Kirk-Othmer Encyclopedia of Chemical Technology.

IRON BY DIRECT REDUCTION

Direct reduction (DR) is the process of converting iron ore (iron oxide) into metallic iron without melting. The metallic iron product, known as direct reduced iron (DRI), is used as a high quality feed material in steelmaking.

The most common method of converting iron ore to metallic iron utilizes a blast furnace wherein the material is melted to form hot metal (pig iron). Approximately 96% of the world's iron is produced this way (see Iron). However, in the blast furnace process energy costs are relatively high, pollution problems of associated equipment are quite severe, and capital investment requirements are often prohibitively expensive. In comparison to the blast furnace method, direct reduction permits a wider choice of fuels, is environmentally clean, and requires a much lower capital investment.

Commercial production of DRI began in the 1950s, but did not achieve significant growth until the 1970s. In 1993 world production of DRI was 23.9 million metric tons, and is expected to reach 35 million metric tons annually by the year 2000. The driving force behind this rapid increase in production is the demand for DRI as a high purity supplement to ferrous scrap in electric arc furnace steelmaking.

1. Physical Properties

DRI can be produced in pellet, lump, or briquette form. When produced in pellets or lumps, DRI retains the shape and form of the iron oxide material fed to the DR process. The removal of oxygen from the iron oxide during direct reduction leaves voids, giving the DRI a spongy appearance when viewed through a microscope. Thus, DRI in these forms tends to have lower apparent density, greater porosity, and more specific surface area than iron ore. In the hot briquetted form it is known as hot briquetted iron (HBI). Typical physical properties of DRI forms are shown in Table 1.

HBI is produced by molding hot (ca 700°C) DRI into pillow-shaped briquettes using a pocketed roll press. HBI is almost twice as dense as nonbriquetted DRI and it has substantially less surface area, which makes it 100 times more resistant to reoxidation. It is stronger and more massive, making it more resistant to fines generation, and it takes up less volume for storage and shipping owing to its high bulk density. It has minimum water absorption when saturated, thus it is ideally suited for merchant applications where shipping, handling, and storage characteristics are important.

2. Chemical Properties

DRI retains the chemical purity of the iron ore from which it is produced, therefore it tends to be very low in residual elements such as copper, chrome, tin, nickel, and molybdenum. Typical ranges of DRI chemical compositions are shown in Table 2.

Table 1. Physical Characteristics of DRI[a]

Parameter	Pellets/lump	HBI
density, t/m^3		
bulk	1.6–1.9	2.4–2.8
apparent	3.5	5.0–5.5
porosity, %	50	15
saturated water absorption, wt %	12–15	2–3
nominal size, mm	4–20	30 × 50 × 110

[a] Produced in the MIDREX Direct Reduction Process.

Table 2. Composition of DRI Produced in the MIDREX Process

Parameter	Pellet/lump	HBI
iron, wt %		
total	90–94	90–94
metallic	83–89	83–89
metallization, %	92–95	92–95
FeO, wt %	6.5–9.1	6.5–9.1
C, wt %	1.0–2.5	0.8–1.2
gangue, wt %	2.8–6.0	2.8–6.0
P, wt %	0.005–0.09	0.005–0.09
S, wt %	0.001–0.03	0.001–0.03
other	trace	trace

Metallization is defined as the percent of total iron in the DRI which has been converted to metallic iron. For example, DRI having a total iron content of 92% and a metallic iron content of 85%, has 92.4% metallization.

$$\text{metallization }(\%) = \frac{\text{metallic Fe}}{\text{total Fe}} \times 100\%$$

Reduction is the percentage of oxygen present in the ore as iron oxide which has been removed.

$$\text{reduction }(\%) = \frac{\text{oxygen removed}}{\text{initial oxygen}} \times 100\%$$

Assuming that the initial iron oxide is hematite, Fe_2O_3, and this ore is completely converted to FeO, ie, no metallic iron is formed, the reduction would be 33.33%. Thus the relationship between metallization and reduction is

$$\text{metallization }(\%) = \left[\text{reduction }(\%) - 33.33\%\right] \times 1.5$$

From this relationship it can be seen that a reduction level of 95% compares with a metallization level of 92.5%. A reduction level of 33.33% or less has a metallization level of 0%. DRI normally has at least 90% reduction or 85% metallization. Processes producing solid, partially reduced iron, ie, <90% reduced or <85% metallized, are classified as prereduction processes. The partially reduced product, called prereduced iron, is not acceptable for steelmaking but can be used as a feed for iron smelting.

Although it is theoretically possible to convert all of the iron oxide in iron ore to metallic iron, it is not economically feasible. The reduction reaction slows significantly in the last stages and to complete the reduction process would result in low production rates. In practice, it is advantageous to retain a small amount of iron oxide in the DRI. During melting in an electric arc furnace, the iron oxide in DRI reacts with carbon in the DRI to form metallic iron and carbon monoxide. The carbon monoxide foams the slag during steelmaking, and this improves the operation of the electric furnace.

The carbon content of DRI depends primarily on the direct reduction process used and the way the process is operated. Carbon content can be adjusted within limits by operating changes within the DR process. Most steelmakers prefer slightly more carbon than is required to balance the remaining FeO in the DRI. DRI from gas-based processes typically contains 1 to 2.5% carbon, mostly in the form of cementite [12169-32-3], Fe_3C. DRI containing approximately 6 to 7% carbon in the form of cementite is called iron carbide. DRI from coal-based, rotary-kiln processes contains very low (ca 0.5%) levels of carbon.

The gangue content of DRI is typically comprised of oxides such as SiO_2, Al_2O_3, CaO, MgO, TiO_2, K_2O, Na_2O, MnO, etc, and is dictated by the chemistry of the iron ore used. The phosphorus in DRI is normally in the form of P_2O_5. Sulfur content in the DRI depends on the sulfur level in the ore and reductant, and the amount of sulfur released or absorbed by the DRI during the reduction process.

3. Production

The reduction of iron ore is accomplished by a series of reactions that are the same as those occurring in the blast furnace stack. These include reduction by CO, H_2, and, in some cases solid carbon, through successive oxidation states to metallic iron, ie, hematite [1309-37-1], Fe_2O_3, is reduced to magnetite [1309-38-2], Fe_3O_4, which is in turn reduced to wustite [17125-56-3], FeO, and then to metallic iron, Fe. The typical reactions follow.

