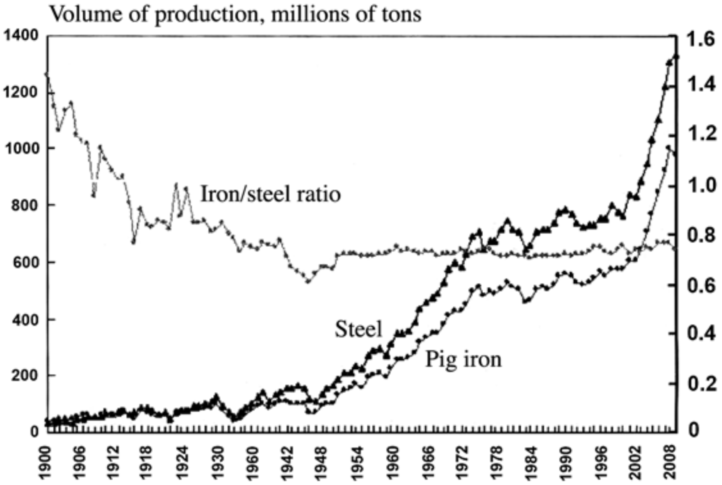

Fig. 1. Dynamics of steel production at the beginning of the 20th Century.

TABLE 1. Metal Production in the Main Nations Producing Pig Iron and Steel in 2008 [1]

Countries	Steel, million tons	Pig iron, million tons	DRI, million tons	Pig iron + DRI, million tons	Pig iron/steel, tons/ton
China	502	471.0	–	471.0	0.938
Japan	118.7	86.2	–	86.2	0.726
U.S.	91.5	33.0	–	33.0	0.361
Russia	68.5	48.3	–	48.3	0.705
India	55.0	28.9	20.2	49.1	0.525
South Korea	53.5	31.2	–	31.2	0.583
Germany	45.8	29.1	–	29.1	0.635
Ukraine	37.1	31.0	–	31.0	0.835
Worldwide	1329.7	926.7	56.8	983.5	0.740

Gas-based technologies for the direct production of iron. In 2007, the Midrex technology was responsible for the production of 39.7 million tons of sponge iron. This amount was 59.7% of the total amount of sponge iron produced in the world. The HYL/ENERGIRON technology was used to obtain 11.3 million tons, or 16.8% of world sponge-iron output [2]. The Midrex and HYL methods have undergone significant improvements in recent years, especially in regard to the use of coke-oven gas, synthetic gas from coal, and COREX export gas. Table 2 shows the main steps that have been taken to improve the Midrex process.

The present unit capacity of *Midrex modules* ranges from 0.5 to 1.7 million tons a year (SUPER MEGAMOT), but of the 60 existing Midrex modules only one operates on synthetic coal gas. The proportions that should be maintained for the use of this gas in Midrex technology: $H_2/CO = 0.5–4.0$; $(H_2 + CO)/(CO_2 + H_2O) \geq 10$. These requirements are met by the gas production facilities that have traditionally been used in the industry. These facilities produce gas with a ratio $H_2/CO = 0.5–1.0$. The Midrex module in Saldanha (South Africa) can be considered the first to have been operated on synthetic gas. A COREX-Midrex complex at this location uses export gas from the COREX module in the Midrex module after it has been cleaned of CO_2. The annual capacity of the complex in terms of pig iron and SI is 650,000 tons and 800,000 tons, respectively.

TABLE 2. Stages of Development and Indices of the Midrex Process [2]

Stage	Productivity of module, tons/h	Percentage of natural gas in the blast, %	Oxygen injection, m^3/ton	Natural-gas consumption, m^3/ton	Electric-power consumption, kWh/ton
Original technology	88.8	4.5	0.0	268.6	135
Use of lump ore	100.3	3.5	0.0	262.3	120
Use of coated pellets versus sinter	110.2	3.5	0.0	257.9	109
Technology with oxygen injection	121.5	4.5	17.5	260.3	99
OXY+ technology	129.2	3.0	30.2	265.8	93
Combined use of oxygen injection and OXY+ technology	133.6	3.0	41.2	264.6	90

TABLE 3. Commercial Technologies for Coal Gasification [2]

Company	Coal used	Coarseness	(H_2 + CO) in the gas, %	Content of CH_4, %	Pressure	Gasification temperature, °C
Lurgi	Lignite, bituminous	6–50 mm	~65	9–12	2.0–3.0 MPa	950–1050
Udok	Lignite, gas, weak-coking, non-coking	<10 mm	65–73	0.6–2.0	Normal	~1050
Texaco	Bituminous, petroleum coke	<0.074 mm 60–65% suspension of coal in water	~80	<0.1	2.7–8.4 MPa	1300–1400

The composition of the COREX export gas with the ratio $H_2/CO = 0.3–0.5$ is as follows (%): CO 43–45; H_2 12–22; CO_2 30–32; N_2 1–6; H_2O 1–6; CH_4 1–2.

