CHAPTER 6

Iron Making

The National Steel Policy (revised 2008), envisages domestic steel production of the country to be 180 million tonnes per annum by 2019-20. The situation calls for proportionate development and expansion in the iron making facilities and adequate raw material supply to meet the demand of the Indian Steel Industry.

Iron ore is the basic raw material for production of metallic iron. Of the total domestic consumption of iron ore, about 98% accounts for pig iron and sponge iron industries. Lumpy iron ore (-30+10 mm) and agglomerates like sinter & pellets form the feed for the production of pig iron in blast furnace, whereas steel scrap, lumpy iron ore (-18+6 mm) or pellets are the feed for sponge iron production.

The blast furnace has remained the traditional route & would continue to dominate iron making in India. However, in view of the high investments, limited availability of metallurgical coke, and negative environmental issues associated, there is an increasingly growing awareness that the blast furnace route needs to be supplemented with alternative iron making processes.

Over the past two decades, alternative technology to produce solid iron in the form of sponge iron also referred to as Direct reduced iron (DRI), based both on coal and gas as well as to produce hot metal (liquid) without using high-grade coke via reduction smelting

(SR) route have played a significant role in iron making technology in India. It is pertinent to note that today India is the largest producer of DRI (sponge iron) in the world.

The NSP assumes that 60% of the new steel capacity would come up through blast furnace route, 33% through sponge iron & EAF/IF route and 7% through other routes.

Iron making processes can be broadly classified/categorised into:

1. Conventional Blast furnace/mini Blast furnace

2. Alternative Processes

(I) Solid iron Sponge/ DRI Iron	**(a) Coal-based**	**Rotary Kiln**	**Krupp Rein, ACCAR, DRC etc**
		Rotary Hearth	**Fastmet etc.,**
	(b) Natural gas-based	**Shaft furnaces,**	**Midrex,**
		Fluidised beds or Retorts,	**HYL-III etc.,**
(ii) Liquid Iron Smelting Reduction (SR)		**Corex, Romelt, HIsmelt & ITmK3 etc.,**	

Smelting is a process or a combination of processes to produce molten metal. Smelting of iron in the blast furnace is an example of reduction smelting in which coke serves both as a fuel and as a source of reducing agent. In presence of an excess of carbon monoxide, iron oxide can be completely reduced at about 900°C but the melting point of the metal is 1535°C. Hence, the iron produced in primitive furnace was always solid and contained little carbon and was soft and malleable in nature. Our present-day operations for the manufacture of sponge iron are simply refinements of the primitive iron smelting operation.

Iron ore specification required by major Integrated Steel Plants (2008-09) in the country is presented in Table-11.

In '000 tonnes

	Iron Ore Consumption			
Steel Plant	**Blast Furnace**		**Steel Melting Shop (SMS)**	**Specifications**
	Lumps	Fines*		
Bokaro Steel Plant, Bokaro, Jharkhand	2107	4287	-	Lumps: Fe 63.46%, SiO_2 2.56%, Al_2O_3 2.22%. Size: 10 to 40mm. Fines: Fe 61.87%, SiO_2 3.4%, Al_2O_3 2.72% Size: -10 mm.
Bhilai Steel Plant, Bhilai, Chhattisgarh	3109	5395	40	BF : Fe-64% (min.), Size: 10 to 40mm Sinters : Fe 62.6% (min.), Size: -10 mm
Rourkela Steel Plant Rourkela, Orissa	1062	2598	21	Lumps : Fe 63.23%, SiO_2 1.69%, Al_2O_3 3.01%, Size-10 to 50 mm, Fines: Fe 62.83%, SiO_2 2.48%, Al_2O_3 3.04%, Size: -10 mm
Durgapur Steel Plant, Durgapur, West Bengal	1060	2278	10	Lump : Fe >63%, Size-10 to 50 mm, Fines : Fe > 63%, mm Size: -10
IISCO Steel Plant, Burnpur, West Bengal	NA	1246	15	Lumps : Fe 62.0 to 63.3%, SiO_2 2.5%, Al_2O_3 4.5% (max.). Size: 8 to 10 mm
Visvesvaraya Iron & Steel Ltd Bhadravati Karnataka	273	NA	NA	Fe 62–63%, SiO_2 1–2%, Al_2O_3 1–2%, Size 10 to 30 mm
Visakhapatnam Steel Plant, Visakhapatnam, Andhra Pradesh	1439	3718	NA	Lumps: Fe 66.9%, Al_2O_3 1.60%, SiO_2 0.9%. Size: 10 to 25 mm for BF, Fines : Fe 63.07%, Al_2O_3 3.5%, SiO_2 2%, Size: -10 mm
Tata Steel Ltd, Jamshedpur, Jharkhand	3047	6091	263	NA
IDCOL, Kalinga Iron Works, Barbil, Dist. Keonjhar, Orissa	NA	NA	NA	Fe 65% $SiO_2 + Al_2O_3$ 5% max., Size: 10 to 30 mm.
Visa Steel Ltd. Kalinga Nagar, Dist. Jajpur, Orissa	150	-	-	Fe + 62%, Size 10 to 40 mm in BF & Fe +62% , Size 10–18 mm in DRI
Neelachal Ispat Nigam Ltd, Dist. Jajpur, Orissa	210	633	-	Lumps : Fe 65% (min.), Size: -40+10 mm , Fe 63% (min.), Size: -10 mm

**Sinters & Pellets*

Table-11: Consumption and Specifications of Iron Ore by Integrated Steel Plants (2008-09)

6.1 BLAST FURNACE

The iron making blast furnace is a circular shaft furnace with about 30 m high with a maximum internal diameter of about 10 m. The furnace is a refractory-lined steel shell and practically all the refractory material is fireclay brick. The brick used in the hearth and crucible is the best quality fireclay brick-hard dense super duty material. Some furnace linings are made of carbon blocks. The thickness of refractory brick layer is about 1m in the bosh and 1–2 m in the upper part of the shaft. The bottom of crucible is built of high grade fireclay brick with closely fitting joints to prevent molten metal from seeping through and floating up the bottom, 2–4 m thick. Just below the bosh there are 10 to 16 equally spaced tuyeres along with circumference through which the pre-heated air (at 1000–1100 ^{0}C) enters the furnace at a pressure of 2kg/sq.cm. The bosh is the portion of the furnace between the mantle and the upper part of the crucible; it is the smelting zone, the hottest part of the furnace (1900–2000 ^{0}C). As the hot reducing gas travels upwards, it heats up the solid charges as well as participates in various reactions at different zones of the furnace.

Below the bosh is the hearth or crucible where the molten metal and slag collect. Near the bottom of the hearth is the tap hole through which the molten iron is removed and about 1.5 m above the tap hole is the cinder notch through which the molten slag or cinder is withdrawn. The cross-section showing the construction of the modern iron blast furnace is presented in Fig-49.

The top of the furnace is sealed by means of a double bell and hopper which permits the solid material to be charged without allowing the furnace gases to escape to the atmosphere. The charge is dumped from the skip on the upper bell, and the bell is then lowered to permit the charge to drop on the lower bell; the lower bell is dropped while the upper bell is closed, so that at least one of the bells is always closed to prevent escape of the gases. The top offtake gas is known as blast furnace gas. It has a considerable fuel value since it contains lot of CO; the gas is de-dusted and used for pre-heating of air & running turbines to drive air blowers.

Modern blast furnace runs continuously day and night for some three to seven years and thereafter the furnace must be shut down for repairs.

Charge : Lumpy iron ore (10/40 mm), in the form of hematite or magnetite or iron oxide in the form of pellets and sinters, flux and metallurgical coke form the charge to the blast furnace. The physical nature of the solid material and lateral distribution of the charge are of great importance – fundamentally the action of the iron blast furnace (or any shaft furnace) involves the chemical reaction between the solid charge and the rising column of gas in the furnace. The charge must, therefore, be uniformly porous to permit a uniform flow of gas through the interstices.

A blast furnace cannot be charged with all fine material because a good deal of it would be blown out by the gas current, and part of it would pack in such a way as to cause the gases to channel and leave portions of the charge cold and un-smelted.

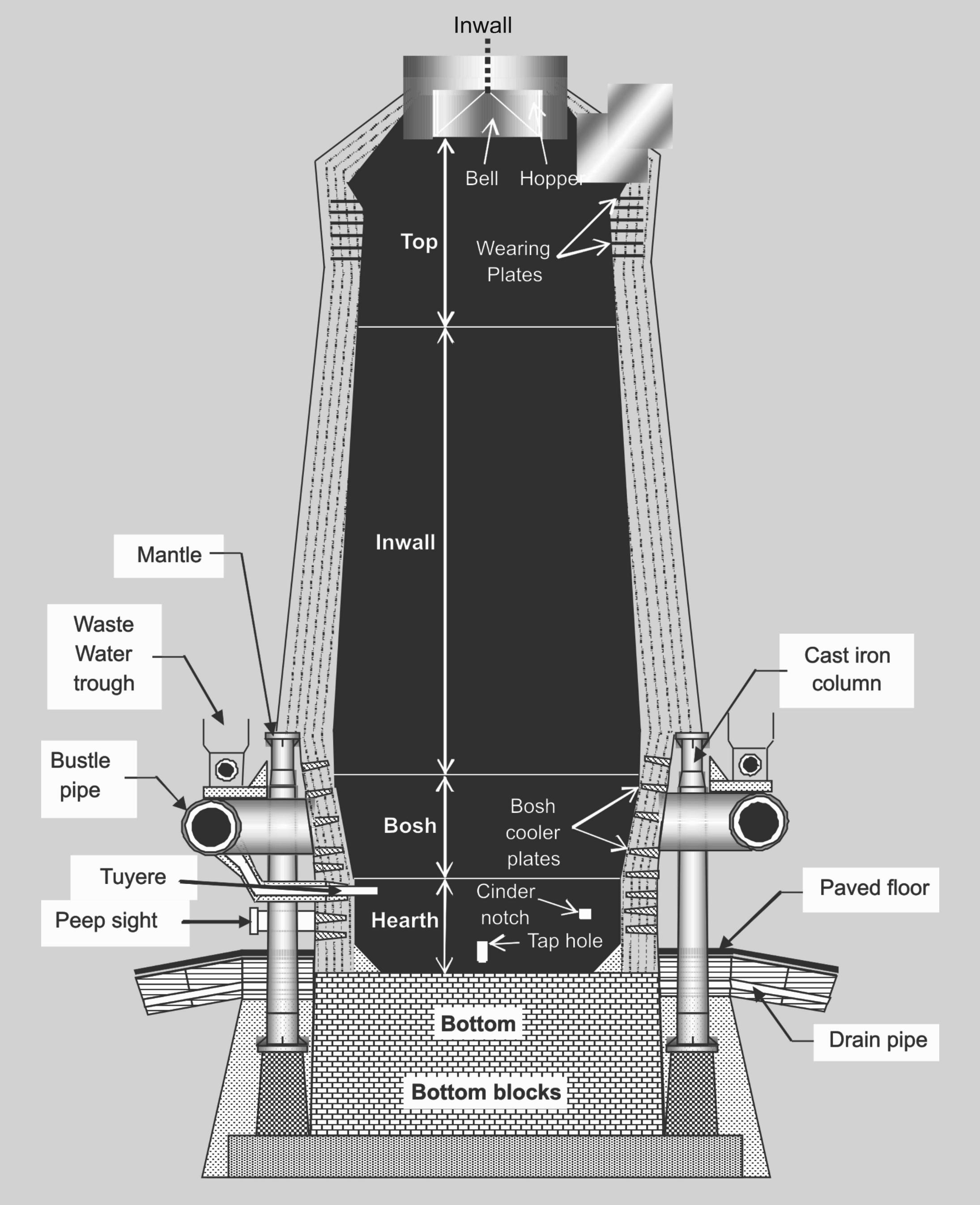
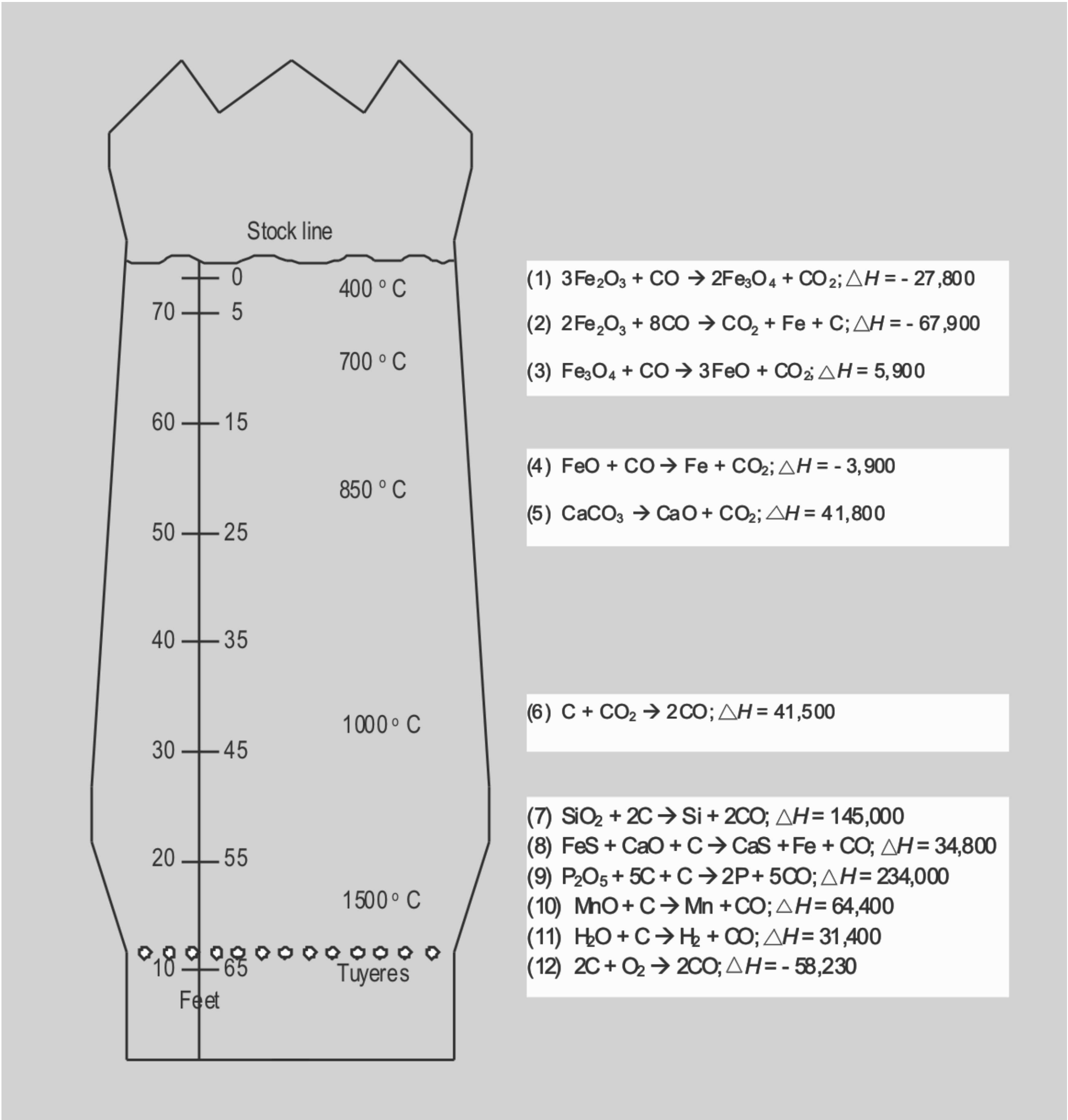