Reduction reactions

$$3\ Fe_2O_3 + H_2 \longrightarrow 2\ Fe_3O_4 + H_2O \qquad (1)$$

$$3\ Fe_2O_3 + CO \longrightarrow 2\ Fe_3O_4 + CO_2 \qquad (2)$$

$$Fe_3O_4 + H_2 \longrightarrow 3\ FeO + H_2O \qquad (3)$$

$$Fe_3O_4 + CO \longrightarrow 3\ FeO + CO_2 \qquad (4)$$

$$FeO + H_2 \longrightarrow Fe + H_2O \qquad (5)$$

$$FeO + CO \longrightarrow Fe + CO_2 \qquad (6)$$

$$FeO + C \longrightarrow Fe + CO \qquad (7)$$

Carburization reactions

$$3\ \mathrm{Fe} + \mathrm{CO} + \mathrm{H_2} \longrightarrow \mathrm{Fe_3C} + \mathrm{H_2O} \qquad (8)$$

$$3\ \mathrm{Fe} + 2\mathrm{CO} \longrightarrow \mathrm{Fe_3C} + \mathrm{CO_2} \qquad (9)$$

$$3\ \mathrm{Fe} + \mathrm{C} \longrightarrow \mathrm{Fe_3C} \qquad (10)$$

Reforming reactions

$$\mathrm{CH_4} + \mathrm{CO_2} \longrightarrow 2\ \mathrm{CO} + 2\mathrm{H_2} \quad (\mathrm{CO_2}\ \text{reforming}) \qquad (11)$$

$$\mathrm{CH_4} + \mathrm{H_2O} \longrightarrow \mathrm{CO} + 3\ \mathrm{H_2} \quad (\text{steam reforming}) \qquad (12)$$

$$\mathrm{CH_4} + 1/2\ \mathrm{O_2} \longrightarrow \mathrm{CO} + 2\ \mathrm{H_2} \quad (\text{methane partial oxidation}) \qquad (13)$$

$$\mathrm{CO_2} + \mathrm{C} \longrightarrow 2\ \mathrm{CO} \quad (\text{Boudouard reaction}) \qquad (14)$$

$$\mathrm{H_2O} + \mathrm{C} \longrightarrow \mathrm{CO} + \mathrm{H_2} \quad (\text{water--carbon reaction}) \qquad (15)$$

$$1/2\ \mathrm{O_2} + \mathrm{C} \longrightarrow \mathrm{CO} \quad (\text{carbon partial oxidation}) \qquad (16)$$

$$\mathrm{CH_4} \longrightarrow \mathrm{C} + 2\ \mathrm{H_2} \quad (\text{methane cracking}) \qquad (17)$$

At reduction temperatures below about 1000°C, the reducing agents usually are restricted to CO and H_2. Above about 1000°C, solid carbon can react with CO_2 and H_2O to renew the reducing potential of the gas. Above 1200°C, the metallic iron that has formed absorbs any carbon that is present, which results in melting point depression (from 1530°C) and subsequent fusing or melting of the solid.

Processes operating in the range of 1300–1530°C produce molten iron, called hot metal or pig iron. These processes are classified as direct smelting processes. Processes operating above 1530°C produce molten steel (qv) and are called direct steelmaking processes.

Table 3. Heats of Reaction for Reductions in DR Processes, kJ / kg Fe[ab–c]

	$Fe_2O_3 \longrightarrow Fe_3O_4$			$Fe_3O_4 \longrightarrow Fe_{0.95}O$			$Fe_{0.95} \longrightarrow Fe$		
Temperature, °C	H_2	CO	C	H_2	CO	C	H_2	CO	C
600	−800	−6, 873	21,771	17,380	7,271	54,945	16,154	−22, 328	159,164
700	−1, 829	−7, 744	20,779	16,258	6,417	53,886	15,471	−22, 006	158,716
800	−2, 373	−8, 129	20,256	15,882	6,300	53,539	16,459	−20, 026	159,830
900	−2, 541	−8, 142	20,093	15,614	6,292	53,284	16,166	−19, 331	159,574
1,000	−2, 733	−8, 183	19,892	15,463	6,392	53,112	15,672	−18, 858	159,018
1,100	−2, 951	−8, 251	19,649	15,417	6,597	53,032	14,216	−19, 364	157,410
1,200	−3, 194	−8, 347	19,369	15,484	6,911	53,037	12,822	−19, 821	155,782
1,300	−3, 462	−8, 468	19,050	15,664	7,330	53,129	11,499	−20, 231	154,133

[a] All heats of reaction are based on stoichiometric equation for 1 mol Fe in reactant oxide.

[b] Conventional signs are employed: negative values are exothermic; positive values are endothermic.

[c] To convert kJ/kg Fe to Btu/lb Fe, multiply by 0.43.

The equilibrium for the reactions of CO and H_2 with the oxides of iron are well established (see IRON). There is nearly complete conversion of CO to CO_2 and H_2 to H_2O for the reduction of Fe_2O_3 to Fe_3O_4. Below 570°C, Fe_3O_4 is reduced directly to Fe by CO and H_2; above 570°C, Fe_3O_4 first is reduced to FeO which then is reduced to Fe. In the reduction of Fe_3O_4 to FeO, the conversions of CO and H_2 increase with increasing reaction temperature. However, in the reduction of FeO to Fe, the conversion for H_2 increases with increasing reaction temperature, whereas that for CO decreases. This decrease of equilibrium CO conversion with increasing temperature for the reduction of FeO to Fe is not a limitation on the overall conversion because most DR processes are operated using countercurrent flow of solids and reducing gases. Thus the spent reducing gas leaves in contact with the entering solids which are in their highest oxidation state, and the equilibrium for the reduction of Fe_3O_4 to FeO governs the final gas composition. For DR processes that are based on reduction using mixtures of CO and H_2, the final gas composition usually satisfies the equilibrium for the water gas reaction at the exit temperature, ie,

$$CO_2 + H_2 \longrightarrow CO + H_2O, \quad K_{eq} = \frac{[CO]\ [H_2O]}{[CO_2]\ [H_2]} \tag{18}$$

The description given applies to DR processes that are based on the use of gaseous reductants in shaft furnaces, batch retorts, and fluidized beds. In the processes that use solid reductants, eg, coal (qv), the reduction is accomplished to a minor extent first by volatiles and reducing gases that are released as the coal is heated and then by CO that is formed by gasification of fixed carbon contained in the coal char with CO_2. Reduction by solid carbon and coal volatiles in kilns is insignificant.

The energy requirements for DR processes are related directly to the heats of reaction for the reduction reactions over the temperature range of practical interest for DR processes. A summary is presented in Table 3.