The *HYL technology* employs steam conversion of natural gas (NG), so the reducing gas contains roughly 80% H_2. In contrast to the classical HYLIII technology, its later modification – the ZR technology – does use a reformer. Reducing gas is generated simultaneously with the reduction of iron oxides inside a metallization reactor by reforming NG through its partial combustion. Inside the reactor, freshly reduced iron serves as a catalyst for reforming the hydrocarbons. This technology lowers the necessary initial investment and maintenance costs. The SI that is produced is also of better quality but contains iron carbide. The ZR technology is used in Mexico.

Working with Danieli company (in Italy), the company HYL developed the *ENERGIRON technology* on the basis of the ZR method. The new technology can be quickly adapted to customers' needs and employs standard modules with capacities 0.2, 0.5, 0.8 1.2, 1.6, and 2.0 millions of tons a year. The technology allows the direct use of hydrogen, CO, or any gas that contains hydrocarbons. The gas that leaves the reactor is cleaned of H_2O and CO_2 and used again in the reactor after heating to 950°C. Some of the NG that is injected is oxidized as a result of the injection of oxygen, which heats the inside of the reactor to the 1000°C temperature needed to reform the hydrocarbons and form carbides. The temperature of the reducing gas is lowered to 820°C thanks to endothermic reactions in which iron oxides are reduced by hydrogen, and at this temperature the pellets do not stick together and form clusters.

Seven ENERGIRON modules with capacities (millions of tons/yr) of 0.2 (Egypt), 0.5 (India and Mexico), 0.8 (Venezuela), 1.6 (Abu Dhabi), and 1.7 (India and Brazil) were placed in service in 2007–2008. Most of these units are being used to make high-carbon SI. The modules in Abu Dhabi (1.6) and India (1.7) are being operated in combination production units that also include electric steelmaking furnaces. Here, hot SI from the reducing reactors of the ENERGIRON modules is immediately transferred to the electric furnace. The module in Jindalee (India, 1.7) uses synthetic gas obtained by the gasification of coal.

Synthetic gas is currently obtained by three coal-gasification technologies (Lurgi, Germany; Undok, North Korea; Texaco, U.S.) that differ appreciably from one another in terms of the parameters of the product gas, the characteristics of the coal that is used, and the parameters of the gasification process (Table 3).

A gas-based technology for the direct production of iron is being used in the Ghaem process that was developed in Iran. This process was introduced at the Isfahan Metallurgical Plant in 1996 (the productivity of the module is 600,000 tons of metallized pellets a year). A distinguishing feature of this process is that reducing gas is obtained from natural gas by its partial oxidation by oxygen and by gases leaving the reactor, without the use of a catalyst. The SI that is obtained is 90–96% metallized (average of 93%) and contains 1.8–2.0% carbon in the form of iron carbide, which keeps the product from undergoing oxidation [3].

Included among the coal-based technologies for the direct production of iron are obsolete methods (SI production in rotating tubular furnaces) used mainly on hard-to-concentrate ores and more promising methods (SI production in annular reverberatory rotary-hearth furnaces) invented roughly 50 years ago. The concept of using an RHF for the direct production of iron was developed in 1960 by the company Midland of America (which later became Midrex). This method was successfully tested in 1965–1966 but was then forgotten. The specific technology that was developed was called *Heat Fast Technology*, and the company Midland Ross and Engineering (in the U.S.) later used it as a basis for developing the *DRyIron technology* to recycle finely dispersed metallurgical waste products. In this method, the wastes are mixed with coal and are dry-briquetted under pressure, the briquets then being subjected to metallization in an RHF [4].

