

Chapter 8

Iron Ores

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8.1 The Nature and Occurrence of Iron Ores

Of the many natural raw materials that are required for the making of iron and steel, the most important as to tonnage and value is iron ore. For each net ton of raw steel produced by the American steel industry, approximately one net ton of iron ore (including agglomerates) is consumed, according to statistics of the American Iron and Steel Institute (AISI).

The gross ton or long ton (2240 lb) formerly was the usual commercial unit weight for iron ore. The net ton or short ton (2000 lbm) was sometimes used in statistics. The tonne (metric ton) of 1000 kgm (approx. 2205 lbm) will be used throughout this chapter except where net tons or long tons are expressly specified

8.1.1 Iron Bearing Minerals

A large number of minerals contain iron; however, only a few are used commercially as sources of iron. Minerals containing important amounts of iron may be grouped according to their chemical compositions into oxides, carbonates, sulfides and silicates. Table 8.1 illustrates the oxide and carbonate classes of iron minerals and indicates the mineral species commonly used as sources of

Table 8.1 Chief Iron Bearing Minerals

Class and Mineralogical Name	Chemical Composition of Pure Mineral	Common Designation
Oxide		
Magnetite	Fe ₃ O ₄	Ferrous-ferric oxide
Hematite	Fe ₂ O ₃	Ferric oxide
Ilmenite	FeTiO ₃	Iron-titanium oxide
Limonite	HFeO ₂ ^(a) FeO(OH) ^(b)	Hydrous iron oxides
Carbonate		
Siderite	FeCO ₃	Iron carbonate

^(a) Goethite

^(b) Lepidocrocite

iron. Oxide minerals are the most important sources of iron, with the carbonates, sulfides and silicates being of minor importance. In the descriptions of the important iron ore minerals or mineral groups that follow, the chemical compositions are for the pure minerals the iron content of commercial ores or concentrates generally is lower, due to the presence of gangue and other impurities.

8.1.1.1 Magnetite

Magnetite has a chemical composition of Fe_3O_4 , corresponding to 72.36% iron and 27.64% oxygen; has a color of dark gray to black, and a specific gravity, 5.16 to 5.18. It is strongly magnetic, sometimes possessing polarity so it will act as a natural magnet. The magnetic property of magnetite is important, for it permits exploration by magnetic methods and makes possible the magnetic separation of magnetite from gangue materials to produce a high quality concentrate. Magnetite occurs in igneous, metamorphic, and sedimentary rocks. It has become increasingly important as a source of iron as a consequence of the continued improvements in magnetic concentration techniques and in the expanded use of the high grade products. At times, magnetite contains titanium in small amounts as inclusions of ilmenite. When the titanium content reaches 2–15% or more, the magnetite is termed titaniferous magnetite.

8.1.1.2 Hematite

Hematite has a chemical composition of Fe_2O_3 corresponding to 69.94% iron and 30.06% oxygen, has a color from steel gray to dull red or bright red, can be either earthy, compact or crystalline, and has a specific gravity of 5.26. Common varieties are termed crystalline, specular, martite (pseudomorphic after magnetite), maghemite (magnetic ferric oxide), earthy, ocherous, and compact.

Hematite is one of the most important iron minerals. It has a wide occurrence in many types of rocks and is of varying origins. It occurs associated with vein deposits, igneous, metamorphic, and sedimentary rocks, and as a product of the weathering of magnetite. Some low-grade deposits of disseminated crystalline hematite have been successfully treated by both gravity and flotation techniques to produce high quality concentrates.

8.1.1.3 Hydrous Oxides

Limonite is the name commonly given to hydrous iron oxides that mineralogically are composed of various mixtures of the minerals goethite or lepidocrocite. The chemical formula for goethite is HFeO_2 and that for lepidocrocite is $\text{FeO}(\text{OH})$. Goethite contains 62.85% iron, 27.01% oxygen, and 10.14% water; has a specific gravity in the range of 3.6–4.0, is commonly yellow or brown to nearly black in color, and is compact to earthy and ocherous. In non-technical parlance, the term limonite is used to denote unidentified oxides with a variable moisture content due to absorbed or capillary water. It is a secondary mineral, formed commonly by weathering, and occurs in association with other iron oxides and in sedimentary rocks.