The reduction of Fe_2O_3 to Fe_3O_4 using H_2 and CO is mildly exothermic and the reduction of FeO to Fe using CO is moderately exothermic. The other reactions are moderately endothermic, with the exception of the reduction of Fe_3O_4 to FeO and of FeO to Fe by carbon; both are highly endothermic. The heat of reduction is not a principal factor in establishing the energy requirements for the gas-based DR processes. Instead, the energy requirements for these processes come mainly from the energy that is needed to generate the reducing gas, which in most cases is catalytic steam (qv) or CO_2 reforming of natural gas, and the chemical energy in the reductants that are consumed in the process (see GAS, NATURAL). For the DR processes that are conducted in shaft furnaces, total energy requirements can be minimized by recovering most of the sensible heat in the DRI and in the spent reducing gases. Such recovery is not practical in the fluidized-bed processes. For the DR processes based on the direct use of solid reductants, the highly endothermic reaction of CO_2 and solid carbon is compensated for by the highly exothermic combustion reactions in the free space above the reaction bed.

The productivity of DR processes depends on chemical kinetics, as well as mass and heat transport factors that combine to establish the overall rate and extent of reduction of the charged ore. The rates of the reduction reactions are a function of the temperature and pressure in the reduction beds, the porosity and size distribution of the ore, the composition of the reducing gases, and the effectiveness of gas–solid contact in the reduction beds. The reduction rate generally increases with increasing temperature and pressure up to about 507 kPa (5 atm).

Reduction of iron ore containing magnetite in gas-based DR processes is difficult owing to the massive structure of magnetite which hinders gaseous diffusion. If the magnetite is first oxidized to hematite, the reduction proceeds much more rapidly, because of a physical change in the crystal structure which opens up the structure and enhances gaseous diffusion.

4. Direct Reduction Processes

In 1993, 23.9 million metric tons of DRI were produced worldwide. Five principal processes produced 95.6% of this total. Natural gas-based direct reduction accounts for 92.5% of worldwide production and coal-based direct reduction accounts for the other 7.5%. A comparison of the five principal processes is given in Table 4.

4.1. MIDREX Process

The primary components of a MIDREX process plant include the shaft furnace, reformer, and heat recuperator. These components are supported by ancillary systems for handling iron ore, gas, water, and direct reduced iron. A flow sheet is shown in Figure 1.

Reduction is carried out continuously in the shaft furnace. Iron oxide in pellet (6–16 mm) or lump (10–35 mm) form is fed to the top of the furnace, flows downward by gravity, and is discharged from the bottom in the form of DRI. The shaft furnace has two separate processing zones, both of which use recycled gas. In the upper reduction zone, iron oxide is preheated and reduced by counterflowing reducing gas containing hydrogen and carbon monoxide. In the lower cooling zone, the reduced product is carburized and cooled by counterflowing cooling gas.

When incorporating hot briquetting in the MIDREX process, the cooling gas circuit is eliminated, and the hot DRI is continuously discharged from the shaft furnace into a hopper and directly fed into a hot briquetting machine. The resulting HBI is continuously discharged from the hot briquetting machine, separated into individual briquettes, and cooled.

Reducing gas is generated at low pressure in the reformer by catalytically reforming a preheated mixture of fresh natural gas and recycled top gas from the shaft furnace. The reformer is a gastight, refractory-lined furnace containing alloy tubes filled with catalyst. The preheated gas mixture flows through the catalyst bed where it is heated and reformed. The hot (1000°C) reducing gas leaves the reformer at near equilibrium condition, containing 90 to 92% H_2 plus CO. Therefore, the reducing gas can be fed directly to the shaft furnace.

4.2. HYL I Process

In the HYL I process (Fig. 2), four batch retorts are operated sequentially through four steps to achieve a semicontinuous operation. While one retort is discharging DRI and being filled with pellets, two other retorts are reducing pellets and a fourth retort is carburizing and cooling DRI. Reducing gas is generated in a steam reformer and must be quenched to remove excess water vapor. Heat is transferred to the cold reducing gas by

Table 4. Comparison of Direct Reduction Processes

Parameter	MIDREX	HYL I	HYL III	SL/RN	FIOR
world production[a],[b] 1993, $t \times 10^6$ (%)	16.0 (67.1)	3.4 (14.2)	2.3 (9.8)	0.7 (3.0)	0.4 (1.5)
reduction vessel	shaft	batch retort	shaft	rotary kiln	fluid bed
reductant source	natural gas	natural gas	natural gas	coal	natural gas
iron oxide form	pellet/lump	pellet/lump	pellet/lump	pellet/lump	sized fines
DRI					
form	pellet/lump or HBI	pellet/lump	pellet/lump or HBI	pellet/lump	HBI
metallization, %	92–95	85–90	90–93	92–93	92–93
carbon content, %	1–2.5	2–2.5	1.5–3	0.2–0.5	1–1.5
reduction					
temperature, °C	760–900	870–1030	850–925	1000–1100	690–780
pressure, kPa[c]	30	253–456	507	0	1115
time, h	4–6	6–9	4–8	8–10	6–7
reformer type	catalytic $H_2O + CO_2$	catalytic steam	catalytic steam	none	catalytic steam
reducing gas H_2/CO ratio	1.5–1.8	5.35	2.25–4.65		9–10
reducing gas $(H_2 + CO)/(H_2O + CO_2)$	11–12	11	4.33–19		12–14
specific productivity[d], $t/(d{\cdot}m^3)$	7–12	1–2	4–12	0.3–0.5	2–3
range unit capacity installed, $t \times 10^6/yr$	0.33–1.0	0.23–0.7	0.25–0.75	0.04–0.18	0.4
consumption per ton of DRI					
iron oxide, t	1.45	1.45	1.45	1.465	1.6–2.0
natural gas, GJ[e]	10	15–21	10–11		15–27
coal, t				0.8[f]	
electricity, kWh	100–130	100	0–100	60–80	250
water, m^3	1.5	2.5	1.8	2–3	2.5

[a] Ref. 1.

[b] Other processes accounted for 1.1×10^6 t or 4.4% of total 1993 world production.

[c] To convert kPa to psig, multiply by 0.145.

[d] Based on reactor volume.

[e] To convert GJ to Btu, multiply by 1.054×10^{12}.