The essence of the DRyIron process is as follows. Ore-coal pellets or briquets are charged into the rotating hearth of the RHF in one or two layers. An oxidizing atmosphere is maintained in the *heating zone* of the furnace, where the main heat source is fuel that undergoes combustion in a burner. *In the reduction zone*, iron oxides are reduced by carbon, and the CO formed in this process undergoes secondary combustion above the layer of pellets or briquets. Heat is transferred to the layer solely by radiation. Combustion of the CO provides 85% of the heat needed for the process and combustion of the fuel in the burners provides the remaining 15%. The iron oxides are reduced by carbon within the temperature range 1200–1400°C over a period of 6–12 min. The resulting SI is discharged from the furnace at 900–1000°C. The pellets or briquets are in the RHF for a total of 20 min. The direction of motion of the gas in the working space of the RHF is opposite the direction of rotation of the hearth. The temperature and composition of the gas are monitored and kept at the prescribed levels with the use of burners mounted in the side walls of the furnace. The waste gases are removed from the furnace on the charging side, and their heat is used in a heat exchanger to heat the combustion air to 500–600°C. The waste gases are subsequently burned in a steam boiler, cleaned of dust, and discharged through a smokestack [4].

Zinc oxides undergo reduction in the RHF in addition to the reduction of iron oxides by carbon and CO. At 950–1000°C, metallic zinc is vaporized and leaves the furnace together with the waste gases. These gases oxidize the zinc to ZnO, and particles of zinc oxide are captured in bag filters along with volatile alkali compounds and halides. The captured dust is a raw material for use in nonferrous metallurgy. Recycling the iron- and zinc-bearing waste products of the steelmaking operation by shaping them into briquets or pellets and metallizing them in an RHF helps make the modern metallurgical plant a green industrial facility. The world's first commercial RHF, with a diameter of 16.7 m, was built by the company INMETCO in Elwood (in the U.S.) for recycling wastes containing nickel, chromium, and iron. This furnace has also successfully produced SI from iron-ore concentrate. The DRyIron unit has a capacity of 200,000 tons a year and was built in 1997. The company Iron Dynamics Inc. (U.S.) began operation of an IDP (Iron Dynamics Process) unit in 1999. This furnace has a capacity of 500,000 tons of sponge iron a year and is the largest such furnace in the world [4].

The company Kobe Steel (Japan) collaborated with the Midrex company to develop the *Fastmet* technology for the production of SI in an RHF from finely dispersed iron-bearing wastes and coal. A pilot facility with an annual capacity of 20,000 tons was built in 1985 at a metallurgical plant in Kakogawa, a demonstration Fastmet unit was built in 1995, and a commercial unit with a capacity of 160,000 tons a year was built in 2001. The first commercial Fastmet unit, with a annual capacity of 190,000 tons of SI, was sold by Nippon Steel (Japan) in 2000. The SI obtained in the RHF is used in blast furnaces, which realizes a coke savings of 23 kg/ton pig iron for each DRI charge of 100 kg/ton [4].

It has been found that fluctuations in the sulfur and ash contents of the coal used in the production of the sponge iron have a significant effect on its quality. Refinement of the process to resolve this problem led to the development of the

TABLE 4. Composition of Products in the Fastmet and Fastmelt Processes

Process	Content, %								Metallization η_{met}, %
	C	Si	S	P	Fe_{met}	FeO	Fe_{tot}	Rock material	
Fastmet (for sponge iron)	4.0	–	0.15	–	78.2	11.3	86.9	6.35	90
Fastmelt (for pig iron)	2.0–4.5	0.1–0.6	<0.05	<0.04	95.5–98.0	0	95.5–98.0	0	100

Fastmelt technology, in which hot SI obtained in an RHF is charged into an electrical furnace designed to refine pig iron. The sponge iron is melted inside the furnace, the pig iron is separated from the slag that is formed, the metal is desulfurized, and the carbon content of the pig iron is stabilized. The CO-bearing gas leaving the refining furnace is used as fuel in the RHF. The pig iron that is obtained (Table 4) can be used in steel production. The world's first Fastmelt unit, with a capacity of 140,000 tons of pig iron a year, was built by Nippon Steel at a plant in Hirohata (Japan).

In China, research on technologies for making SI in an RHF was begun in 1980. The first experimental RHF, 3 m in diameter, was built in 1992 by engineers at Peking Technological University together with the metallurgical company WISCO. In 1994, the new *COF-R* process was developed at the university on the basis of Fastmet technology and a 7.4-m-diam. pilot RHF was built. The Shanxi Mingliang Iron and Steel Company collaborated with the university in 2000 to build the first commercial RHF in Yicheng (Shanxi). This facility achieved stable operation in 2006–2007 [4].