8.1.1.4 Ilmenite

Ilmenite has a chemical composition of FeTiO_3 , corresponding to 36.80% iron, 31.57% titanium, and 31.63% oxygen. This is commonly considered an iron titanate. Ilmenite is often associated in small amounts with magnetite. Although generally mined as a source of titanium rather than as an ore of iron, iron may be recovered as a byproduct.

8.1.1.5 Siderite

Siderite has a chemical composition of FeCO_3 corresponding to 48.20% iron, 37.99% CO_2 and 13.81% oxygen, a specific gravity of 3.83–3.88, and a color from white to greenish gray and brown. Siderite commonly contains variable amounts of calcium, magnesium or manganese. Siderite varies from dense, fine grained and compact to crystalline. The siderite ores are sometimes termed spathic iron ore or black-band ore. Carbonate ores are commonly calcined before they are charged into the blast furnace. They frequently contain enough lime and magnesite to be self-fluxing.

8.1.2 Geology of Iron Ore Deposits

8.1.2.1 Geologic Ages of Iron Ore Deposits

Iron ores have a wide range of formation in geologic time as well as a wide geographic distribution. They are found in the oldest known rocks of the earth's crust, with an age in excess of 2.5 billion years, as well as in rock units formed in various subsequent ages; in fact, iron ores are forming today in areas where iron oxides are being precipitated in marshy areas, and where magnetite placers are being formed on certain beaches.

Many thousands of iron occurrences are known throughout the world. They range in size from a few tonnes to many hundreds of millions of tonnes. Many of the world's largest deposits of iron ore are located in the oldest geologic series—the Pre-Cambrian. Table 8.2 illustrates the geologic age for selected iron deposits.

Table 8.2 Geologic Age of Selected Iron Ore Deposits

Geologic Age	Deposit	Location
Cenozoic Era		
TERTIARY PERIOD		
Pliocene Epoch	Kerch Oolitic Limonite(a)	Crimea, Russia
	El Tofo Magnetite	Chile, South America
Oligocene Epoch	Cheikh-ab-Charg Hematite	Iran
Eocene Epoch	Upper Assam Clay Ironstones	India
	Bahariya Hematite	Egypt
Mesozoic Era		
CRETACEOUS PERIOD		
	Salzgitter Limonite and Hematite(a)	Germany
	Bilbao Hematite	Spain
	Algerian and Moroccan Magnetite and Hematite	North Africa
JURASSIC PERIOD		
	Minette Limonite and Hematite	France, Germany
	Iron Springs Magnetite	Utah
TRIASSIC PERIOD		
	Kashmir Calcareous Iron Ore (Hematite)	India
Paleozoic Era		
PERMIAN PERIOD		
	Damuda Sandstone (Hematite)	India
Pre-Cambrian Era^(b)		
	Minas Gerais and Serra dos Carajás Hematites ^(a)	Brazil
	Krivoi Rog Hematite ^(a)	Ukraine, Russia
	Bihar, Orissa and Mahya-Pradesh Hematites ^(a)	India
	Labrador Hematite ^(a)	Quebec and Labrador
	Lake Superior Taconites and Jaspilites, Hematites and Magnetites ^(a)	Michigan, Wisconsin, Minnesota, Ontario
	Cerro Bolivar and El Pao Hematites ^(a)	Venezuela
	Kirunavaara Magnetite ^(a)	Sweden
	Hamersley Range Hematites ^(a)	Western Australia
	Nimba Range Hematite ^(a)	Liberia and Guinea
	Sishen Hematite ^(a)	South Africa

^(a) Well-known, important deposits.

^(b) Represents the time span of the combined Proterozoic and Archeozoic Eras.

8.1.22 Genesis of Iron Ore Deposits

Iron ores occur in a wide variety of geological environments in igneous, metamorphic or sedimentary rocks, or as weathering products of various primary iron bearing materials. For convenience of study and comparison, iron ores may be grouped into types of similar geological occurrence, composition and structure. The following simplified classification based on genesis of the deposits and geological environment shows the chief modes of occurrence of iron ores and illustrates the varied geology of iron ore deposits. Some of the examples listed may be approaching the end of their productive life or they may no longer be active, but they are generally well known and have been described in the geological literature.