Fig-49: Cross-section Showing the Construction of the Modern Iron Blast Furnace

Smelting Action : The iron blast furnace operates on a counter-current principle; the charge moves slowly down in the furnace shaft and the current of gas that reacts with the charge moves upward. This operation is reduction smelting. The furnace has two functions to perform (1) to reduce the oxides of iron to the metallic state, and (2) to fuse the entire mass to form molten metal and liquid slag.

Fig-50 is a schematic drawing to indicate the temperature at various points in the charge column and some of the chemical reactions that take place.



(1) $3Fe_2O_3 + CO \rightarrow 2Fe_3O_4 + CO_2; \triangle H = -27,800$

(2) $2Fe_2O_3 + 8CO \rightarrow CO_2 + Fe + C; \triangle H = -67,900$

(3) $Fe_3O_4 + CO \rightarrow 3FeO + CO_2; \triangle H = 5,900$

(4) $FeO + CO \rightarrow Fe + CO_2; \triangle H = -3,900$

(5) $CaCO_3 \rightarrow CaO + CO_2; \triangle H = 41,800$

(6) $C + CO_2 \rightarrow 2CO; \triangle H = 41,500$

(7) $SiO_2 + 2C \rightarrow Si + 2CO; \triangle H = 145,000$

(8) $FeS + CaO + C \rightarrow CaS + Fe + CO; \triangle H = 34,800$

(9) $P_2O_5 + 5C + C \rightarrow 2P + 5CO; \triangle H = 234,000$

(10) $MnO + C \rightarrow Mn + CO; \triangle H = 64,400$

(11) $H_2O + C \rightarrow H_2 + CO; \triangle H = 31,400$

(12) $2C + O_2 \rightarrow 2CO; \triangle H = -58,230$

Fig-50: Different Temperature Zones and Chemical Reactions in the Blast Furnace

The coke passes down the column practically unchanged until it reaches the level of the tuyeres, where it burns to form carbon monoxide (Equation 12) with the liberation of a large amount of heat. This combustion zone is the hottest portion of the furnace, and the temperature attained is greater than what would be calculated from the heat of reaction (Equation 12) because both the coke and air are preheated; the air comes directly from the hot-blast stoves, and the coke becomes progressively hotter as it moves down the stack. The gaseous products of combination contain about 35% CO and 65% N_2 by volume, and this very hot reducing gas sweeps up through the charge column. Any moisture in the air will be decomposed by carbon (Equation 11), and this strongly endothermic reaction will lower the temperature in the combustion zone.

As the gases pass upward, their sensible heat is absorbed by the colder solid material and hence resulting in an endothermic chemical reaction taking place; by the time the gases reach the stock line they are quite cool at about 180 °C.

The reduction of the iron oxides Fe_2O_3 begins almost as soon as it enters the furnace. They are generally reduced in stages – first to Fe_3O_4, then to FeO and finally to metallic iron. By the time the charge has reached a point about 5 to 6 meters below the stock line where the temperature is above 750 °C, all the oxides get reduced to spongy metallic iron. Limestone begins to decompose at about 800 °C (Equation 5) and it would be completely decomposed at 1000 °C. By the time the charge reaches the upper portion of the bosh it consists of particles of sponge iron and the slag-forming oxides – CaO, SiO_2, MnO, Al_2O_3 etc.

The principal reducing agent is the CO in the gas, and Equation (1) through (4) in Fig. 50 indicates that the iron oxides are reduced by CO. The coke itself has practically no reducing action in the upper part of the furnace. At high temperatures carbon dioxide oxidises carbon (Equation 6) and CO_2 cannot exist above 1000 °C in the presence of free carbon; CO therefore, cannot act as a reducing agent in the lower part of the furnace, without being oxidised to CO_2. Refer Equations (7) through (12) in Fig. 50 the reducing agent is carbon and CO is formed.

The sponge iron in the upper part of this furnace absorbs some carbon, and as the iron melts and trickles down over the incandescent coke, it dissolves carbon until it is practically saturated. In the smelting zone the more refractory oxides are reduced by hot carbon – SiO_2, P_2O_5 and MnO_2 as indicated by Equations (7) (9) and (10) in Fig. 50 – in this same region (Equation 8) some of the sulphur is converted from FeS to CaS. The reduced elements pass into the iron and the oxidised elements dissolve in the slag.

The iron will therefore contain dissolved C, Si, Mn, S and P; the slag will contain CaO, CaS, SiO_2, Al_2O_3, MgO and some MnO (Sulphur in the form of FeS is soluble in the iron but CaS will dissolve in the slag). The composition of the pig iron can be regulated to a certain extent by increasing or decreasing the amount of fuel and hence regulating the temperature of the smelting zone. High temperatures promote the reactions shown in Equation (7) through (10) and therefore, the iron from a "hot" furnace is comparatively high in silica and manganese and low in sulphur. All the phosphorus in the charge will be reduced and enter the iron; most of the manganese will be reduced, but only a small part of the silica will be reduced to elemental silicon.

Air : About 4 tonnes of air is required per tonne o iron.

Pig Iron: The molten iron tapped from the blast furnace is called pig iron. The composition of this alloy will be Fe 90–95%, C 3.5–4.5%, Mn 0.5–0.8%, Si 0.7–3.5%, S 0.02–0.12% and P 0.10–0.90%.

Iron and slag are collected continuously in the crucible and are tapped at regular intervals 4-5 times a day.

Slag: The composition of blast furnace slag would be SiO_2 30–35%, CaO 35–40%, Al_2O_3 10–15%, MgO 2–10%, Mn 0.1–1.2%, Fe 0.2 – 0.4% and S 1.0 –2.0%.

Furnace Gases: The gases leaving the top of the charge will contain CO_2 14–16%, CO 23–25%, H_2 3–5% and N_2 56–57%.

Alternative Processes

In the alternate process two different physical forms of iron are produced i.e., solid iron (sponge iron or DRI) and liquid iron (smelting reduction). During direct reduction of iron oxide to sponge iron, almost the entire amount (never the total) of oxygen present in the iron oxide is removed in the solid state. As a result the final product has a high degree of metallisation. Whereas those processes which utilise oxygen & non-coking coal to produce liquid iron (hot metal) deploying a combination of direct reduction & smelting of iron oxides in various forms. Some of the useful and commercial Alternate Process of Iron Making is presented in Table-12.

Table-12: Alternate Process of Iron Making

Processes	Unit Operations	Type of Reactor Used	Process Step	Combustion Medium Used	Reductant	Ore Form	Product	Applicability in Indian Scenario
Corex	Pre reduction in shaft furnace followed by melting in melter-gasifier.	Shaft	Multi step	Reformed Natural gas & non-coking coal & partially coke	Coal lump, CO & H_2	Lump (40%) & pellets (60%)	liquid	Jindal
Romelt	Rectangular shape, Single reactor, single stage process	Non Shaft	Single Step	Reformed Natural gas & non-coking coal & partially coke	Coal (Indigenous & imported at the ratio of 1:1.	Lumps, fines & waste iron oxides generated in integrated steel plants & iron ore slimes	liquid	NMDC, Jagdalpur
Midrex	Continuous counter current shaft reactor.	Shaft	Single Step	Reformed Natural gas	Non-coking Coal, CO & H_2	Lumpy ore & pellet (40:60)	Sponge	ESSAR, Vizag
Hismelt	Pre-reduction up to FeO stage in circulating fluidised bed followed by melter-gasifier	Non Shaft	Multi Step	Reformed Natural gas	Imported Non-coking coal (-6 mm)	Iron oxide (-6 mm) of various types including steel plant waste Non-coking coal (-6mm) & fluxes & slimes from iron ore mines.	liquid	
Fastmet	Pre-reduction in rotary health furnace (RHF) to produce DRI /HBI	Rotary Hearth	Single Step	Fuel Gas, oil or pulverised Coal	Coal fines & carbonaceous matter	Iron oxide, concentrate fines & coal fines are made into Composite Pellet	Sponge	
Itmk^3	Green composite pellets of iron oxide & coal heated to 1350–1500 ^{0}C in RHF. Partial melting helps *in situ* slag separation.	Rotary Hearth	Single Step	Pre-heated air	Coal fines	Pellet grade iron ore fines, coal & fluxes are made into composite pellet	iron nuggets	SAIL Durgapur Plant modernisation

- **Reformed Natural Gas:** Steam oxygen mixture is used to reform the natural gas in presence of a nickel catalyst at about 700 ^{0}C to generate CO & H_2 which is used as a reducer.
- **Composite Pellet:** is prepared by mixing of iron oxide in various forms, iron ore fines with coke, coal & carbonaceous reductant and made it to pellets with binder

6.2. SPONGE IRON MAKING PROCESSES (SOLID IRON/ DRI)

Iron produced as a solid by the reduction of iron oxide is known as sponge iron. It is also referred to as direct reduced iron (DRI). It is often compacted to reduce the porosity and to convert into hot briquetted iron (HBI) for storage or sale. Direct reduction (DR) includes a family of processes in which iron ore (in the form of lumps or pellets) is reduced to the solid-state either by solid or gaseous reducing agent. Reformed natural gas or non-coking coal is generally employed as the reductant as well as the primary source of energy. The final product from all DR processes is a solid, which has to be melted during steel making in a manner similar to scrap. For coal-based DR, rotary kilns, rotary hearth furnaces and multi-hearth furnaces are employed, while for gas-based processes, the reactors used are shaft furnaces, fluidised beds, or retorts. Globally the natural gas is a preferred reductant for producing sponge iron. In India, however, coal-based rotary kiln processes are more popular because of restricted and localised availability of natural gas. Specifications of iron ore consumed by major sponge iron plants in the country are presented in Table-13.