[f] Dolomite [17069-72-6] is also added at a rate of 57 kg/t of DRI.

using it to carburize and cool the DRI in one of the retorts. The gas is quenched after passing through each retort and is reheated by a combination of indirect firing and partial oxidation of residual hydrocarbons to about 1050°C prior to the next stage of reduction. Reducing gas flows downward through the static bed inside the retorts and leaves a reduction gradient through the bed. The product is typically 85 to 90% metallized with 2.0 to 2.5% carbon. An auger is available if necessary to help remove DRI from the retorts.

4.3. HYL III Process

The HYL III process is similar to the MIDREX process, however, it uses a conventional steam reformer and pressurized shaft furnace. As shown in Figure 3, sized iron ore (pellet or lump) is charged via lock hoppers into a pressurized shaft furnace wherein the ore is heated, reduced, carburized, and cooled as it descends by gravity. The upper reduction zone of the shaft furnace is separated from the lower cooling zone by an isobaric zone. The cooled product is discharged via a rotary valve and lock hoppers onto a conveyor belt. In the case of hot briquetting, the cooling gas circuit is eliminated and the hot DRI is discharged through lock hoppers into the hot briquetting units.

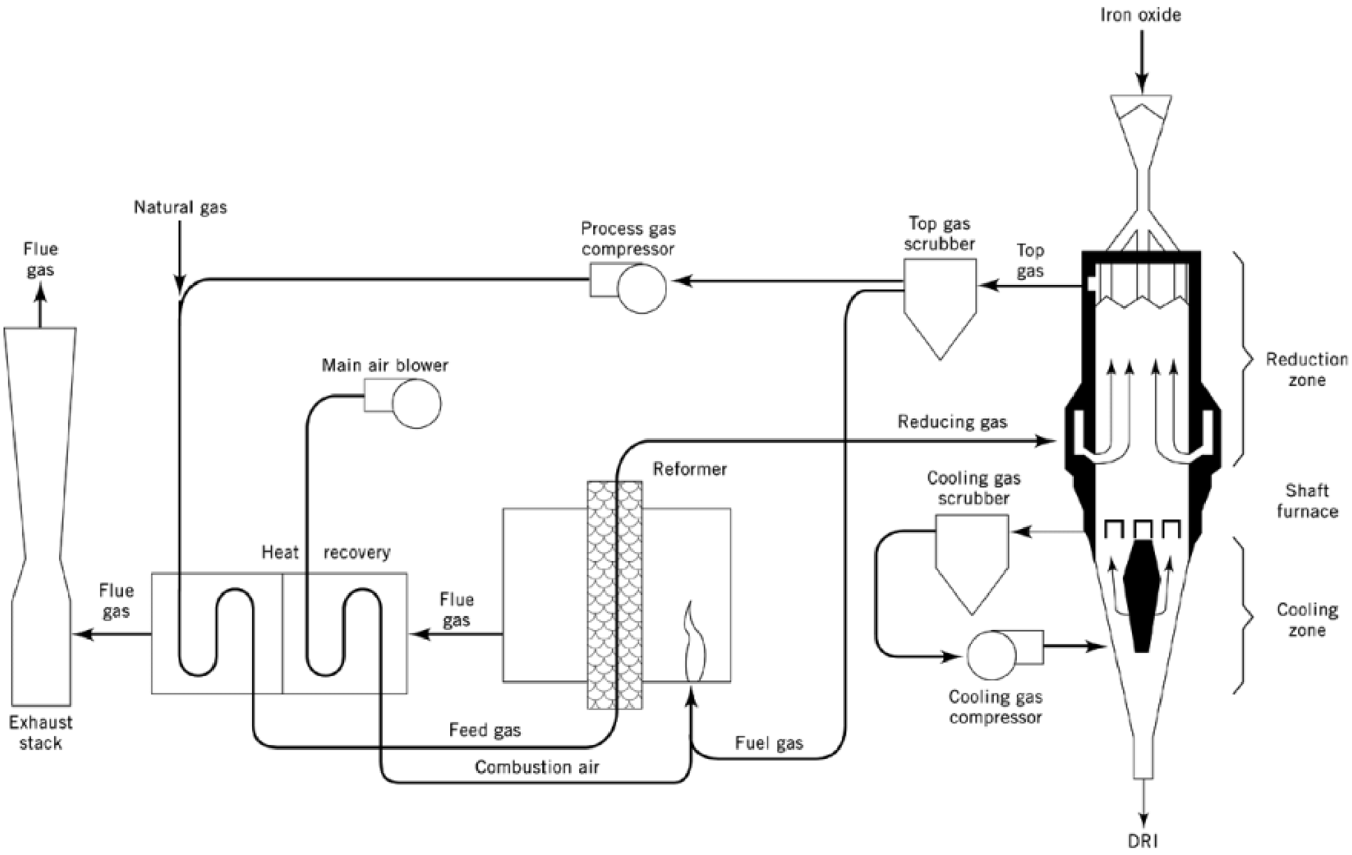

Fig. 1. The MIDREX process.

Fresh reducing gas is generated by reforming natural gas with steam. The natural gas is heated in a recuperator, desulfurized to less than 1 ppm sulfur, mixed with superheated steam, further preheated to 620°C in another recuperator, then reformed in alloy tubes filled with nickel-based catalyst at a temperature of 830°C. The reformed gas is quenched to remove water vapor, mixed with clean recycled top gas from the shaft furnace, reheated to 925°C in an indirect fired heater, and injected into the shaft furnace. For high (above 92%) metallization a CO_2 removal unit is added in the top gas recycle line in order to upgrade the quality of the recycled top gas and reducing gas.

4.4. SL/RN Process

In the SL/RN process (Fig. 4), sized iron ore, coal, and dolomite are fed to the rotary kiln wherein the coal is gasified and the iron ore is reduced. The endothermic heat of reduction and the sensible energy that is required to heat the reactants is provided by combustion of volatiles and carbon monoxide leaving the bed with air introduced into the free space above the bed. The temperature profile in the kiln is controlled by radial air ports in the preheat zone and axial air ports in the reduction zone. Part of the coal is injected through the centerline of the kiln at the discharge end. The hot reduced iron and char is discharged into an indirect rotary drum cooler. The cooled product is screened and magnetically separated to remove char and ash.