8.1.23 Igneous Ores

Iron ores may be formed by crystallization from liquid rock materials, either as layered-type deposits that possibly are the result of crystals of heavy iron bearing minerals settling as they crystallize to form iron-rich concentrations, or as bodies which show intrusive relationship with their wall rocks. These ore bodies may be tabular or irregular and are composed largely of magnetite with varying amounts of hematite. Igneous ores are usually high in iron content and are often high in phosphorus or titanium content. Deposits of this type include the ores at Gallivare and Grangesberg, Sweden; Iron Mountain and Pea Ridge, Missouri; titaniferous magnetite deposits at Lake Sanford, New York; Talberg, Sweden; and Bushveld, Transvaal, Union of South Africa.

8.1.24 Contact Ores

Iron ore deposits formed at or near the contact between igneous rocks and sedimentary rocks, the latter usually limestoneis, are commonly composed of magnetite and hematite with associated carbonates and pyrite. The ore deposits are commonly in the sedimentary rocks as irregular or tabular replacement bodies. Deposits of this type include: Iron Springs, Utah; Mount Magnitnaya, Russia; and Marcona, Peru.

8.1.25 Hydrothermal Ores

Iron ore deposits formed by hot solutions which transported iron and replaced rocks of favorable chemical composition with iron minerals to form irregular ore bodies, commonly in limestoneis, are termed hydrothermal deposits. The iron often occurs as siderite (FeCO_3) or sometimes as oxides. Examples of hydrothermal deposits include those at Bilbao, Spain; Kenifra, French Morocco; Ouenza, Algeria; and hard ores of the Marquette Range, Michigan.

8.1.26 Sedimentary Ores

8.1.261 Bedded Ores Sedimentary bedded iron ores, often composed of oolites of hematite, siderite, iron silicate or, less commonly, limonite in a matrix of siderite, calcite or silicate, have a wide geographic distribution associated with other sedimentary rocks. The Clinton ores in Alabama also have fossil fragments coated or replaced with hematite, or sand grains and pebbles coated with hematite in a hematite and calcite matrix. These ores often have a fairly high phosphorus content and may be self-fluxing. Ores of this type include the Minette ores, France; Robe River, Yandi, Australia; and Kerch ores, Russia.

8.1.262 Siderite Ores These ores consist of beds of siderite or siderite nodules associated with shales. They are common in the coal measures and are often termed clay ironstones or black-band ironstones. These ores commonly contain associated sulfides and often have a fairly high sulfur and phosphorus content. They were formerly of considerable importance in Great Britain and Germany.

8.1.263 Placer Ores Iron oxides, when compact, are rather resistant to weathering and erosion and under favorable conditions may form placer deposits which, in a few instances, constitute iron ores. In general they are of rather minor importance as sources of iron. Magnetite sands are mined in Japan and are known in many areas. Deposits of iron bearing rubble cemented with limonite and clay, that occur on hill slopes in tropical areas adjacent to pre-existing iron deposits, are termed

canga. These are sometimes mined as ore. Placer iron ore deposits include beach sands in Japan and New Zealand. Canga occurs in Brazil, India and Venezuela.

8.1.264 Bog Iron Ores Bog ores occur in many swampy areas particularly in glaciated areas in Europe, Asia and North America. They occur commonly as dark brown, cellular masses, or granular or fine particles of limonite. In years gone by, such deposits were mined rather widely to supply small iron furnaces locally. However, they have long ago ceased to be important commercially.

8.1.265 Metamorphosed Iron Formations These include the metamorphosed bedded ferruginous rocks composed usually of alternating thin layers of chert or fine-grained quartz and ferric oxides. The iron is normally present in the mineral form of magnetite or hematite, along with lesser amounts of iron silicates and iron carbonates. Essentially all of the Pre-Cambrian sedimentary iron formations are of this type: these include the magnetic and nonmagnetic taconites of Minnesota; jaspilites of Michigan; itabirites of Brazil; quartz banded ores of Norway and Sweden; iron formations of Quebec and Labrador; banded hematite quartzites of Africa; hematite jaspers of India; and the banded iron formations of Manchuria, Korea and Australia. The metamorphosed types also include those in which the original form of the ores has been obscured by extensive recrystallization. In recent years, some of these iron formations have become important economically as iron ores because of their amenability to beneficiation by fine grinding and by concentration of the ore minerals principally by magnetic methods.