Sl. No.	Name of the Plant	Specifications				
		Size	Fe	$Al_2O_3 + SiO_2$	P (max.)	S
1	**Orissa Sponge Iron Plant**	5–18 mm	65% min.	4.5% max.	0.03%	N. A.
2	**Vikram Ispat**	9–16 mm	66%	2.6% max.	0.05%	0.01%
3	**HEG Ltd**	5–18 mm	65% min.	5% max.	0.05%	0.03%
4	**Sunflag Iron & Steel Ltd**	5–20 mm	67.5%		-	--
5	**Sponge Iron India Ltd**	6–20 mm	55–58% & 64–66%	-	-	-
6	**Essar Steel Ltd**	10–40 mm	67%	2.60% max.	0.05%	0.01%
7	**Jindal Steel & Power Ltd**	10–30 mm	65% min.	3% max. (SiO_2)	0.05%	-
8	**Tata Sponge Iron Ltd**	5–18 mm	65% min.	5% max.	-	-
9	**GSAL India Ltd**	10–40 mm	62%	-	-	-
10	**Raipur Alloys & Steel Ltd**	5–18 mm	65–66%	-	-	-
11	**OCL India Ltd**	Sized	62% min.	-	-	-
12	**Nalwa Steel & Power Ltd**	5–20 mm	63% min.	-	-	-
13	**Shri Bajrang Power & Ispat Ltd**	5–18 mm	64% min.	-	-	-
14	**Jai Balaji Industries Ltd**	5–18 mm 10–30 mm 10–150 mm	65%	5%	0.05%	0.03%

Table-13: Specifications of Iron Ore Consumed by Major Sponge Iron Plants

6.2.1 Coal-based Sponge Iron Processes

In these processes, the reductant is coal. Sponge iron making is the process of removing oxygen from the ore under controlled parameters. This is done in a rotary kiln followed by a rotary cooler. The process is most suitable for Indian raw material of high-grade iron ore and non-coking coal. The carbon monoxide gas has the affinity for oxygen thereby it reacts with oxygen of iron oxide to form carbon dioxide and gets released. The carbon dioxide again reacts with the carbon from coal to form carbon monoxide and the reaction continues.

To sustain this reaction continuously CO is maintained higher to CO_2 inside the kiln by controlling the air supply to the system. The iron ore in its hematite state gets converted to metallic state by losing its oxygen as below :

Constituent Composition	Hematite Fe_2O_3	Magnetite Fe_3O_4	Wustite FeO	Metallic Iron Fe
% Fe	69.9	72.4	77.7	100.0
% Oxygen	30.1	27.6	22.3	0.0

Process Technology: A simplified flow diagram of sponge iron making in rotary kilns is given in Fig-51. In all coal-based DR processes using rotary kilns, sized lumps iron ore (or pellets) and a relatively coarse fraction of non-coking coal are fed into the kiln from the feed inlet end. Coal not only acts as a reducing agent, but it also supplies the heat required for maintaining the temperature profile of the charge within the kiln. A finer fraction of coal is introduced from the discharge end of the kiln to help complete the reduction, since by the time the charge travels to around 70% of the length of the kiln, very little coarse coal is available to complete the last stages of reduction.

All rotary kiln-based DR processes operate on the countercurrent principle i.e. the gases move in a direction opposite to the flow of solids. Various unit operations and unit processes like transport, mixing, charge separation by size, heating, gas generation, and reduction occur both in parallel as well as in series. Segregation of the charge materials (ore, coal, flux) on account of size and density differences, as well as because of the slope and rotation of the kiln, has to be prevented to the extent possible, by adopting the appropriate kiln design and through proper operating measures.

The temperature of the charge bed inside the kiln has to be confined to a maximum of around 950–1050 °C so that the ash in coal does not fuse, and the entire charge remains strictly in the solid state. High reactivity of coal encourages reaction of CO_2 in the gas phase with solid carbon in the bed resulting in the formation of CO. Since this is a highly endothermic reaction, high reactivity automatically ensures that the gas temperature does not exceed the solid bed temperature by more than the stipulated limit of 150 °C maximum. A flux (like limestone or dolomite) has to be added along with coal so that CaO forms CaS by reaction with sulphur, thereby controlling the sulphur in sponge iron.

The product discharged from the kiln is cooled to room temperature in an indirectly cooled rotary cooler. No water normally comes in direct contact with the reduced product in the cooler and, therefore, there is very little chance of re-oxidation. Since sponge iron is magnetic in nature, it can be easily separated from the non-magnetic portion of the cooler discharge, consisting mainly of coal ash (or char), by using magnetic separators.

The most critical part of rotary kiln reduction is the controlled combustion of coal and its conversion to carbon monoxide.This conversion is also aided by controlled introduction of air from the discharge end of the kiln as well as through blowers mounted on the kiln shell, which rotate with the kiln and supply air to the secondary air pipes protruding up to the centre line of the kiln. The shell-mounted blower and the secondary air pipe assembly, thus provide air at several locations in the space above the charge bed, axially along the kiln length.

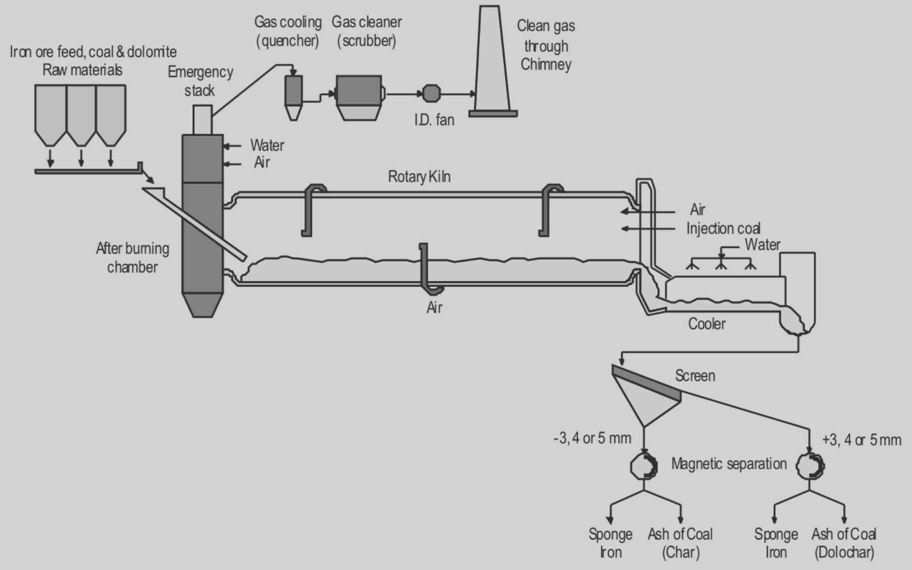


Fig-51: Flow Diagram of Sponge Iron Making in a Rotary Kiln

Reaction Mechanism : There are two major temperature zones in the kiln. The first preheat zone is where the charge is heated to 900–1000 ˚C. The second metallisation zone is held fairly constant at 1000–1050 ˚C.

In the pre-heat zone, the reduction of iron oxide proceeds only to ferrous oxide (FeO): $Fe_2O_3 + CO = 2\ FeO + CO_2$ .... (I)

Final reduction to metallic iron occurs in the metallisation zone by reaction of CO with FeO to form CO_2 and metallic iron. $FeO + CO = Fe + CO_2$ .... (II)

The CO_2 reacts with the excess solid fuel in the kiln and is converted to CO according to the Boudouard reaction. $CO_2 + C = 2\ CO$ .... (III)

Coals with higher reactivity are preferred as they provide rapid conversion of CO_2 to CO, thereby maintaining reducing conditions in the kiln metallisation zone. The highly endothermic reaction of coal with CO_2 prevents the bed from overheating and attaining high temperature that could lead to melting or sticking of the charge.

Air admitted to the ports below the bed in the pre-heat zone will burn some of the gases that otherwise leave the kiln un-burnt to improve fuel consumption.

Raw Material Characteristics : The principal burden material used for production of steel making grade DRI in the sponge iron making process is iron oxide lump ore, non-coking coal and limestone/dolomite. The iron ore should be preferably high in Fe content (>65% Fe) and non-decrepitating type. Coals with a high reactivity and high fusion temperature are preferred. The coal should also be non-coking. A low ash fusion temperature is undesirable as it promotes formation of accretions in the kiln. The coal ash composition is also important as a siliceous ash might react with ferrous oxide to form low melting ferrous silicate and interfere with the reduction to metallic iron.

Available Module Size : Coal based plants are available in module sizes in the range of 50 tpd (15000 tpa), 100 tpd (30,000 tpa), 300/350 tpd (100,000/120,000 tpa) and 500 tpd (150,000 tpa).

6.2.1.1 Rotary Kiln Process : Technology options for coal-based plants in India is mostly rotary kiln based processes that are similar in technology and industrial versions of one another. Amongst the various coal based processes, only a few have attained commercial significance. Most of the processes such as SL/RN, KRUPP-CODIR, DRC, TDR, SIIL, JINDAL, OSIL, Popuri utilise rotary kiln for reduction, whereas Kinglor Metor process utilises an externally heated vertical retort in an Indian scenario.

6.2.1.1.1 Krupp-Renn process : The Krupp-Renn process was developed to treat high silica ore with a basicity ratio as low as 0.2 to 0.3, with the addition of limestone. In this process a mixture of minus 64 mm (2.5 inch) ore and fine grained carboneous reducing agent (coke breeze or bituminous coal fines) is fed continuously in rotary kiln. The process flow diagram of Krupp-Renn process is shown in Fig-52.

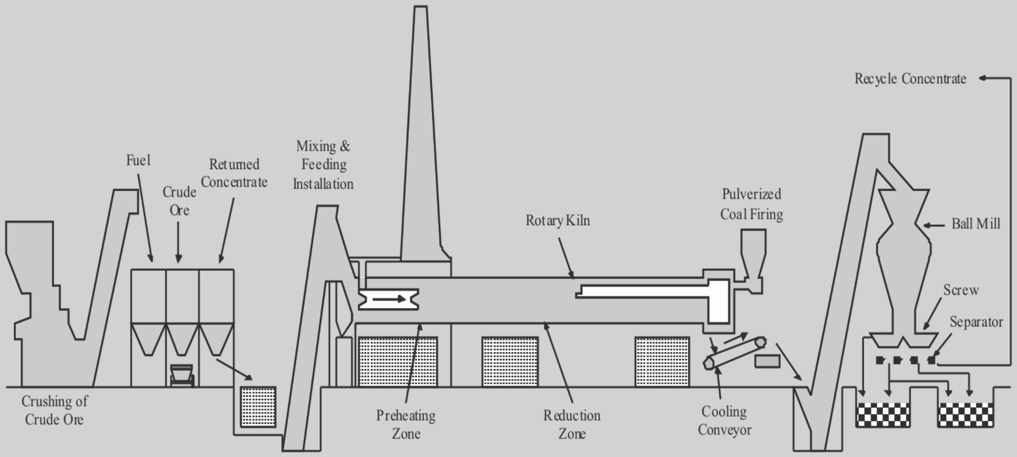


Fig-52: Krupp-Renn Process Flow Diagram

The maximum temperature of kiln is kept at 1230 to 1260 ^{0}C, which is sufficient to convert the gangue in the ore to very viscous high silica sludge and also to effect coalescence the sponge iron obtained from the reduction of the iron ore. The reduced iron welds into nodule called “luppen” which become embedded in the pasty sludge. This product is discharged from the kiln. After cooling it is crushed and luppen are magnetically separated from the sludge. Recovery of iron in the luppen varies from 94% to 97.5%.

High Titania ore can also be used in this process and iron can be separated from titanium since the latter is not reduced. Almost any solid carboneous fuel can be use as a reducing agent. Since a large part of the sulphur contained in the reducing agent goes in the luppen, the sulphur content of the metal becomes high and difficult for economically conversion of the luppen into steel by the conventional steel making practices. In some places, the process is used to concentrate low-grade iron ores containing up to 30% silica, and the luppen been fed into blast furnaces. process is used to concentrate low grade iron ores containing up to 30% silica, and the luppen been fed into blast furnaces.