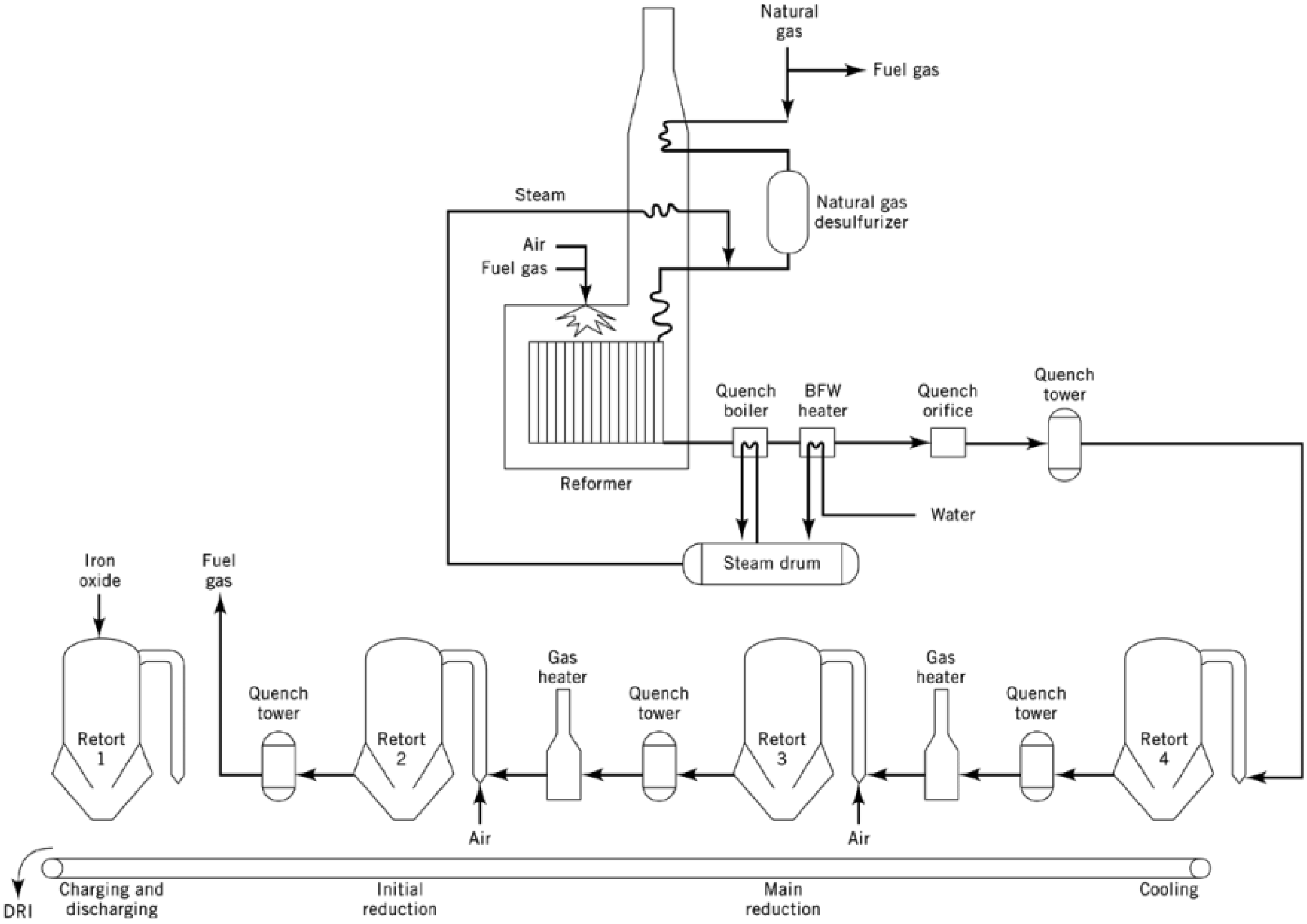

Fig. 2. The HYL I process, where BFW = boiling feed water.

The latest installations incorporate a waste heat boiler in the off-gas cleaning system to recover sensible heat from the rotary kiln off-gas. There is sufficient sensible heat in the off-gas from the SL/RN process to generate 500 to 700 kWh/t of DRI, depending on the type of reductant used.

4.5. FIOR Process

In the FIOR process, shown in Figure 5, sized iron ore fines (0.04–12 mm) are dried in a gas-fired rotary dryer. A skip hoist delivers the dry fines to lock hoppers for pressurizing. The fines pass through four fluidized-bed reactors in series. Reactor 1 preheats the ore to 760°C in a nonreducing atmosphere. Reactors 2, 3, and 4 reduce the ore at 690–780°C. At higher (ca 810°C) temperatures there is a tendency for the beds to defluidize as a result of sticking or bogging of the reduced material.

The hot reduced fines are pneumatically transported to an atmospheric pressure holding drum from which they are fed to the briquetting machines. The hot briquettes are separated, cooled on a circular grate, and delivered to an outdoor storage pile.