8.1.266 Residual Ores Residual ores are commonly products of the surficial weathering of rocks but may include ores formed by hydrothermal oxidation and leaching. Ores of this type were formed extensively in Pre-Cambrian iron formations by leaching of silica, which commonly constituted in excess of 50% of the rock. Oxidation changes iron carbonate, silicate minerals, and magnetite to hematite or limonite. Examples of residual ores include: iron laterites formed by the weathering of basic igneous rocks as in Cuba, Conakry (Guinea, Africa), and Mindanao in the Philippine Islands; the brown ores of Alabama, Georgia and Missouri; soft hematite and limonite Pre-Cambrian ores such as occur in the Lake Superior District, Estado Bolivar, Venezuela; Western Australia; Krivoi Rog, Russia; Minas Gerais, Brazil; Quebec-Labrador, Canada; Nimba, Liberia; Nimba, Guinea; and India.

8.1.3 Ore, Definition of the Term

The term ore is often used loosely—as it has been up to this point—in discussions of a general nature. However, a more restrictive definition must be used in discussions of ores used by the iron and steel industry and particularly in discussing iron ore reserves.

Iron is one of the more abundant and widely distributed elements in the earth's crust, constituting not less than 4% of the total. Its supply is essentially limitless in almost all regions of the world. However, most of this iron, because of its position or concentration in the earth's crust, is not available to us, and much of it is in a form that cannot be used in current ironmaking practices. That part of the total iron in the earth's crust that is available to industry, both economically and spatially, may correctly be termed ore. However, what constitutes ore varies widely from place to place and time to time. For example, up to the mid 1980s the principal ores mined and used in France contained less than 30–35 % iron. Such material would not be considered suitable furnace feed in most other sections of the world. However, in this particular case, the spatial proximity of this ore to sources of coking coal and to an important market area for steel, as well as its adaptability to the furnace practices developed in that area, had given it a favorable price-quality relationship with respect to higher grade but more distant ores. These mines in France are now shut down as higher grade imported ores can be economically shipped. Much the same situation had existed in the Birmingham, Alabama, area, where ores containing only 37% iron were mined and used locally, although such low-grade, high phosphorus ore would not be considered as commercial ore in other mining districts. There are many factors which enter into determining what iron bearing material can be classed as an ore, but basically it is a question of economics. Keeping this concept in mind, a logical definition of iron ore for commercial purposes is as follows: "iron bearing material that can be economically used at a particular place and time under then current cost and market price conditions."

With the advent of improved methods of beneficiation, concentration and agglomeration, the variety of iron bearing materials that can now be used has been broadened and many low-grade material types which were once uneconomic, may now be considered as ore. The beneficiation methods discussed in Section 8.4 are used not only to make iron ore concentrates from taconites, but also are used to improve high-grade ores by controlling particle size and by reducing the content of gangue minerals. These methods are currently being used on a world-wide basis in almost every major iron ore producing district. Ferruginous byproducts derived from the processing of materials for their content of sulfur, titanium, copper, or other metals would not be considered as iron ore in the strict sense of the term, nor would beach sands unless they were actually being utilized, as for example, beach sands in New Zealand. Other iron bearing material would also have to be denied classification as ore because of impurities, geographic inaccessibility, or, in some cases, simply because there is insufficient available information for a valid appraisal.

8.1.4 Iron Ore Reserves

The potential iron ore known to exist is called iron ore resource. Identified resources include both reserves and other iron bearing materials that may become profitable to mine under future economic conditions. Identified resources are those whose location, grade, quality and quantity are known or estimated from specific geologic evidence. Identified resources include economic, marginally economic and sub-economic components, and depending upon the degree of geologic certainty, each of those economic divisions can be further subdivided into measured, indicated and inferred.

Reserves are defined as those resources that can be economically mined at the time of determination.

Such reserves can best be specified by using the definition of ore given in the preceding section. Because the iron content of different ore bodies is sometimes widely different, it is often more realistic to compare them on the basis of the iron they contain rather than on the basis of the amount of ore.

Based on these definitions, the United States Geological Survey (with input from former Bureau of Mines files and personnel) has compiled an estimate of the identified world iron ore resources in terms of contained iron-in-ore. Their data are shown in Table 8.3. The geologic descriptions of the individual countries in Section 8.2 contain resource data in terms of ore grades and tonnes of ore.