6.2.1.1.2 Krupp-CODIR process: The process is similar to original Krupp-Renn process. The process operates at a lower temperature than the Krupp-Renn thus producing a standard DRI product. Furthermore, limestone or dolomite in the furnace charge absorbs a substantial part of the sulphur introduced with fuel.

In this process lump ore or oxide pellets, solid reductant, dolomite or limestone as flux is needed. The feed size of the solids is closely controlled to expedite separation. Typically, the preheating zone extends from 25% to 40% along the CODIR process kiln. The process flow diagram of Krupp-CODIR process is shown in Fig-53.

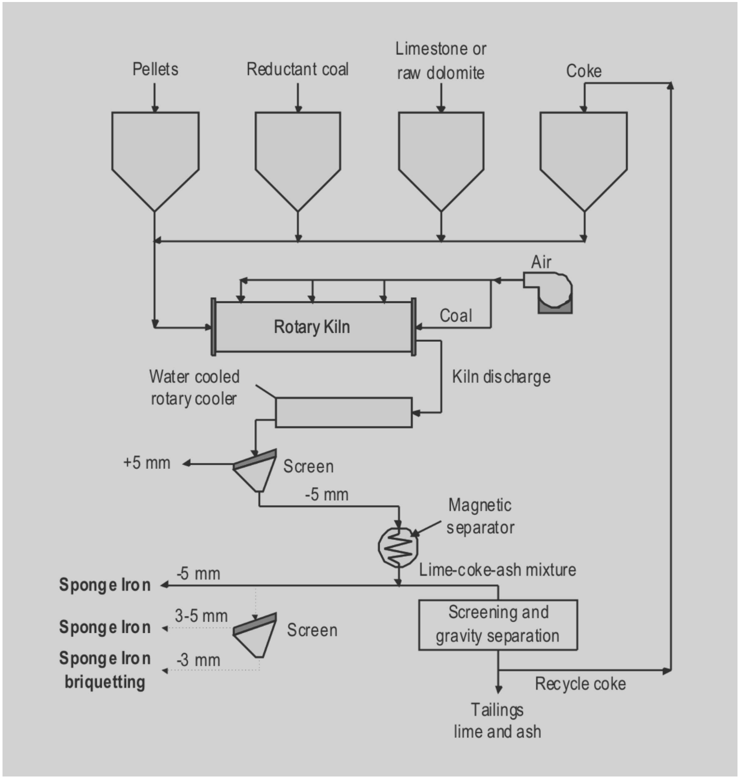


Fig-53: Krupp-CODIR Process Flow Diagram

Primary heat is supplied to the kiln by the combustion of pulverised coal injected at the solids discharge end of the kiln. Secondary heat is supplied by injecting air into the kiln gas space through tubes spaced along the entire length of the kiln. The secondary air is introduced axially (along the kilns centre line). In this way, a uniform charge temperature profile between 950 and 1050 ^{0}C is achieved in the reaction zone of the kiln. The DRI, char, coal ash and spent flux are discharged via an enclosed chute from the rotary kiln burner hood into a shield rotary cooler. Cooling is accomplished by spraying a controlled amount of water directly into the hot solids and by spraying additional water on the outside of the cooler shell. The cooled solids are discharge over a 5 mm screen. The minus 5 mm fraction is processed through further screening at 3 mm and magnetic separation to separate the final DRI from recycled char, spent flux and coal ash. Minus 3 mm DRI is separated as cold briquettes and 5-3 mm DRI is combined with plus 5 mm fraction. Char is separated by gravity for return to the kiln feed, and ash and spent flux are separated for disposal.

6.2.1.1.3 SL/RN Process (Outcompu) : The SL/RN process flow sheet is typically a rotary kiln operation described earlier. The process consists of lump ore or pellets, coal, recycled char and flux that scavenge sulphur from the coal. In the kiln preheat zone, the charge is heated to about 980 ^{0}C by counter flowing hot freeboard gases. For high kiln efficiency the reheated zone is made as short as possible usually 40 to 50% of kiln length. Reduction begins when the charge reaches temperature in excess of 900 ^{0}C when the carbon gasification reaction starts generating carbon monoxide. To maintain a uniform reduction zone temperature by burning combustibles released form the bed, air is blown by shell, mounted fans feed air into the freeboard gas stream, through burner tube space uniformly along the length of the kiln. Air is introduced axially into the kiln and additional combustion air is blown into the kiln through a central airport of the discharge end. The process flow of SL/RN process is shown in Fig-54.

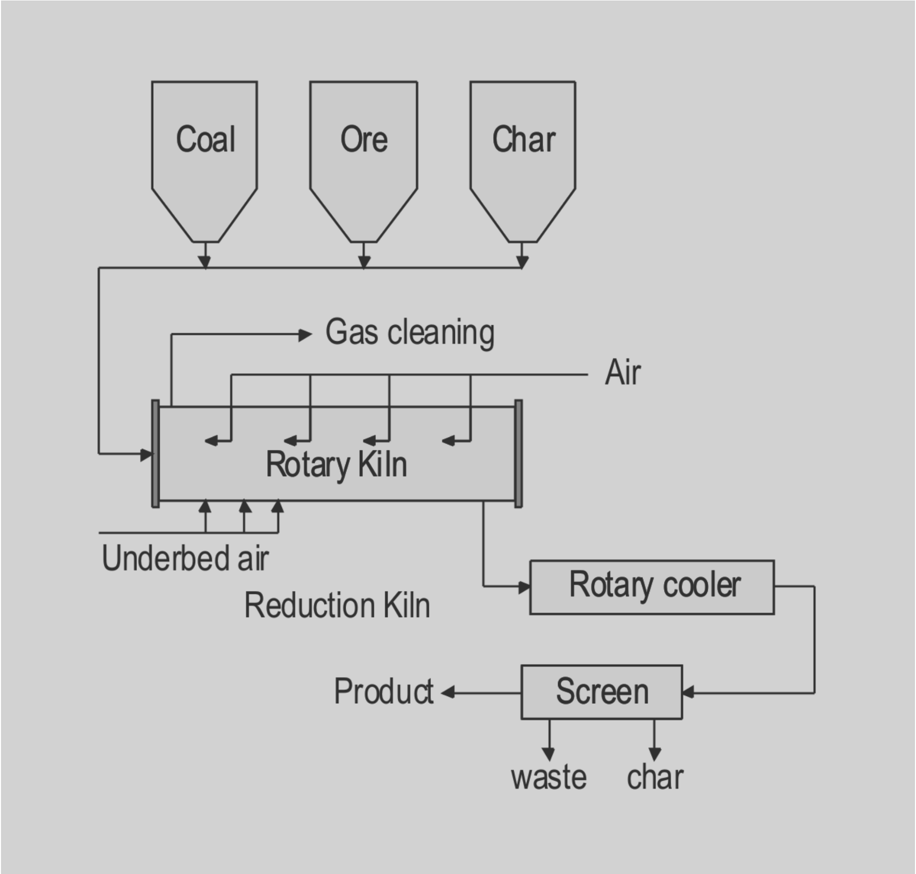


Fig-54: SL/RN Process Flow Diagram

The solids are discharged from the rotary kiln via transfer chute into a sealed rotary cooler. Water sprays on the cooler shell reduces the temperature of solids to about 95 ^{0}C in a non-oxidising atmosphere. External lifter, aide heat transfer in the cooler discharge material, that are continuously separated into DRI, DRI fines, non-magnetic by a system of screen and magnetic separation. Char is separated from the waste by gravity separation.

The SL/RN process kilns are also equipped with nozzles for under-bed injection of about 25% of the process air in the preheating zone of kiln. The air is available for combustion of the volatile matter in the coal within the bed in the preheating zone. As a result, the length of preheating zone of the kiln is reduced because of improved heat transfer and fuel utilisation. More of the kiln length can therefore be used as a reduction zone.

6.2.1.1.4 ACCAR Process: The Allis Chalamers Controlled Atmosphere Reactor (ACCAR) produces highly metabolised DRI in a rotary kiln. Liquid, solid and gaseous fuels singly or in combination are used directly in the kiln with an external reformer or gasifying plan. The ACCAR kiln is equipped with an intricate port system and with valves arranged radically around the circumference of the kiln and spaced uniformly along its length, for liquid or gases fuel injection. Versatility in the use of fuel is claimed as an advantage for this process as it permits use of the most economical fuels available.

The plant operates with coal and oil. The oil can be injected under the bed for two third of the kiln length. The kiln design was modified to permit the addition of fine coal from the discharge end. Around 80% of the hydrocarbon fuel is released by coal. The process flow diagram of ACCAR process is shown in Fig-55.

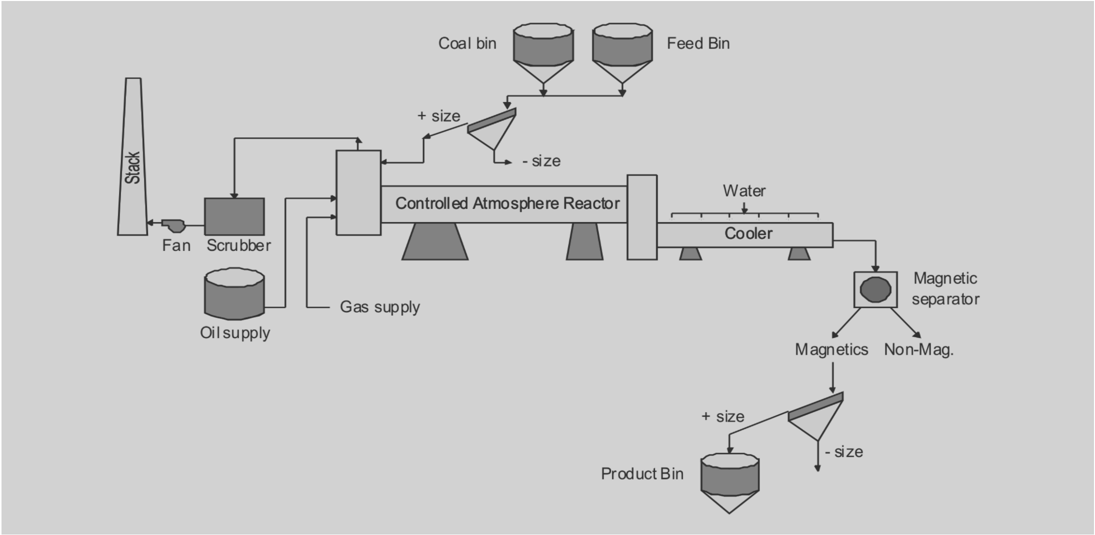


Fig-55: ACCAR Process Flow Diagram

Because gases and liquid fuels are in short supply, operation of the ACCAR process with coal is popular. Coal has been used successfully to supply from 80 to 90% of the fuel for the ACCAR kiln, with the remaining fuel requirement being supplied by liquid and gaseous fuels. Coal and lump ore and or oxide pellets are fed into the fed end of the rotary kiln. The solids are heated to reduction temperature by the counter-current flow of hot gas. Volatile matter is released from the coal during heat up and carried out along the kiln exhaust gas. As the coal and iron oxide travel through the kiln, reduction is accomplished by the carbon and carbon monoxide reduction mechanism. The coal feed is controlled so that it is essentially consumed as the burden enters the final stage of the reduction. Combustibles released from the bed are burned in the kiln freeboard with air introduced through the port in the kiln shell.

The final degree of reduction is achieved by introducing liquid and or gaseous fuel through the kiln shell port near the product end of the kiln as they pass under the solid bed. In passing through bed, this fuel is corrected to form hydrogen and carbon monoxide to complete the iron oxide reduction and to provide a protective atmosphere for the highly metalised product. This method of fuel injection permits operation with the excess of coal required to maintain a reducing atmosphere in the bed in other coal based DR process. Thus, char recycling is eliminated.

Solids are discharged from the rotary kiln into a rotary cooler where cooling is accomplished with external water spray. The DRI is separated from the coal ash by magnetic separator, and is then screened to achieve coarse and fine product separation. If waste heat recovery is not practiced, the kiln gas is cleaned and the heavier solids are removed in dry dust collector, and the fine solids are removed in a wet scrubber, which also cool the gas before it released to the atmosphere.

6.2.1.1.5 DRC Process: The DRC process of the DAVY Reduction Corporation (DRC).The process gives stress on high operability and control of their plant (including sulphur in the product) through complex consideration regarding raw material and proprietary design and operating future for the rotary kilns and ancillaries. The process flow diagram of DRC process is shown in Fig-56.