Production of iron granules by the Itmk3 technology. The Itmk3 method was developed as an outgrowth of the Fastmet technology but differs from the latter in the composition of the ore-coal pellets, operating temperature in the RHF, and the nature of the product – which consists of iron granules (nuggets). At 1350–1400°C, the iron reduced in the pellets is carbonized and melted, forming bean-shaped granules upon cooling. The oxides in the ore's country rock and the coal ash form low-melting compounds in solid-phase reactions, and a semi-molten slag is then obtained from the compounds. After being cooled on the hearth by a gas, the slag and the iron granules are discharged from the RHF and separated. The process just described was given the name Itmk3 (Ironmaking Technology Mark 3). The granules have an iron content of 96–97%, while the rock contains no iron [4].

Technology for obtaining liquid pig iron without a blast furnace. The depletion of natural raw materials and fuel is becoming an increasingly important concern that is impeding the growth of metallurgy for reasons beside the rising cost of these materials. This pertains especially to fuels (coking coal and gas) that are being used with success in other sectors of industry (power generation, the chemicals industry, fertilizer production). Environmental requirements are also becoming a financial consideration, and not just because of greenhouse gases. The tightening of environmental regulations is requiring metallurgists to modernize the technologies that they use. These factors collectively pose an overall problem for extractive iron metallurgy, making it necessary to develop processes for obtaining iron from ore and coal that can be an alternative to the blast furnace and be more cost-effective, less energy-intensive, and less polluting. Metallurgists have been trying to find such alternatives for more than 50 years and have developed commercially viable technologies for iron metallurgy that do not involve the use of blast furnaces (COREX, FINEX, Hismelt, ROMELT). However, none of these processes yet play a very large role in extractive iron metallurgy and are not having an effect on the dominant role of blast-furnace smelting. That dominance is a reflection of the blast furnace's economic advantages and the high degree of efficiency of the smelting operation, which grew appreciably in the second half of the Twentieth Century. The dominance also stems from the reliability of the blast furnace from the technical and technological standpoints. The most advanced alternative, the *COREX technology*, shares with blast-furnace smelting the need to have a previously prepared agglomerated iron-ore-based material, coal, and coke. However, the COREX technology consumes less than half the amount of coke that the blast furnace requires. This technology is carried out in two separate reactors: in a reducing shaft and in a melting furnace-gasifier. The ore-based materials (pellets and graded ore) in the shaft-type reducing reactor are reduced by a gas supplied by the furnace-gasifier. The furnace-gasifier then completes the process of direct reduction of the iron oxides. The material partially reduced in the shaft furnace is transferred to the furnace-gasifier by screw conveyors. Coal and coke are charged directly into the melting furnace-gasifier through special charging doors. Some of the coke is also charged into the reducing shaft. Slag and pig iron are tapped from the melting furnace through notches by the usual method.

In the FINEX process, fine ore is reduced in fluidized-bed reactors. Coal and coke are charged directly into a melting furnace-gasifier to be oxidized by injected oxygen, which forms a reducing gas that is then used to reduce the fine ore in the fluidized-bed reactors.

The COREX and FINEX processes, currently used at metallurgical plants in four countries (China, India, Korea, and South Africa), produce about 7 million tons of pig iron. The largest COREX module, the COREX-3000, has an annual capacity of 1.5 million tons of iron. One of these modules was built at the Shanghai, China plant of Baosteel in 2007. A second module of the same size is expected to begin operation at the same plant in 2011. The smaller COREX-2000 module is in use at the plant of Jindal South West Steel Ltd in India, while another COREX-2000 module is in operation together with a Midrex module at the plant operated by ArcelorMittal in Saldanha, South Africa [5]. The combined use of COREX modules and blast furnaces is allowing the Jindal company to make use of more than 70% of all of the blast-furnace sludge, limestone and dolomite screenings, and converter slag formed at the plant. These materials are used either directly or through the sinter or pellet plants, thus making it possible to minimize iron production costs. In addition, the export gas of the COREX module is being used to heat the blast in the blast-furnace stoves, in boilers, and at the sinter and pellet plants [5].

FINEX modules with an annual capacity of 1.5 million tons are in operation at plants owned by Baosteel (North Korea) and Posco (South Korea). In these modules, pulverized-coal fuel is injected into the melting furnace-gasifiers.