Table 8.3 World Iron Ore Reserves^(a) (From Ref 1)

Country	Crude Ore		Contained Iron	
	Reserves (million tonnes)	Reserve Base (million tonnes)	Reserves (million tonnes)	Reserve Base (million tonnes)
Australia	18,000	32,200	11,250	20,100
Brazil	11,000	17,000	6,500	10,000
Canada	12,000	26,000	4,600	10,000
China	25,000	49,700	7,500	14,900
India	5,400	12,000	3,300	6,300
Kazakhstan	7,600	9,300	2,800	3,500
Liberia	900	1,600	500	800
Mauritania	400	700	200	300
Russia	34,300	42,000	12,700	15,600
South Africa	4,000	9,300	2,500	5,900
Ukraine	21,800	27,000	8,000	10,000
United States	16,000	25,000	3,800	6,000
others	7,400	16,000	2,300	6,300

^(a) Most of these reserves do not conform to the U.S. Geological Survey MRCS

8.2 Major Iron Ore Deposits

Following are brief descriptions of the major sources of iron ore available to the United States iron and steel industry and the particular markets these sources serve. Also covered are the principal sources of iron ore in international commerce. Included in this category are iron ore sources of North America as well as South America, Africa, Australia, Europe and Asia. Information on other world iron ore deposits can be obtained from the bibliography at the end of this chapter.

It should be borne in mind that the iron ore industry is changing as new steel plants are built, as ironmaking technology advances, as transportation facilities improve, and as ore sources of major importance are developed or expanded. The following comments refer to conditions as they existed in 1998.

The principal iron ore deposits of North America are in the Lake Superior District of the United States and the Quebec-Labrador Region of Canada, as well as deposits in Mexico. Deposits of lesser importance are found in Missouri and Utah. Iron ore deposits still exist, but are no longer mined in Ontario, Texas, New York, Nevada, Wyoming, California, and Alabama. Each iron ore source has its market area which may overlap market areas with other iron ore sources. The Lake Superior ores serve the Great Lakes Region furnaces in the United States and Canada. Quebec-Labrador ores are shipped to the Great Lakes Region furnaces and Eastern seaboard plants, as well as being exported to Europe and Japan; ores from Mexico are used locally.

The general ore reserves for North America are included in Table 8.3. In addition to mined iron ore, byproduct iron or iron oxide is currently available from sources in both Canada and the United States.

8.21 Iron Ore Deposits of the United States

The areas of principal iron ore reserves and resources in the United States are shown in Fig. 8.1. Some are being mined actively while others, for economic reasons, are either inactive or have never