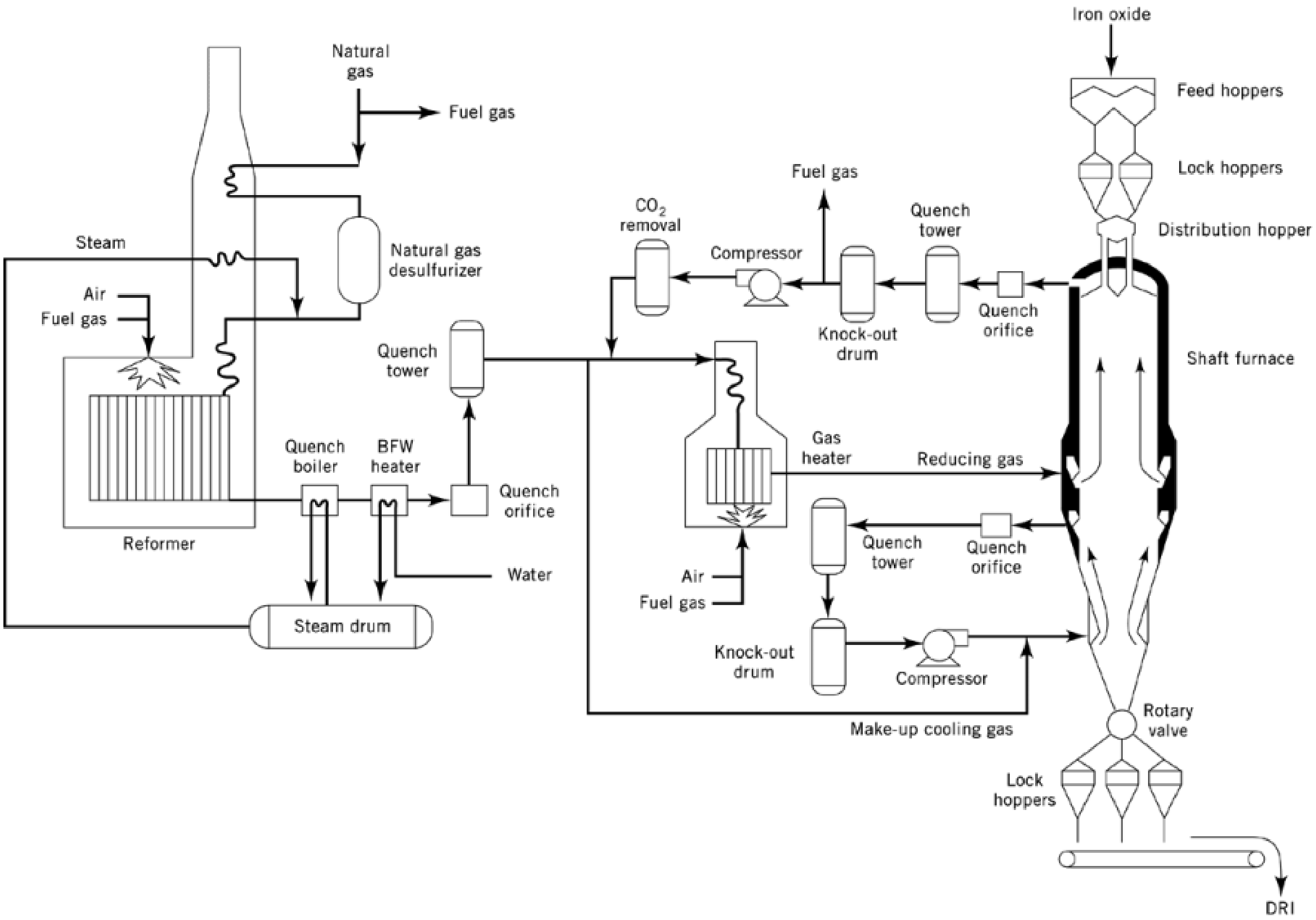

Fig. 3. The HYL III process, where BFW = boiling feed water.

Reducing gas is generated from natural gas in a conventional steam reformer. The natural gas is preheated, desulfurized, mixed with steam, further heated, and reformed in catalyst-filled reformer tubes at 760°C. The reformed gas is cooled to 350°C in a waste heat boiler, passed through a shift converter to increase the H_2 content, mixed with clean recycled top gas, heated to 830°C in an indirect-fired heater, then injected into reactor 4.

The reducing gas is distributed in reactor 4 by an alloy grid, passes through the fluid bed, then exits the reactor via cyclones. The gas passes through reactors 3 and 2 so that a counter flow between gas and solids is established. The spent reducing gas is scrubbed to remove dust and water vapor. Part of the cleaned top gas is recycled and the remainder is used as fuel.

4.6. Other DR Processes

The other DR processes, eg, the CODIR, DRC, ACCAR, and Dav Steel processes, make up 4.4% of worldwide production and mostly consist of coal-based, rotary-kiln processes. All of these are similar to the SL/RN process. In addition, one small coal-based, shaft-furnace plant based on the Kinglor-Metor process is operating.

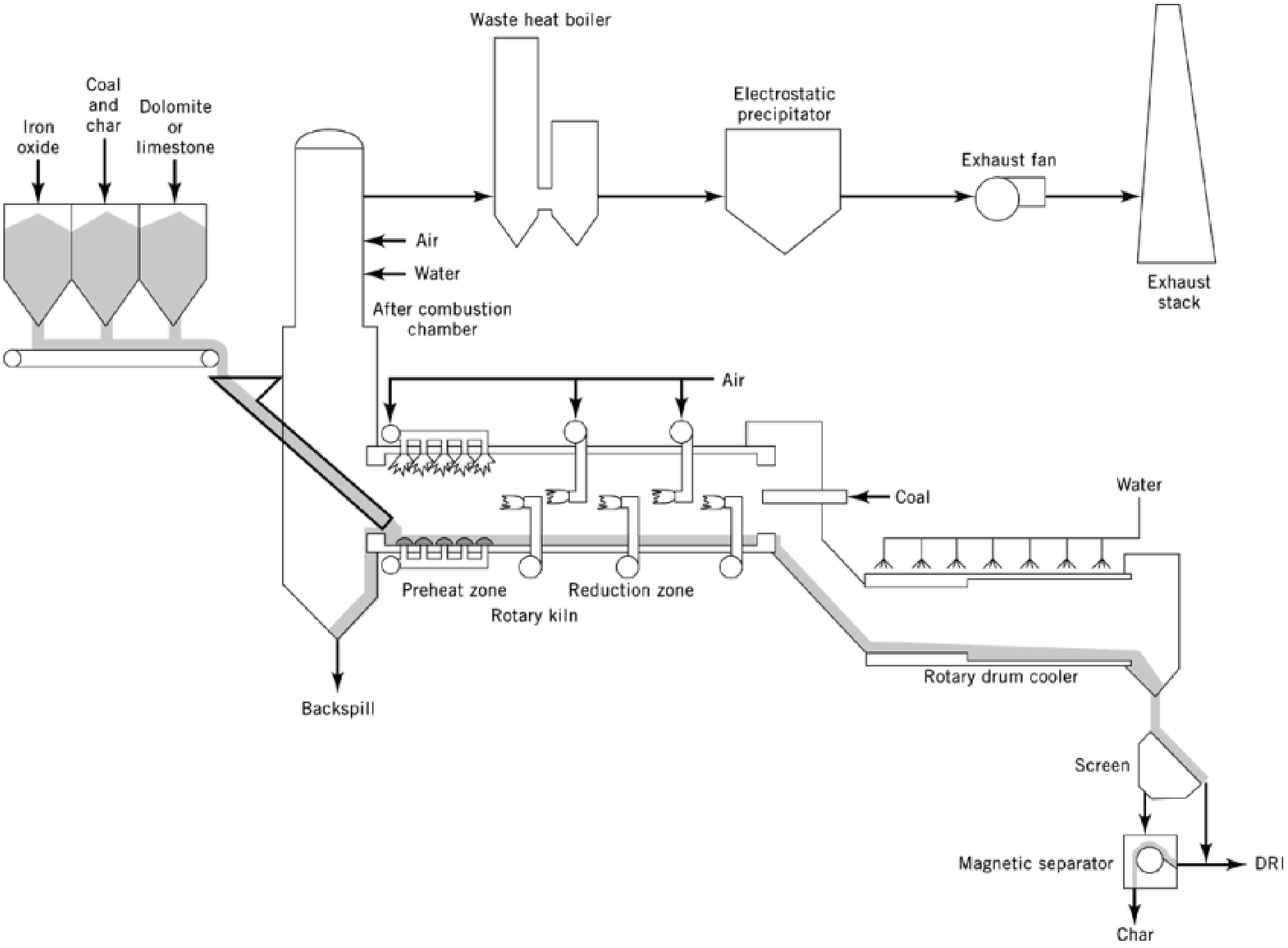

Fig. 4. The SL/RN process.