Work is proceeding on a method for recycling the export gas from the COREX and FINEX processes after it is cleaned of CO_2. The gas would be used for partial metallization of pellets or ore that would then be smelted in blast furnaces. Calculations show that recycling the export gas would cut total fuel consumption in the COREX process by 20% and reduce the oxygen consumption by 12% [5]. Strictly speaking, the COREX and FINEX technologies cannot be considered coke-less processes for iron metallurgy. The melting furnace-gasifier essentially functions as a blast-furnace hearth and requires a column of coke for its operation. Coke is charged into the furnace-gasifier and – in the COREX process – also into the reducing shaft. The fact that the coke is not screened, unlike for blast furnaces, causes problems in the operation of the unit – particularly when the coke's moisture content is high. The COREX process cannot equal the blast furnace in terms of the cost of iron production. This is due largely to the higher fuel consumption in the COREX technology, but it is also related to technical and technological problems that complicate the operation of the unit. Among these problems: the need to periodically remove encrusted material from the shaft (this operation accounts for 2/5 of the scheduled downtime of the unit); obstruction of the channels that transport materials from the shaft to the melting furnace-gasifier; hanging of the charge in the shaft; blockage of the charging line and dust-recycling line; burn-through of the tuyeres and difficulties with tapping the smelting products (loss of the notch). After the COREX-3000 module came on line in 2007, the degree of readiness of the equipment to operate for its scheduled time of service increased from 25 to 80% [6].

In contrast to the COREX and FINEX processes, the *Hismelt process* is a single-stage technology. It is executed in a single melting-reducing furnace (MRF). The upper part of the furnace's vertical cylindrical shaft is water-cooled, while the lower part (the hearth) is lined with refractories. One of the distinguishing features of the technology is the high-speed injection of powdered dried coal (0–3 mm), preheated fine (0–3 mm) iron ore, and calcined dolomite through water-cooled downward-inclined lances into a melt inside the unit. The coal is dissolved in the melt and converted to metal (containing about 4% carbon) and the ore is melted when it comes into contact with the metal. A weak oxidizing potential is maintained in the lower part of the MRF (the FeO content of the slag is 5–6%) so as to not inhibit reactions in which carbon directly reduces iron from the melt while at the same time ensuring that 80–90% of the sulfur is transferred to the slag [7]. The heat needed for the process comes from the top part of the MRF, where CO undergoes final combustion by a blast that has been heated to 1200°C and enriched with oxygen (up to 35%). The blast air is fed into the top of the MRF by a central tuyere. The degree of secondary combustion of the gas is 50–60%. A key feature of the Hismelt process is the efficiency with which heat is transferred from the top zone to the bottom zone. This transfer takes place through rapid foaming (emulsification) of the liquid phase located between the top and bottom zones. A substantial percentage of the heat in the water-cooled walls of the MRF and the lances is lost with the coolant water.

Development of the Hismelt process started in the beginning of the 1980s. After two pilot tests performed on units with annual capacities of 10,000 tons and 100,000 tons, construction was completed in 2005 in Kwinana (Western Australia) on a commercial module with a capacity of 800,000 tons/yr. This module was funded by venture capital provided by the companies Rio Tinto (Australia – 60%) Nucor (U.S. – 25%), Mitsubishi (Japan – 10%), and Shougang (North Korea – 5%) [7]. The gas leaving the MRF is cooled in a radiator, cleaned in a scrubber, and burned in a boiler. The combustion products in the boiler are cleaned of SO_2 in a special scrubber before being released into the atmosphere. By design, the steam generated in the boiler is used in the air flues, the compressor in the oxygen plant, and the turbine of the electrical generator. The energy that is thus obtained completely offsets the cost of the energy used in the Hismelt process and produces a small excess (5%). For several reasons, it turned out to be difficult to bring the Hismelt unit up to its design capacity. Among those reasons: design flaws in the tapping system (the receiver); deficiencies in the system used to generate steam in the radiator; design flaws in the ore preheater; the dependence of the supply of electric power for the air blower on steam generation; design flaws in the system that desulfurizes the waste gases; the lack of a system for real-time monitoring of the carbon content of the metal (a decrease in its carbon content leads to the growth of steel crusts on the water-cooled panels); inadequate reliability of the lining and cooling system of the hearth of the MRF.

The solution of these problems in 2008 increased the productivity of the unit to 75–80 tons/h with a coal consumption of 800 kg/ton. The unit is expected to reach its rated capacity of 100 tons/h and a coal consumption of 700 kg/ton in 2010 [7].