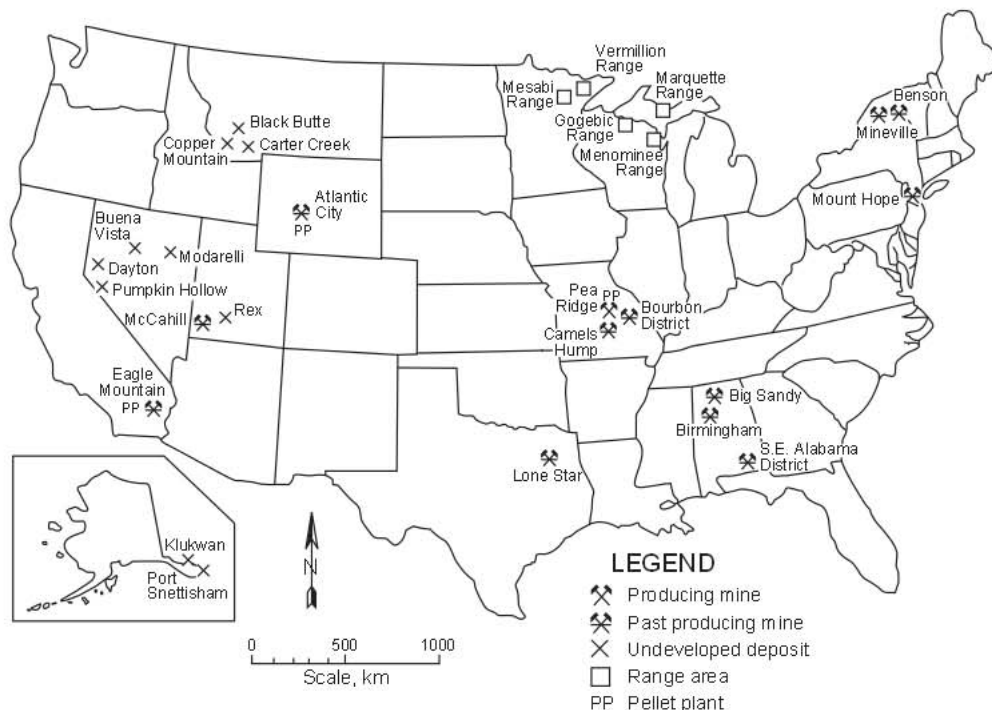


Fig. 8.1 Principal iron ore deposits of the United States.

been developed. They conveniently can be grouped into five areas: Lake Superior, Northeastern, Missouri, Southeastern and Western.

8.2.1.1 Lake Superior District

The iron mining region known as the Lake Superior District is situated on the southwestern margin of a vast area of Pre-Cambrian rocks, geologically termed the Canadian shield, which covers much of Eastern Canada. The district includes several separate mining centers, known locally as ranges, some of which lie within the United States and others in Canada, Fig. 8.2. The only ranges of current interest are in the United States: the Mesabi range in northern Minnesota, and the Marquette ranges in northern Michigan. With the closure of the Wawa mine in 1998 iron ore is no longer mined in Ontario. The Lake Superior District ores are accessible to the blast furnaces in the southern Great Lakes areas by water transportation after short rail hauls to lake ports. The Lake Superior District is one of the great iron mining regions in the world, both on the basis of past production and future potential

8.21.1.1 General Geology The rocks of principal importance to the iron mining industry in the Lake Superior region are of Pre-Cambrian age. For convenience of reference, these rocks are divided into Archean and Proterozoic Eons with subdivisions of Early, Middle and Late within each, Table 8.4. Rocks of the Archean are dated as older than 2.5 billion years, and the Proterozoic rocks range in age from 2.5 to 0.6 billion years. Rock formations in the Lake Superior District display a wide variety of lithologic types including metamorphic sedimentary rocks, quartzites, slates, dolomites and iron formations associated with volcanic extrusive and pyroclastic rocks, many of which are grouped under the general term of greenstones. Intrusive rocks in the region include granites and basic intrusives of various types.

Table 8.4 is a general summary of the geochronology and succession of the principal Pre-Cambrian stratigraphic units and geologic events associated with iron ores in the Mesabi and Marquette Ranges in the Lake Superior region. The table incorporates the principal unit names and their relative stratigraphic positions as presently used, however, the Lake Superior region is the focus of continuing geologic studies which in the future will undoubtedly result in changes being made as the results of more geologic investigations and more radiometric age datings become available.

Iron ore deposits in the Lake Superior region are related to sedimentary banded iron formations of the Archean and Proterozoic Eons in rocks of the Keewatin system and Animikee group in the United States and in the Keewatin and Timiskamian systems in Canada. The term iron formation is applied to banded sedimentary rocks which are composed of layers rich in iron minerals and layers which are largely silica either in the form of chert or finely granular quartz. The iron formations are variously termed ferruginous cherts, ferruginous carbonates, carbonate cherts, jaspers, ferruginous slates and taconite, depending upon mineralogy and texture. Mineralogically the iron formations consist of iron oxides as hematite, goethite or magnetite, iron carbonate (siderite), and the iron silicates—greenalite, minnesotaite, stilpnomelane, grunerite, fayalite, and iron amphiboles and pyroxenes. The iron formation, as originally deposited, probably consisted of layers of iron oxides or iron carbonates and iron silicates interbedded with layers predominantly chert. Upon compaction and metamorphism the original sediments were transformed into materials which are termed magnetic taconites, ferruginous cherts, jaspers, carbonate chert, etc. The magnetite taconites in Minnesota and the jaspers in Michigan are examples of metamorphosed iron formations which are currently important as sources of iron ore. The term magnetite taconite is applied to iron formations in which the principal iron mineral is magnetite associated with varying but lesser amounts of iron carbonate and iron silicate. The silica bands are either chert or granular quartz. The term jasper is applied to the iron formation in Michigan where the principal iron mineral is a flaky, crystalline hematite, steel-gray in color, associated with the finely granular quartz. The jaspers in Michigan are either red-brown or gray-white in color. In some cases, the metamorphism of the iron formation resulted in the extensive development of iron silicate minerals through the chemical combination of iron and silica, so that only a minor part of the total contained iron is in the form of magnetite. In these cases, the material is not of interest as an iron ore.