4.7. DR Processes Under Development

The 1990s have seen continuous evolution of direct reduction technology. Short-term development work is focusing on direct reduction processes that can use lower cost iron oxide fines as a feed material. Use of fines can represent a \$20 – 30/t (20%) savings in DRI production cost compared to use of pellets or lump ore. Some examples of these processes include FASTMET, Iron Carbide, CIRCOFER, and an improved version of the FIOR process.

In the FASTMET process iron oxide fines (minus 0.1 mm), pulverized coal, and binder are mixed together and pelletized. The green pellets are heated in a dryer to remove moisture and fed to a rotary hearth furnace, where the pellets are placed on a flat rotating surface (hearth) in an even layer one to two pellets deep. As the hearth rotates the pellets are heated to 1250–1350°C, and the iron oxide is reduced to metallic iron in 6 to 10 minutes.

The iron carbide process is a low temperature, gas-based, fluidized-bed process. Sized iron oxide fines (0.1–1.0 mm) are preheated in cyclones or a rotary kiln to 500°C and reduced to iron carbide in a single-stage,

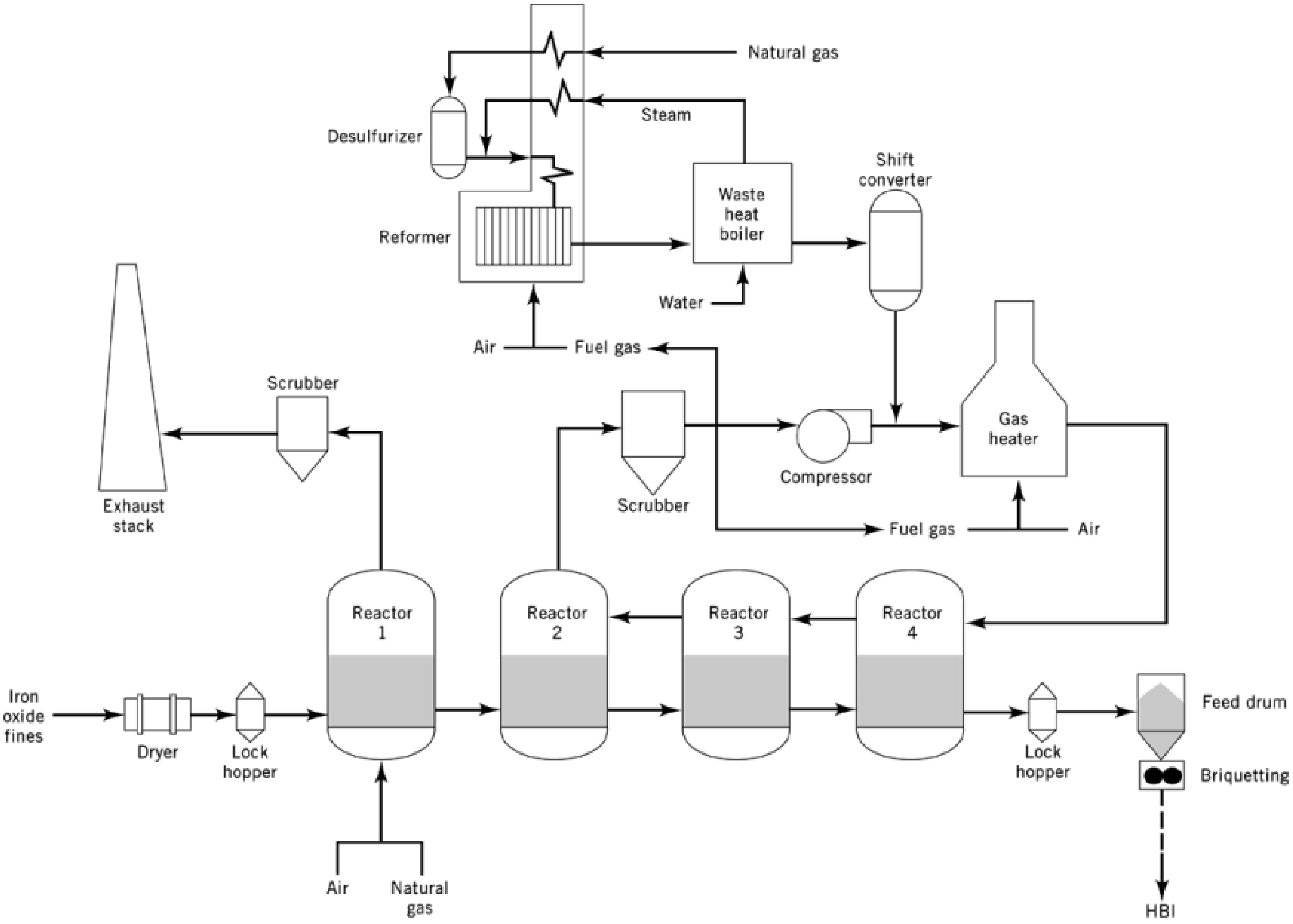

Fig. 5. The FIOR process.

fluidized-bed reactor system at about 590°C in a process gas consisting primarily of methane, hydrogen, and some carbon monoxide. Reduction time is up to 18 hours owing to the low reduction temperature and slow rate of carburization. The product has the consistency of sand, is very brittle, and contains approximately 6% carbon, mostly in the form of Fe_3C.

The CIRCOFER process uses a two-stage fluidized-bed reactor system to gasify coal and reduce iron oxide fines. The coal gasification and initial reduction is performed in a circulating fluidized bed and final reduction occurs in a conventional fluidized bed. The spent reducing gases are recycled after removing water vapor and carbon dioxide. The metallized product is magnetically separated at 700°C prior to hot briquetting.

Long-term development work is focusing on direct smelting technologies. Multimillion dollar development programs are underway in the United States (AISI Direct Ironmaking process), Australia (HIsmelt process), and Japan (DIOS process). A direct smelting process, called the COREX process, already is in commercial operation in South Africa.