Ore, coal, recycled char and flux if required, are continuously fed into the rotary kiln. Passage of the burden through a preheat zone and a reducing zone in the kiln flows typically rotary kiln operation. Some minus 9.5 mm coal, about 12.5 % of the total coal is blown by low pressure air into the discharge end of the kiln. Process heat is supplied by burning combustible in the kiln freeboard combustion air is blown into the kiln shell mounted fans via tubes spaced along the length of the kiln. The bed and gas temperature profiles are controlled by adjustment of the air input through the tube.

In the reduction zone iron oxide is reduced by carbon from the coal, with reaction (2), (4), (6) and (9) controlling the complex gas solid reactions:

(1)	$3Fe_2O_3 + H_2 = 2Fe_3O_4 + H_2O$	(2)	$3Fe_2O_3 + CO = 2Fe_3O_4 + CO_2$
(3)	$Fe_3O_4 + H_2 = 3FeO + H_2O$	(4)	$Fe_3O_4 + CO = 3FeO + CO_2$
(5)	$FeO + H_2 = Fe + H_2O$	(6)	$FeO + CO = Fe + CO_2$
(7)	$3Fe + CO + H_2 = Fe_3C + H_2O$	(8)	$3Fe + 2CO = Fe_3C + CO_2$
(9)	$CO_2 + C = 2CO$		

The maximum kiln bed temperature in the reduction zone is about 1060 °C (1940 °F) with a maximum kiln gas temperature of about 1160 °C (2120 °F). Emphasis is placed on maintaining a high ratio of carbon monoxide to carbon dioxide in the kiln bed to achieve a high degree of reduction. Control of the rate of the heat transfer to the bed and control of the bed temperature are also critical for steady operation of the kiln, to achieve stable process chemistry and favorable reaction kinetics. The hot waste gases leave the kiln of about 800 °C (1470 °F).

Solids are discharged from the kiln via a sealed transfer chute into a sealed rotary cooler. Cooling is achieved by spraying water on the outside shell of the screening and magnetic separation circuits. DRI and charge that are recycled and thus separated from the fine waste.

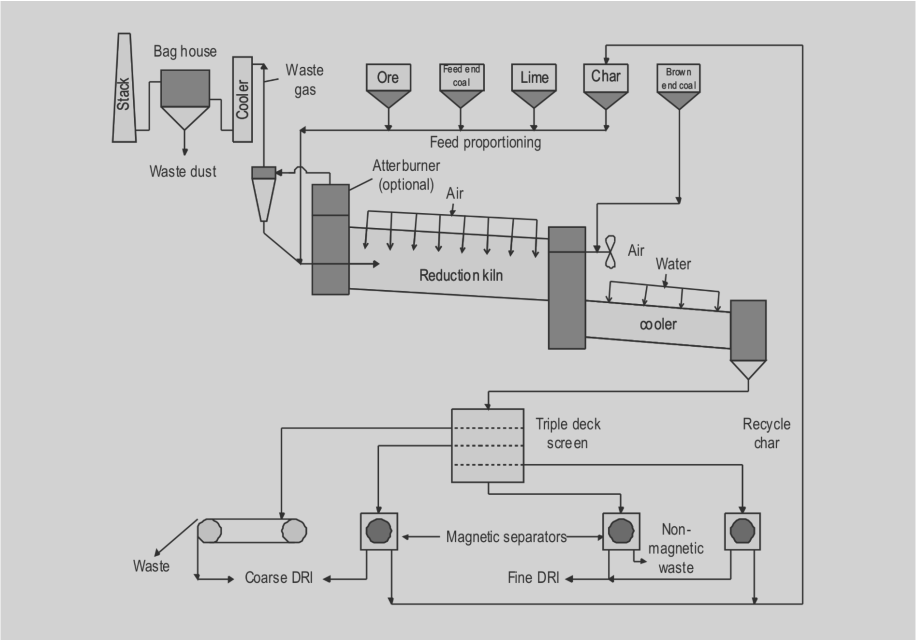


Fig-56: DRC Process Flow Diagram

6.2.1.1.6 Customised or Indigenous Process : In India, the standard DRI processes are modified in a minor way and thereafter referred to as customised/indigenous technology. Only trivial changes in terms of the feed ratio, length and the diameter of the kiln are made in the name of customised technology. These customised technologies are dominating the coal-based sponge iron process in India. Jindal, TDR, Sponge Iron India Limited (SIIL), Orissa Sponge Iron Limited (OSIL), Popurri Engineering, etc have customised, adopted and marketed such technology. Except OSIL none of the customised processes are patented.

In India, the coal based DRI production process employs a rotary kiln as the main reactor wherein the process of reduction of the iron oxide is carried out with coal as reductant. Refractory lining of about 150–200 mm thickness is given inside the kiln to protect the shell. The kiln has a general slope of 2.5–3% down towards the discharge end. There is air blowers mounted on the kiln shell having dampers to provide required air for combustion at different heating zones.

Sized iron ore and coal in required proportion are fed into the kiln with the help of the weigh feeders at the feed end. Due to the rotational motion of the kiln and due to the slope provided, the charge moves forward to the discharge end. Thermocouples are mounted on the kiln to measure and control the temperature of the different heating zones. Fine coal is also injected through the discharge end of the kiln with the help of the coal injector machines & lobe compressor, to meet the additional carbon and volatile matter requirement of the reaction. The process flow diagram is shown in Fig-51.

Kiln discharge material which is a mixture of sponge iron and char (mixture of unreduced iron, un-calcinated limestone, gangue and semi burnt coal) is taken to a rotary cooler. Water is sprayed on the cooler shell to indirectly cool the kiln discharge mix to about 120 ^{0}C. The cooler also has a slope of about 2.5%. The cooler discharge falls onto a hopper and taken through conveyors for screening of fines and coarse materials. After separating the -3 mm and +3 mm sizes in the product screen, the cooler discharge mix is subjected to magnetic separation where sponge iron is separated from char. Sponge iron and char of coarse and fine sizes are stored in separate silos or hoppers.

The reducing gases generated from the combustion of the coal, flow counter current to the direction followed by the solids and emerge from the feed end. The kiln is maintained at a positive pressure of about +5 mm water column. The flue gases then passes through the gravitational Dust Settling Chamber (DSC) and pass on to the After Burner Chamber (ABC) located right above the DSC. In the ABC, the CO is converted to non toxic CO_2. Therefore, in ABC the off-gas laden with combustible matter is burnt. On the top of the ABC, there is an emergency cap to maintain the kiln pressure by letting out the accumulated gases.

The DRI plants installed in early eighties and nineties uses quenching through Wet Scrubber to treat the dust bearing flue gases. In this system the huge amount of sludge is generated, which is disposed in ash ponds. The latest trend in DRI plant is to use Electrostatic Precipitator for dust trapping. In this system, the flue gas, at about 900 –950 ^{0}C, is taken to a Gas Conditioning Tower (GCT) where quenching water is added to cool the gas to about 150 ^{0}C. The cooled gas then travels to the Electrostatic Precipitator (ESP). Dust is trapped in the ESP and the flue gas is let out using chimney.

Of late, some large DRI plants have installed Waste Heat Recovery Boiler (WHRB) after the ABC, to utilise the waste heat content of the flue gas. The WHRB generates steam at high pressure and use it to run turbines and produce electricity. The general technology followed in all the coal based DRI plants is similar to that of SL/RN (Lurgi process).

Some of the Customised or Indigenous Process adopted by various sponge iron industries in India is discussed below:

6.2.1.1.6.1 Sponge Iron India Limited (SIIL) : In India, the first sponge iron plant of 100 tonnes/day capacity was constructed in 1979 by Sponge Iron India Limited (SIIL) at Paloncha in Khammam district of Andhra Pradesh. SIIL is a joint venture between Govt. of India, Govt. of AP, UNDP and UNIDO. The technology supplier to this plant was Lurgi (SL/RN Technology). In this plant, the kiln is 3 m in diameter and 40 m length. The feed rate of iron ore was fixed at 6.7–7.0 tonnes/hour and coal feed rate at 3.5–5.0 tonnes/hour. The feed was retained in the kiln for 4–6 hours and the temperature of the preheating zone was 650–800 ^{0}C, reduction zone was 900–1000 ^{0}C. The production started in 1980 and the DRI output was 100 tonnes/day. Wet scrubber was used to clean the dust laden gases.

The SIIL plant was meant to demonstrate production of DRI from iron ore and non-coking coal available in abundance in India and to establish the suitability of Indian raw material for DRI making. The initial shortcomings in the process were overcome by SIIL engineers and the operation streamlined. Based on the results of operation of these units, other DRI plants started coming up in India. Similar plant was established in 1990s by HEG Ltd at Durg, Bellary Steel & Alloy Limited at Anantapur Road, Bellary in Karnataka and Raipur Alloys Ltd at Siltara in Chhattisgarh.

6.2.1.1.6.2 Popurri Engineering: Today there are over 50 small DRI plants all over India, which are based on process know-how supplied by Popurri Engineering based on the experience gained through SIIL project. Some other engineers who were also associated with the earlier DRI plants also started supplying the process know-how to the upcoming DRI plants, thereby closing the flow of standard technologies into Indian DRI market. Large Indian steel majors however did not support these small time freelancing engineering endeavours driven by the desire to establish their own brand know-how and market them for profits. The steel majors like Jindal and TISCO have also made minor modifications to the original Lurgi technology and came up with their own brand of Jindal Technology and TDR technology.

6.2.1.1.6.3 Jindal Technology : Jindal Steel & Power Limited started their first kiln of 300 tonnes/day capacity in 1991 at Raigarh in Chhattisgarh. Subsequently they have established five similar kilns till 2000. Today they are the world's largest producer of coal-based DRI with an installed capacity of 620,000 tonnes/annum. They have successfully provided the Jindal Technology to Monnet Ispat, Nalwa Sponge, Vallabh Steel and Rexon Strips. The kilns of Jindal Technology are having diameter of 3.8 m and length of 70.8 m. The feed rate is 9–10 tonnes/hour and the size of feed is 5–20 mm for iron ore and 3–20 mm for coal. Coal injection is done from the discharge end of the kiln having lump size of 3–20 mm and fines of -3 mm. The temperature at the feed end is maintained at 750–900 ^{0}C, middle of kiln at 990–1040^{0}C and discharge end at 1010–1050^{0}C.

6.2.1.1.6.4 TDR Technology: Tata Steel established a sponge iron plant in 1983 at Beliapada, near Joda of Keonjhar district in Orissa named Tata Sponge Iron Limited. The process is similar to SIIL. Lurgi provided technical support. The process was called TISCO Direct Reduction (TDR). The first kiln was established in 1986 having DRI output of 300–350 tonnes/day. The kiln diameter is 4.2 m and the length is 72 m. The feed rate is 21 tonnes/hour and the kiln retention time is 8-9 hours. The size of the feed is 5–20 mm for iron ore and 15 mm for coal. At the feed end the temperature is kept about 800 ^{0}C and at the discharge end it is about 1000^{0}C. The second kiln of 350 tonnes/day was established in 1998. The working point at kiln inlet was reduced from 14.9 m to 12.9 m. ESP was used for dust trapping compared to wet scrubber in the first kiln, and the plant was totally automated through the PLC system. The length of the rotary cooler was increased to 42 m against 35 m of the first kiln, at a discharge end a weigh hopper with a variable discharge system has been installed to ensure positive sealing. In order to increase productivity a counter current iron ore fines injection system of 2.5 tonnes/hour was installed. Castable refractory lining was done in Dust Settling Chamber. The third kiln of 500 tonnes/day was established in 2004. Till now, no other plants have come up in the country using TDR technology.

6.2.1.1.5 Orissa Sponge Iron Limited (OSIL) : Orissa Sponge Iron Limited (OSIL) was set up in 1983 in Palaspanga of district Keonjhar in Orissa. It was based on ACCAR process having an under bed injection of diesel from the discharge end. OSIL later used coal fines in place of diesel and patented it as OSIL technology. In 1995 OSIL supplied the technology to Llyods sponge iron plant at Ghuggus in Chandrapur district of Maharashtra. In OSIL, the diameter of kiln is 4.0 m and the length is 84 m, having refractory thickness of 230 mm rendering an effective diameter of 3.54 m. The kiln output is 300 tonnes/day. Non-coking coal is fed from the feed and discharge end as reductant, whereas provision for injecting solid, gaseous and liquid fuels are provided through the 300 portholes located on the kiln shell. The reactor can operate using single fuel or combination of fuels. To facilitate combustion, air is driven into the kiln through the port holes. The reductant product having temperature of 1050 ^{0}C is discharged into the rotary cooler where it is indirectly cooled with water spread on the cooler shell. The cooled product is discharged from the cooler having temperature of about 100^{0}C and brought for magnetic separation. The product usually has a degree of metallisation of +90%.