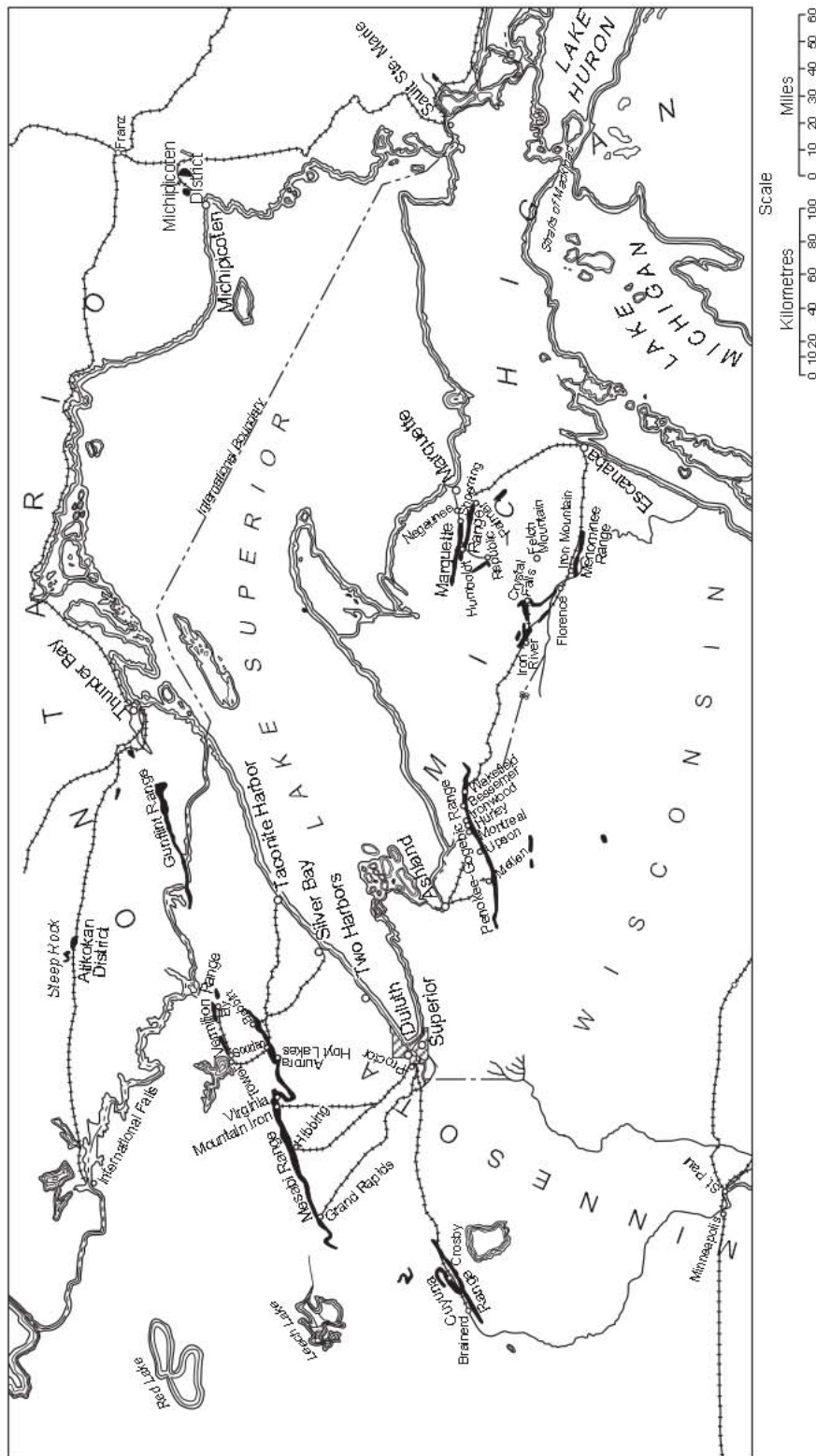


Fig. 8.2 Map of the Lake Superior District, showing location of individual iron ore ranges in the United States and Canada, and the principal lake ports involved in the shipment of iron ore to lower lake ports.