5. Handling, Shipping, and Storing

In handling, shipping, and storing DRI, care should be taken to avoid oxidation. Millions of tons of DRI in pellet and lump form have been shipped by barge, ocean vessel, truck, and rail. The key to avoiding oxidation is simply to keep the material cool and dry. The chemical reactions involved have been well documented. In general, oxidation of DRI takes place in two forms: reoxidation and corrosion (2).

Reoxidation occurs when the metallic iron in hot DRI reacts with oxygen in the air to form either Fe_3O_4 or Fe_2O_3. The reaction continues as long as the DRI remains hot and sufficient oxygen is available. Because reoxidation reactions are exothermic and DRI is a good insulator, it is possible that once reoxidation begins inside a pile, the DRI temperature increases and accelerates the reoxidation rate. Although the inner core of the pile may reach temperatures up to the fusion point of iron, the maximum temperature of the outer parts of the pile will be much lower because of heat dissipation.

Corrosion occurs when the metallic iron in DRI is wetted with fresh or salt water and reacts with oxygen from air to form rust, $Fe(OH)_3$. The corrosion reactions continue as long as water is present. Because water evaporates at approximately 100°C, corrosion reactions have a low temperature limit even though the reactions are exothermic. Small amounts of hydrogen may be generated when DRI reacts with water. However, this poses no safety problem as long as proper ventilation is provided.

Allowing DRI to become wet does not necessarily cause it to overheat. When large piles of DRI are wetted with rain, the corrosion reactions are limited to the outer surface area of the pile and the resultant heat from the corrosion reactions is dissipated into the atmosphere. However, if water penetrates into the pile from the bottom, or if wet DRI is covered with dry DRI, the heat from corrosion reactions can build up inside the pile to the point where rapid reoxidation begins. Corrosion occurs significantly faster with salt water than with fresh water. DRI saturated with water can cause steam explosions if it is batch charged into an electric arc furnace.

In comparison, HBI is almost twice as dense as DRI, and thus does not absorb as much water and is much more resistant to reoxidation and corrosion. Several methods of passivating DRI to make it more resistant to reoxidation and corrosion have been developed, but none has been as effective as hot briquetting. Guidelines for offshore shipping of pellet/lump DRI and HBI have been prepared by the International Maritime Organization.

6. Economic Aspects

The demand for DRI varies depending on local market conditions. In industrialized countries, DRI primarily is used as a supplement to scrap for controlling residual elements in electric arc furnace steelmaking. In regions where scrap is scarce, DRI is used as a replacement in production of all grades of steel. In 1993, Latin America produced 9.4×10^6 t (39.3%) of the world's DRI. Middle East/North Africa produced 6.1×10^6 t (25.6%), Asia/Oceania produced 4.4×10^6 t (18.4%), and CIS/Eastern Europe produced 1.7×10^6 t (7.1%). North America produced 1.2×10^6 t (5.0%); Africa, 0.9×10^6 t (3.8%); and Western Europe, 0.2×10^6 t (0.8%) (1). Nearly 79% of the DRI produced is consumed in steel mills adjacent to the DR plants called captive plants. Plants which are designed to sell and ship DRI on the open market are called merchant plants.

Worldwide production of DRI has increased steadily since 1970, when 7.3×10^5 t were produced, except for a slight dip in 1982 owing to a steel industry recession. By 1985 production had risen to 11.16×10^6 t and in 1990 to 17.89×10^6 t. Projections indicate production of 35×10^6 t of DRI in the year 2000 (1).

Total merchant shipments of DRI and HBI in 1993 reached 5.1×10^6 t. The primary DRI exporting countries were Venezuela, Russia, Malaysia, Trinidad, and India. The price of merchant HBI in 1993 was in the range of \$125 to \$167/t on a delivered basis. Although there are expectations that the value of merchant DRI should some day stand on its own, the historic price has been tied to the price of ferrous scrap. A general rule of thumb has been that the value of merchant DRI is comparable to prime scrap (No. 1 Bundles or No. 1

Bushelings) in industrial countries, and comparable to imported shredded scrap in developing countries (see RECYCLING, FERROUS METALS).

7. Uses

Over 95% of the world's DRI production is consumed in electric arc furnace steelmaking. The remaining 5% is split among blast furnaces, oxygen steelmaking, foundries, and ladle metallurgy (qv) facilities.

The primary use of DRI is as a clean supplement or replacement for the ferrous scrap charge in high quality-oriented electric arc furnace (EAF) steelmaking. By controlling the level of residual elements in the charge, steelmakers can upgrade their product mix and reduce off-grade heats. Also, a low level of residual elements in carbon steel changes its physical properties for the better.

The desired portion of DRI used in the charge depends on economics, the type of steel being produced, and the available scrap quality. When DRI represents over 35% of the charge, it is preferable to feed it continuously through the roof of the EAF. Continuous charging can eliminate the need for back charging, thus improving productivity and energy efficiency. Most EAF steelmakers purchasing DRI on the open market use 10 to 30% DRI in the charge and do not have continuous charging systems installed in the melt shops. In this case, the DRI is batch charged along with scrap using existing scrap handling equipment and practices.

DRI, in pellet/lump or HBI form, can be added to the blast furnace burden to increase furnace productivity and reduce coke requirements. It can be used for short-term increases in blast furnace output when a facility is short of hot metal during times of high steel demand, or when one of several blast furnaces is down for a reline. It also can be justified if the increased output is sufficient to allow operation of fewer blast furnaces long-term.

HBI is used as a trim coolant or scrap replacement in oxygen steelmaking. In the oxygen steelmaking process, the molten steel often is overheated. Trim coolant is fed to the furnace to cool the molten steel to the desired temperature. HBI is preferred for this application because its high density ensures an effective slag penetration and complete melting in the molten steel bath. Steel yield is increased when HBI is used as a trim coolant instead of iron ore. Also, the violent reactions that can occur when using iron ore are eliminated. The relative cooling effect of various materials are as follows: scrap 1.0, HBI 1.2, and iron ore 2.0–3.0.

HBI is an effective trim coolant for molten steel in ladle metallurgy facilities, ladle refiners, ladle furnaces, and vacuum degassers. It provides cold iron units in an ideal size and density for penetrating the ladle slag and cooling the metal.

HBI has been successfully melted in cupolas (hot or cold blast), induction furnaces (coreless or channel), and electric arc furnaces. It can be a valuable charge material for ductile and malleable irons as well as steel. It is of particular value in making ductile iron castings because of its very low residual element content.

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