6.2.1.2 Rotary Hearth Process : Of the various available processes only Fastmet has been a commercial success.

6.2.1.2.1 Fastmet : The process is a solid reductant-based carried out in rotary hearth furnace to treat fine oxides (particularly waste). The process flow sheet is presented in Fig-57.

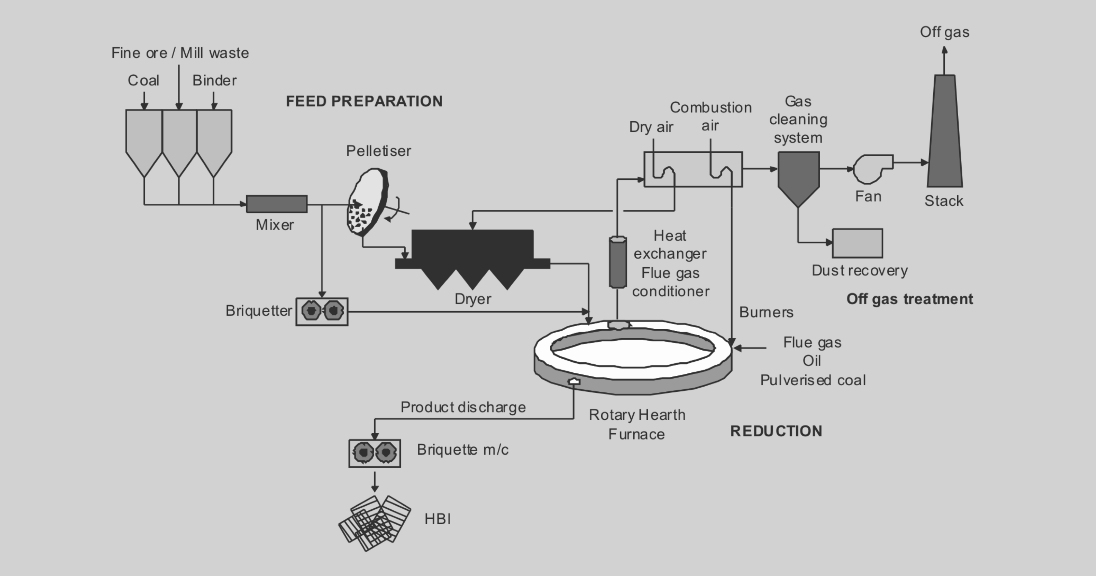


Fig-57: Fastmet Process Flow Diagram

The primary oxide feedstock is iron ore, the oxide in the form of concentrate fines along with reductant fines are palletised, dried and then charged to the Rotary Hearth Furnace (RHF) in a single layer. In case, where the steel mill wastes are primary feed material, the feed is often briquetted before charging on the hearth on a single layer. In the hearth, briquettes are heated to 1250–1400^{0}C by combustion of gas, oil or pulverised coal. The agglomerates containing the reductant gets reduced to metallic iron. The reduction is accomplished by intimate contact between the carbon contained within the pellets/briquettes and the iron oxide fines, at relatively high temperature. The reduction is very rapid, the residence time of the hearth is in the range of 6–12 minutes, during which 90–95% of the iron oxide is converted to metallic iron. The DRI produced is continuously discharged at around 1000 ^{0}C from the furnace into briquetting machines for the production of hot briquetted iron (HBI). The carbon content in the product can be controlled between 1 and 6%. It becomes an ideal material for steel making since it is highly metalised and contains sufficient carbon.

6.2.2 Gas-based Sponge Iron Processes

In this processes, the reductant is natural gas. Today gas based DR plants subscribe to more than 90% of installed DR capacity in the world, of which MIDREX and HYL together have about 85% of the total capacity to their credit. In this processes, the reduction of iron oxide is carried out by a mixture of CO & H_2 at a temperature of about 750–950 ^{0}C. The reducing gas is produced by reformation of natural gas. The reformation is partial oxidation of hydrocarbons. To enhance the reformation process, normally a catalyst is used. Plants based on these technologies are available in India. At present HYL offers only HYL-III modules. The description of the process is as follows:

6.2.2.1 Midrex : Midrex is the most widely used in DRI production in the world. The process flow sheet is presented in Fig-58. In this processes, the reductant is reformed natural gas. In Reformed Natural Gas, Steam oxygen mixture is used to reform the natural gas in presence of a nickel catalyst at about 700 ^{0}C to generate CO & H_2 which is used as a reducer.

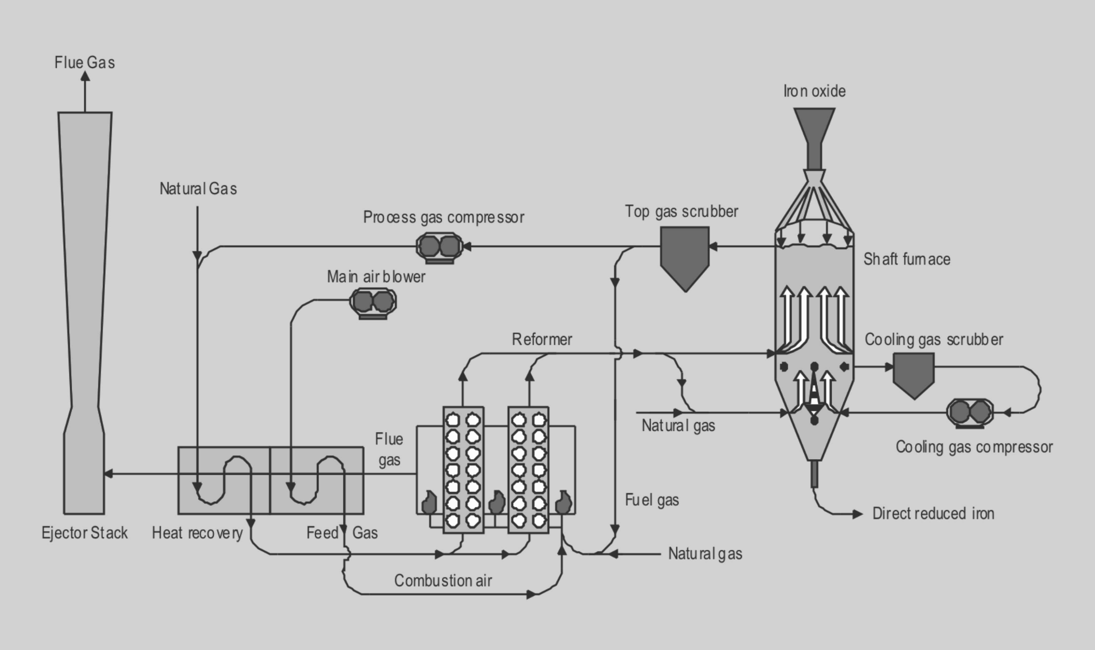


Fig-58: Midrex Process Flow Diagram

The main components of the process are the DRI shaft furnace, the gas reformer and the cooling gas system. Solid and gas flows are monitored and the process variables are controlled within the operating limits. The temperature and composition of each gas stream to the shaft furnace are controlled within specification limits to maintain optimum bed temperature for reduction, degree of metallisation, carbonisation level (Fe_3C contents), and to ensure the most efficient utilisation of the reducing gas.

The DRI furnace is steel vessel with an internal refractory lining in the reducing zone. The charge solids flow continuously into the top of the furnace through seal legs. The reduction furnace is designed for uniform mass movement of the burden by gravity feed, through preheat, reduction, and cooling zones of the furnace. The cooled DRI is continuously discharged through seal legs at the bottom of the furnace. Inert gas is injected into the seal legs to prevent escape of process gases. On discharge from the shaft, the DRI is screened for removal of fines. Special precautions are undertaken to minimise any danger of spontaneous ignition of the pyrophoric DRI product during extended storage or shipment.

Reducing process gas, consisting of about 95% combined hydrogen plus carbon monoxide, enters the reducing furnace through a bustle pipe and ports located at the bottom of the reduction zone. The reducing gas temperature ranges between 760 ^{0}C & 950 ^{0}C. The reducing gas flows countercurrent to the descending solids. Iron oxide reduction takes place according to following reactions.

(1)	$3Fe_2O_3 + H_2 = 2Fe_3O_4 + H_2O$	**(2)**	$3Fe_2O_3 + CO = 2Fe_3O_4 + CO_2$
(3)	$Fe_3O_4 + H_2 = 3FeO + H_2O$	**(4)**	$Fe_3O_4 + CO = 3FeO + CO_2$
(5)	$FeO + H_2 = Fe + H_2O$	**(6)**	$FeO + CO = Fe + CO_2$

The partially spent reducing top gas, containing about 70% carbon monoxide plus hydrogen, flow from an outlet pipe located near the top of the DRI furnace into the top gas scrubber where it is cooled and scrubbed to remove the dust particle. The largest portion (about two-third) of the top gas recompressed, enriched with natural gas, preheated to about 400 ^{0}C (750 ^{0}F) and piped into the reformer tubes. In the catalyst tubes, the gas mixture is purified to form carbon monoxide and hydrogen. The hot reformed gas (over 900 ^{0}C or 1650 ^{0}F), which has been restored to about 95% carbon monoxide plus hydrogen is then recycled to the DRI furnace. The reformation reactions are as follows:

(1)	$CH_4 + CO_2 = 2CO + 2\ H_2$	**(2)**	$CH_4 + H_2O = CO + 3H_2$

The balance top gas (about one-third) provides fuel for the burner in the reformer. Hot flue gas from the reformer is used in the heat recuperates to reheat combustion air for the reformer burners and also to preheat the process gas before reforming. The addition of heat recuperates to these gas streams has enhanced process efficiency, helping to decrease annual fuel to a full usage reported low figure of 11.4 to 11.6 million kilojoules per metric tonne of DRI.

Cooling gases flow countercurrent to the burden in the cooling zone of shaft furnace. The gas then leaves at the top of the cooling zone and flow through the cooling gas scrubber. The cleaned and cooled gas is compressed, passed through a demister, and is recycled to the cooling zone.

An alternative flow sheet uses cold shaft furnace top gas for cooling prior to introduction into the reformer. The DRI absorbs sulphur in the top gas that comes from the raw material. This helps to prevent sulphur poisoning of the catalyst.

6.2.2.2 HYL-III Process: The HYL-III process evolved from the original HYL process by retaining the catalytic reformer, the gas re-heater, and the off gas handling system which condenses water and remove particulate in a scheme that recycles the reduce-reactor off-gas. In the HYL-III process, a single shaft furnace with a moving bed is used in place of the four original fixed bed reactors. The process flow sheet is presented in Fig-59.

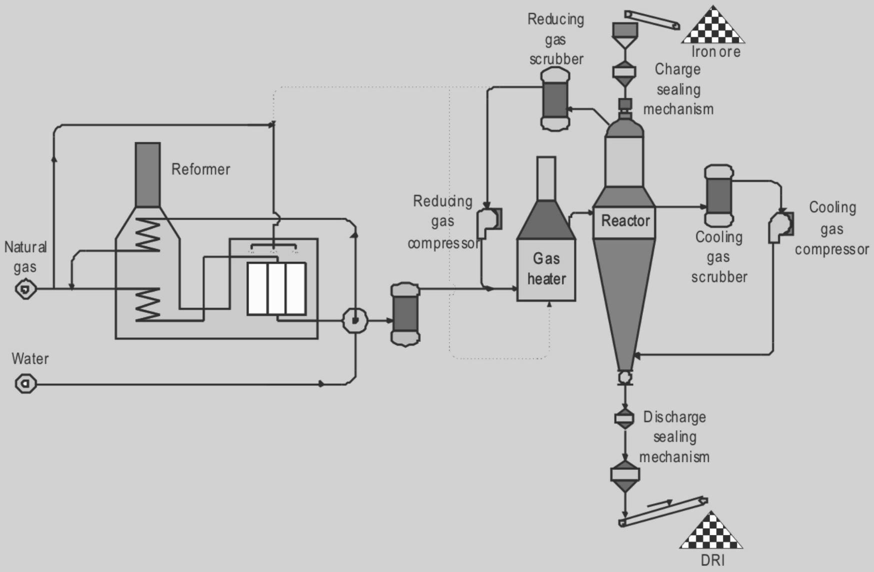


Fig-59: HYL-III DR Process Flow Diagram

The HYL plants operated with iron ore, iron oxide pellets or mixture of the two. The main equipment of HYL-III comprises a DR shaft furnace, a gas reformer and a gas re-heater. The principles of operation of the furnace are similar to the Midrex shaft furnace described previously. The Reduction reactions are as below:

(1)	$3Fe_2O_3 + H_2 = 2Fe_3O_4 + H_2O$	(4)	$Fe_3O_4 + CO = 3FeO + CO_2$
(2)	$3Fe_2O_3 + CO = 2Fe_3O_4 + CO_2$	(5)	$FeO + H_2 = Fe + H_2O$
(3)	$Fe_3O_4 + H_2 = 3FeO + H_2O$	(6)	$FeO + CO = Fe + CO$

A proper selection of iron oxide feed stock permit operation at 950 ^{0}C. The addition of 5 per cent non-sticking ore alters the sticking tendency of iron oxide pellets and improves performance by promoting uniform descent of the burden. This increases productivity and decreases fuel consumption.