The current alternatives to the blast furnace for iron production (COREX, FINEX, Hismelt) are considerably inferior to blast-furnace smelting with respect to the amount of coal consumed per ton of iron [8]:

	Blast furnace	COREX	Hismelt	FINEX
Coal consumption, kg/ton	550	900–1000	900–950	850–1000

Among the ways that researchers are studying for reducing fuel consumption in the COREX and FINEX processes is the high-temperature (1450–1500°C) reduction of iron from the melt by hydrogen and more complete secondary combustion of the gas in the melting furnace. The amount of heat consumed in the reduction of FeO by carbon is 5–9 times greater than in the reduction of this oxide by hydrogen at 1450–1550°C, and the rate constant for the reaction in which FeO is reduced by hydrogen is greater than for CO. Moreover, the reducing potential of hydrogen remains quite high even if the gas undergoes a high degree of secondary combustion [8].

Using results from numerical-analytical study of the energy efficiency of blast-furnace smelting and one-stage (Hismelt) and two-stage (COREX, FINEX) processes for obtaining iron from ore and coal, Prof. W.-K. Lu and others [9] reached the conclusion that neither one-stage nor two-stage blast-furnace-less processes for iron production can compete with blast-furnace smelting based on the amount of carbon consumed per ton of iron produced. Even under ideal conditions, carbon consumption in the two-stage processes cannot be any lower than 650 kg/ton pig, and that value is still significantly greater than the results obtained in the blast-furnace process. The amount of carbon consumed per ton of iron product could be reduced to a level lower than achieved in the blast furnace by using a process based on the principle discovered by Prof. Swen Ekertop (Smelting Reduction @ Ironmaking Proc., ISS, 1968, pp. 36–39). In accordance with this principle, all iron reduction takes place solely by means of carbon, and the amount of heat needed for this reduction is obtained by ensuring that all of the carbon monoxide formed in the reduction process undergoes secondary combustion to CO_2. Such a technology would essentially be more efficient than blast-furnace smelting. The problem lies in efficiently transferring heat from the "oxidative" part of the process unit to its "reductive" part. The most important task here is monitoring (not allowing) repeat oxidation of the metal as it comes into contact with the gaseous oxidants travelling from the oxidative part of the unit. Among the processes currently in use, the technologies that are carried out in an RHF (Fastmet, Fastmelt, and Itmk3) conform to this principle most closely. Processes conducted in an RHF successfully combine the use of a reduction zone (in a bed of ore-coal pellets) and a zone for secondary combustion (above the pellet bed) within a single space inside the furnace, with heat from the latter zone being transferred to the reduction zone by convection and radiation. However, heat transfer by convection is undesirable, since the movement of heat to the reduction zone is accompanied by the arrival of oxidizing gas that can lead to repeat oxidation of the newly reduced iron. This lowers the overall efficiency of the process and the degree of metallization achieved (about 60%) with a pellet bed of 1–2 layers. The deficiency just noted is eliminated in the *PSH process* (PSH – Paired Straight Hearth), which has not yet been introduced commercially. Its most distinctive feature is the use of a deeper bed of charge materials in the RHF (6–8 layers of pellets 16–19 mm in diameter). Coal with a high content of volatile matter is used in the ore-coal pellets. The temperature of the flame above the bed is 1500–1600°C [9]. The process realizes a high degree of metallization and employs a dense bed of metallized pellets while minimizing the total consumption of carbon (fuel and reducing agent). The secret to success is protection of the top layer of pellets by the flow of CO continually emanating from it. This flow keeps the pellets from being oxidized by the carbon dioxide formed in the secondary combustion of CO.

Conclusion. World steel production is based on the basic-oxygen process, and the metallic charge used for basic-oxygen converters is based on liquid pig iron produced in blast furnaces. Liquid pig iron is also used in the production of steel in electric furnaces. The dominance of the basic-oxygen process in steelmaking and of blast-furnace smelting in extractive iron metallurgy will continue in the 21st Century. Direct ironmaking processes that produce a solid product (SI and HBI) which is used mainly in electric steelmaking or in blast furnaces cannot be a true alternative to the blast-furnace process. Existing blast-furnace-less technologies in iron metallurgy are also not viable alternatives to smelting in a blast furnace, since they cannot match it in terms of productivity, energy consumption, or technical and technological reliability. Moreover, the best of them (COREX and FINEX) are not really coke-free processes.

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