After reduction, the hot DRI continues to descend through a constant pressure zone, which separates the upper reducing zone form, the lower cooling zone. The DRI is cooled to below 50 ^{0}C by an independent gas stream. The cooling gas is withdrawn at the top of the cooling zone after cooling, cleaning and compressing. This gas is re-circulated at the bottom of the shaft furnace. The composition and temperature of gas flow to the shaft furnace are carefully controlled to permit independent control of the metallisation and carbon content of the DRI. It is claimed that a high reduction temperature and the formation of an iron carbide shell protect the DRI from spontaneous re-oxidation. Like Midrex, there is provision of hot briquetting facilities in the system.

The HYL III shaft furnace operates at pressure of about 54 kg/cm^2 (5 atm) for this reason; the design incorporates special pressure lock system for charging iron oxide feed materials at the roof and for discharging cold DRI at the bottom. Possible advantages of high pressure operation are enhanced reduction kinetics, higher gas throughput, and condensation at elevated pressure which lowers the moisture content of the re-circulated top gas.

Insofar as reducing gas is concerned, the HYL-III process employs catalytic steam reforming of natural gas. As in the original HYL process excess steam is used, the reformed gas is cooled to condense water, which increases the carbon monoxide plus hydrogen content to a high percentage.

The sensible heat energy of the reformed gas is recovered during cooling by heat exchangers to the steam system. The usual heat recovery system in the flue gas stack of the reformer and gas re-heater is also used. The cold reformed gas is mixed with compressed top gas from the shaft furnace. This top gas had previously been processed to remove a substantial part of its moisture and particulates. The mixed reducing gas is then reheated introduced into the shaft furnace along with natural gas, excess shaft furnace of gas (over that amount re-circulated the process) is used as fuel in the reformer and gas heater.

6.2.3 Liquid Iron Making Smelting Reduction Processes (SR)

Are those processes which utilise oxygen & non-coking coal to produce liquid iron (hot metal) deploying a combination of direct reduction & smelting of iron oxides in various forms. The economics of the SR processes depend largely on effective utilisation of the offtake gases which have a very high calorific value. Utility of the offtake gas for power generation &/or direct reduction of iron by some other method is a must for the economic operation of the processes. Some of the SR processes having commercial applicability/potentiality are discussed below:

6.2.3.1. COREX Process (Liquid Iron) : Corex is a smelting-reduction process, which is cost-efficient and environmental friendly method of production of hot metal from iron ore and coal. The process differs from the conventional blast furnace route in that non-coking coal can be directly used for ore reduction and melting work, eliminating the need for coking plants. The process flow sheet is presented in Fig-60.

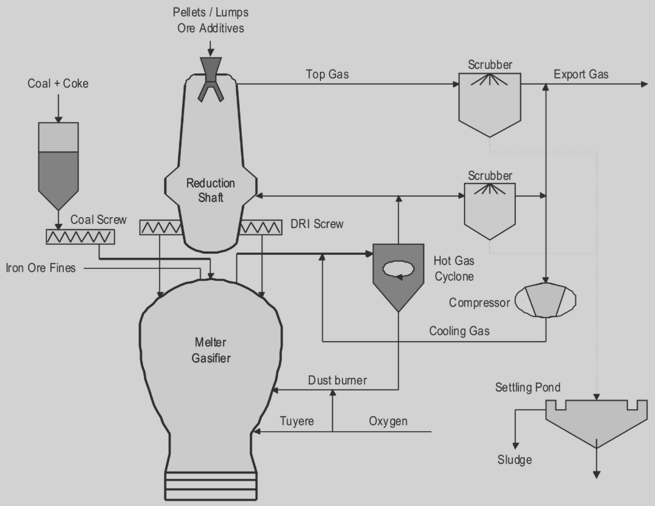


Fig-60: Corex Process Flow Diagram

All metallurgical work is carried out in two separate process reactors—the reduction shaft and the melter gasifier. 40% Lump ore (6–30 mm), 60% pellets and fluxes are fed into a reduction shaft where they are reduced to direct-reduced iron (DRI) by a reduction gas. Discharge screws convey the DRI from the reduction shaft into the melter-gasifier where final reduction and melting takes place in addition to all other metallurgical and slag reactions. The gases from the melter-gasifier contain about 75% CO; and 25% H_2 is used as reduction gas in shaft. The offtake gases from the shaft and the residual gas has high calorific value suitable for wide range of industrial application like power generation etc.

The industrial experience shows that 10–15% of metallurgical coke is required as additional reductant as against claim of 100% use of non-coking coal. In addition, the export gas from the furnace must be effectively utilised for industrial use like power generation etc., in order to keep the cost of hot metal production comparable to that in blast furnace.

6.2.3.2. ROMELT Process (Liquid Iron) : The process was developed to produce liquid iron from iron bearing ores (lumps, fines, slimes as well as waste iron oxides generated in any integrated plant), using non-coking coal and oxygen. Romelt is single stage concept and this is its potential major strength. In this process, iron-bearing materials & coal are charged through one or more openings at the top of a rectangular-shaped reactor. Commercial quality oxygen (>90% pure) is introduced into the reactor above the bath, through a number of tuyeres installed in the two opposite long sidewalls of the reactor. A part of the coal charged gets oxidised, primarily to CO, thereby generating heat that helps in melting the iron bearing materials. The rest of coal is utilised in reducing the iron oxide. Ultimately, two distinct liquid layers of slag and metal are formed in the hearth of the Romelt vessel, with slag floating on top of the metal. Both these liquids are intermittently tapped. The process is simple to operate and environmental friendly as it operates under slightly negative pressure. The process flow sheet is presented in Fig-61.

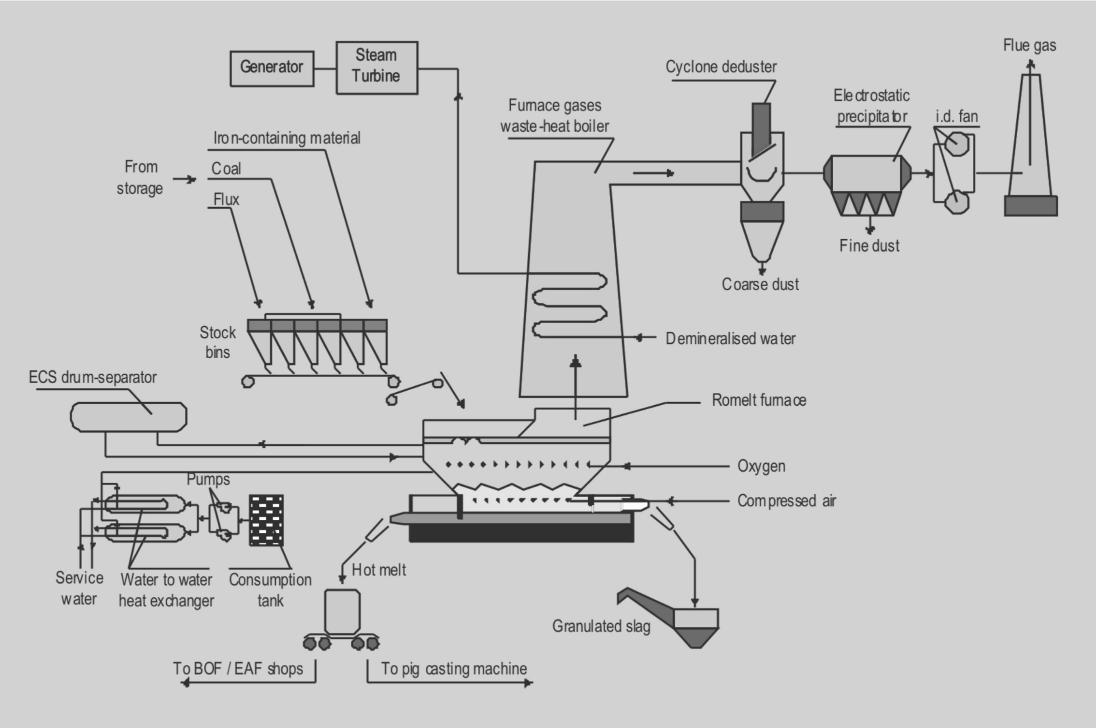


Fig-61: Romelt Process Flow Diagram

The process, however, consumes large amount of coal (around 20–25% ash) as well as oxygen and generates large quantities of very high calorific value gas at the exit temperature of 1600 ^{0}C. This needs to be effectively utilised viz., in power plant etc. for the process to be economical.

6.2.3.3. ITmk3 Technology (Nuggets): It is a unique technology for smelting iron ore fines using non-coking coal to produce premium grade iron in the form of nuggets. Unlike traditional technologies of iron making, it represents a revolutionary change in the way iron is made and also the product quality. In effect, it may be considered as a new method of iron making particularly, for electric steel making. The process flow sheet is presented in Fig-62.

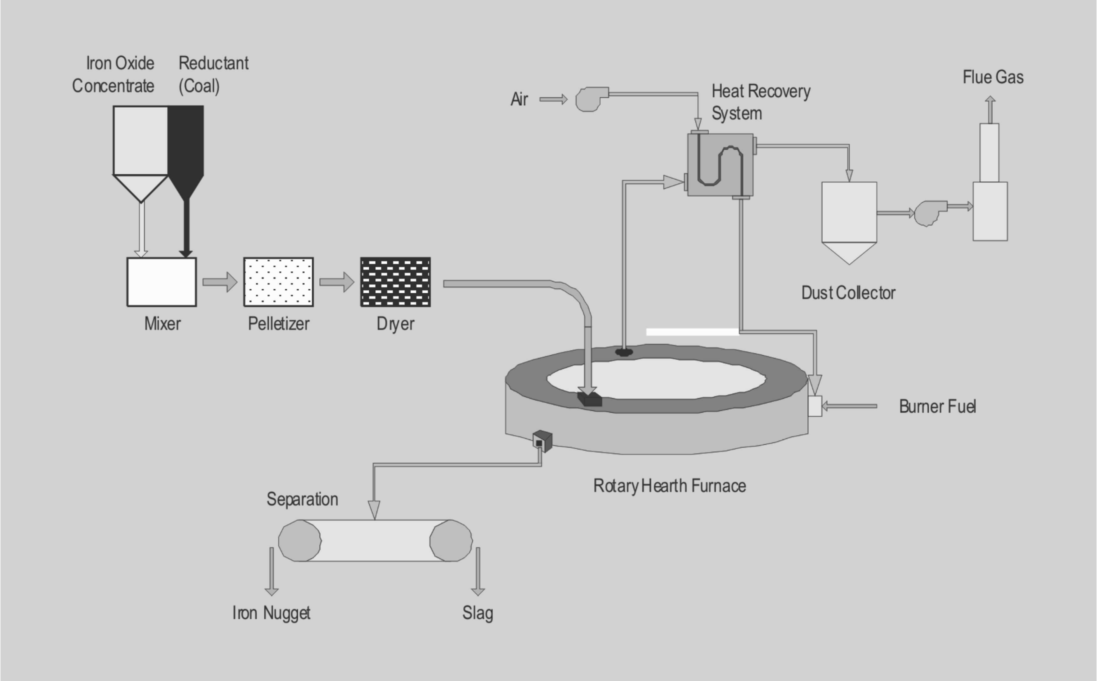


Fig-62: Flow Sheet of the ITmk3 Technology

Raw Material and Other Inputs: The three main inputs are iron ore fines, coal and fluxes. Generally, pellet feed grade iron ore fines are used as it is and sinter feed grade ores are ground to fine size (80% -300 mesh). Coal is ground to 80% minus 200 mesh. Coal is the reductant for conversion of iron ore into iron and also serves as the main source of heat. The quality and quantity of flux is determined based on the nature of iron ore and coal. Besides coal, natural gas is another heat source, which is burnt in the Rotary Hearth Furnace (RHF) to heat up the pellets. In place of natural gas, furnace oil could also be used in the process.

Process: The process is carried out in the Rotary Hearth Furnace (RHF) where iron ore fines are reduced and smelted using pulverised coal. The steps of iron ore reduction and smelting of the process are as below:

1. Iron ore fines, Flux and pulverised coal are mixed in a mixer.

2. Mixed inputs are converted into carbon composite green pellets in a pelletiser.

3. Pellets are dried at a temperature of around 180 ^{0}C using preheated air which is heated by exhaust gas of the furnace.

4. In the RHF, the carbon bearing composite pellets are gradually heated up using natural gas. The smelting reduction process involving reduction and smelting takes place in stages.

Nugget Formation: The series of reactions are completed in around 10 minutes. To begin with, pellets are converted into DRI with un-reacted core which later convert into a dense metallic iron shell containing molten slag and large void space. Immediately thereafter, in the last zone the temperature is raised to 1350–1450 ^{0}C, where the metallic iron melts and starts separating out from slag.

In the last two minutes of the process of the RHF, the molten iron and slag are cooled which further cooling in the cooler follows. The solidified iron nuggets are separated from the slag with the help of a magnetic separator.

Product: The quality of Iron nuggets depends on the quality of iron ore and coal used in the process. However, typically, iron nuggets are highly metalised product containing over 97% metallic iron with very low phosphorous. A typical composition of nuggets is Metallic Iron(Fe) +97%, Carbon(C) 2–2.5%, Sulphur(S) 0.07–0.10% & Phosphorus(P) 0.01–0.02%.

The sensible heat of the off-gas from the RHF is substantially recovered by a recuperator thereby heating the air for combustion of natural gas used in the process. The hot air is also utilised for drying the green pellets.

In ITmk3 process, phosphorous removal is substantial leading to a very low content of phosphorous in iron nuggets as against in blast furnace where phosphorous removal is minimal. This is mainly because of shorter reaction time, essentially around 6 minutes, and iron and slag are separated after 2 minutes cooling time. In other words, the operation does not reach equilibrium to allow phosphorous to transfer to the metal. When iron and slag were allowed to stay together longer during plant demonstration trial it was observed that phosphorous content of the metal was increased.

6.2.3.4. Hismelt Process: Iron ore is preheated in the first of two fluidised bed reactors in series and pre-reduced to 15–25% in the second reactor using cleaned off-gas from the smelter. It is claimed that the high thermal efficiency through pre-reduction operation has the potential for using less expensive coal and lower consumption compared with BF route. In addition, a small amount of coal fines is injected into the smelter off-gas to cool the off-gas and provide additional CO and H_2 for pre-reduction. Coal is gravity fed into the smelter. The process flow sheet is presented in Fig-63.

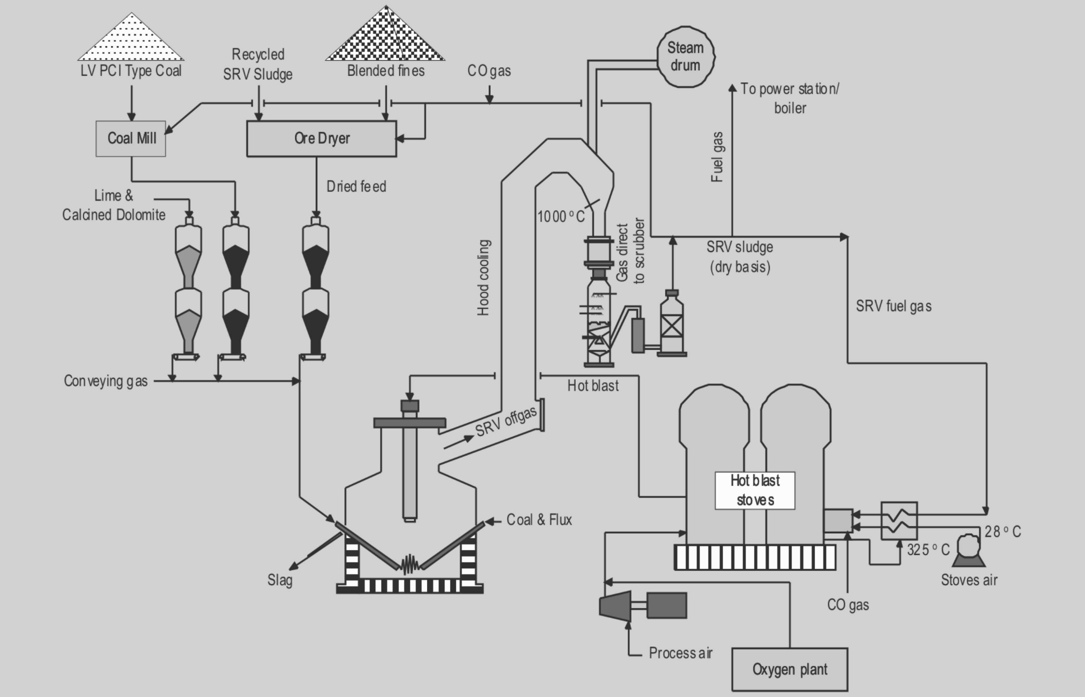


Fig-63: Flow Sheet of the Hismelt Process

Perhaps the most noteworthy feature of the HIsmelt process is that, amongst all the SR processes, it is the most akin, in many ways, to the blast furnace, e.g. in the preheating of the blast in hot blast stoves, etc. It has some unique advantages in terms of the composition of hot metal made. HIsmelt hot metal contains no silicon whatsoever. Further, partition of 90–95% of the input phosphorus into the slag is possible, thereby allowing low phosphorus metal to be produced even from high phosphorus ore fines.

The Hismelt appears to be highly promising smelting reduction process for making 2000 to 3000 tonnes of hot metal per day both in integrated steel plants and green field mini steel plants. The capital cost appears to be on the higher side. Inspite of this short coming, it appears to be the process of the future because of simplicity of operation, the use of iron ore fines (-6 mm) rather than lump ore/agglomerates, and Iron oxides feed of various types and wide range of 100% coal (no coke). In addition to above green technology makes the Hismelt process very unique.

6.3 INDIAN SCENARIO

1. In India, Steel production deploying BF-BOF route, using lumps & sinters as well as alternate route of iron making (DRI-EAF/IF), using lumps/pellets is more or less in the ratio of 1:1.

2. Though Blast furnace route of iron making dominates the iron production in India, increased steel demand in the world and saturated production levels of steel from major integrated steel sector has encouraged the secondary steel making route of DR -EAF (mini steel sector) to grow in small and private sector. The steel industry which otherwise was confined mostly with the ISPs in public sector was taken over by the private sector. Integrated steel plants (ISP) require large capital investment and depend on metallurgical coke which is not available everywhere. DRI units on the other hand require limited capital investment and the reductant can be non-coking coal or natural gas. Consequently, the DRI process became more popular in the country. Such units in large number are coming up at a rapid pace and spread across the country.

3. Raw materials like iron ore, coal and dolomite are available at competitive prices in most part of the country and hence coal-based DRI plants are being established in large numbers. Due to availability of natural gas in western coast of the country, some large DRI plants have also been established. The gas-based DRI plants produce sponge iron and uses it spontaneously for steel making or converts it to Hot Briquetted Iron (HBI) for storage and sale.

4. Pig iron and sponge iron form the feed stock for steel making.

5. Threefold rise in steel production by 2020 (from present level 65 MTPA) calls for enhancement in iron making capacity of almost all the three routes of BF, DRI & Liquid iron process routes followed by BOF, EAF & IF for steel making.

6. Therefore, sponge iron will have to play a key role in immediate future in the development of steel sector and the industry has to depend a great deal on sponge iron for the supply of metal in future.

7. The sponge iron in the country is produced through two routes—one is gas-based using iron ore pellets and other is coal-based using high-grade iron ore lumps. DRI

production of India in the year 2009-10 touched around 23 million tonnes i.e., more than one-third of the world total. Of these, around 16.2 million tonnes were made in rotary kilns (coal-based method for direct reduction) i.e. around 90% of the World's total coal based production. There are approximately 350 of these furnaces operating within India and another 160 units are at different levels of implementation. The growth pattern of DRI plant (coal-based as well as gas-based) in India is presented in Fig-64.

8. Most of the gas-based plants use the successful technology from Midrex and HyL processes. Due to limitations of gas availability the gas-based plants growth was limited and hardly any new plants have come up in recent times.

9. Therefore, to meet the projected demand of sponge iron, coal-based DRI units will be comprehensively burdened and these would continue to dominate the Indian scenario in the future as well.

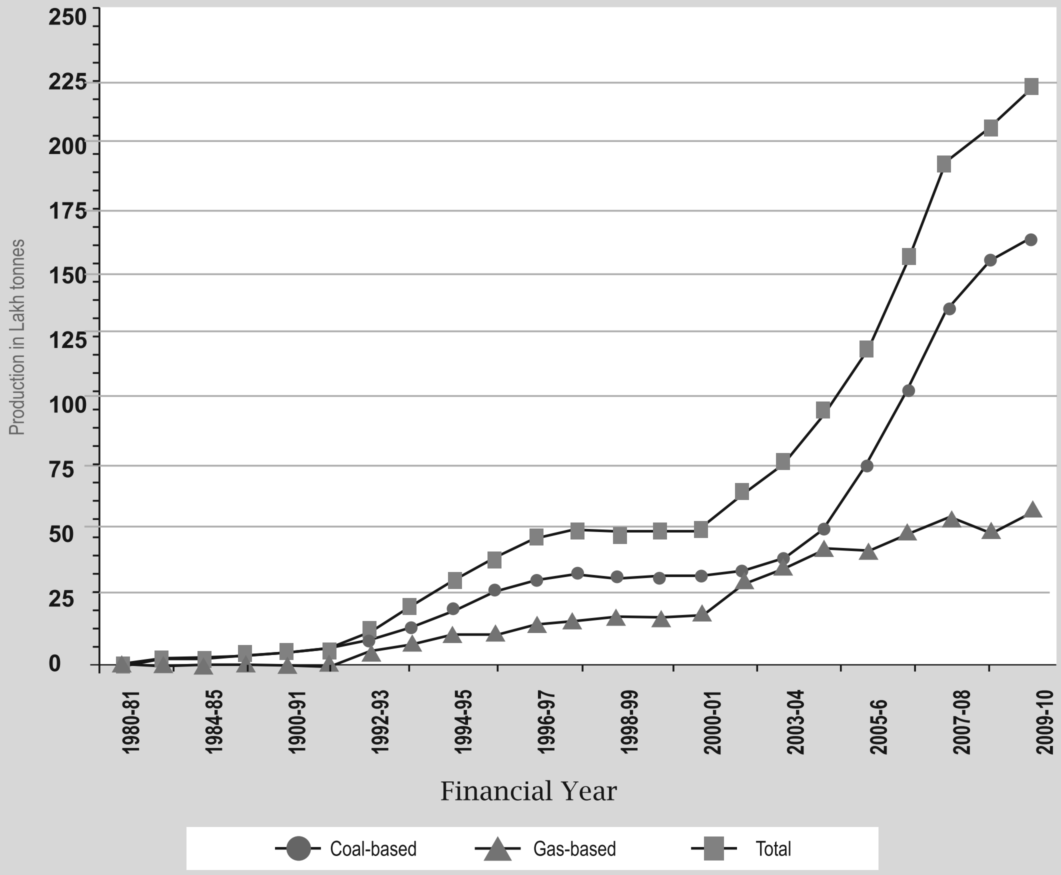


Fig-64: Sponge Iron Production in India

10. Calibrated iron ore lumps are still in use in blast furnace as well as coal-based DRI units. Of this, the high-grade calibrated lumpy ore (Fe +65%) is used very liberally in BF and DRI units. Presently, pellets are not used at all in blast furnace burden. Therefore, the usage of higher percentages of lumpy iron ore in iron making in India is as high as 45%, as against 15–20% used globally.

11. This liberal use of high-grade lumps in DRI plants needs to be discouraged by enforcing use of pellets instead. Besides, blast furnace also needs to use pellets in its burden. Details regarding availability of pellets for use in these units have already been discussed in Chapter 4.