Table 8.4 Generalized Chronology and Stratigraphic Succession of the Lake Superior Region

Eon	Period/System	Orogeny	Mesabi Range	Marquette Range	
PROTEROZOIC					
	KEWEENAWAN	Grenville	Duluth Gabbro		
			North Shore Volcanics Sandstone		
	Animikie Group (Minnesota)	Penokean	(No equivalent rocks)	Granite & Basic Intrusives	
					(No equivalent rocks)
					Upper Slate mbr. Bijiki Iron fm. mbr. Lowert Slate mbr. Clarksburg Volcanics Greenwood Iron fm. mbr. Goodrich Quartzite Negaunee Iron Formation Siamo Slate Ajiibik quartzite Wewe Slate Kona Dolomite Mesnard Quartzite Enchantment Lake fm.
	Algoman	Granite	Granite		
ARCHEAN	TIMISKAMIAN	Laurentian	Knife Lake Slates		
	KEEWATIN		Greenstone		

Iron ores occur within the iron formation either as soft, porous ores which formed by the oxidation and leaching of the iron formation in structurally favorable zones, or as hard ores formed by movement of iron minerals by hot solutions within the iron formation whereby iron oxides (hematite and magnetite) have replaced the silica in favorable areas to form ore bodies; see Fig. 8.3, Fig. 8.4 and Fig. 8.5.

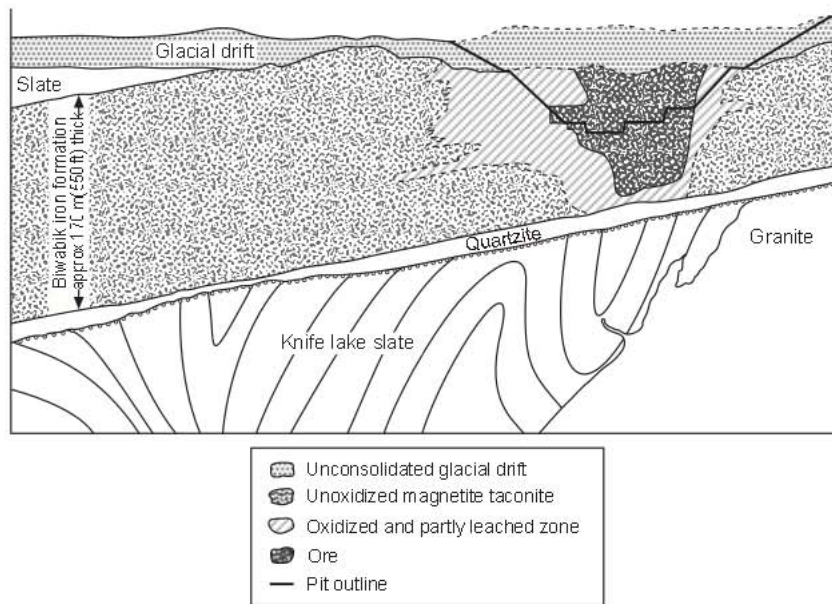


Fig. 8.3 Typical cross-section of an ore body on the Mesabi Range.

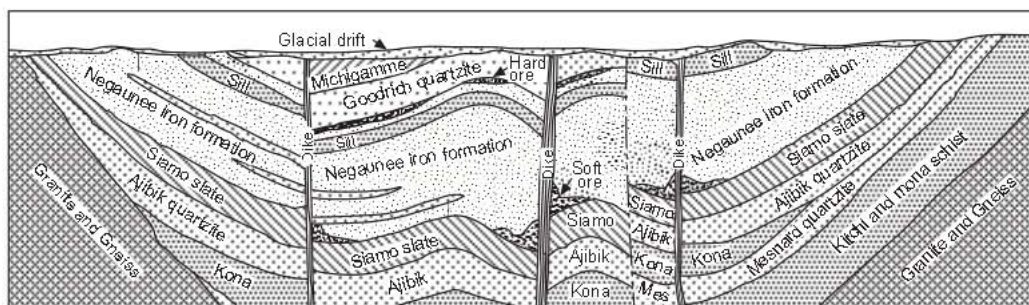


Fig. 8.4 Diagrammatic cross-section of the Ishpeming area of the Marquette Range in Michigan, looking east.

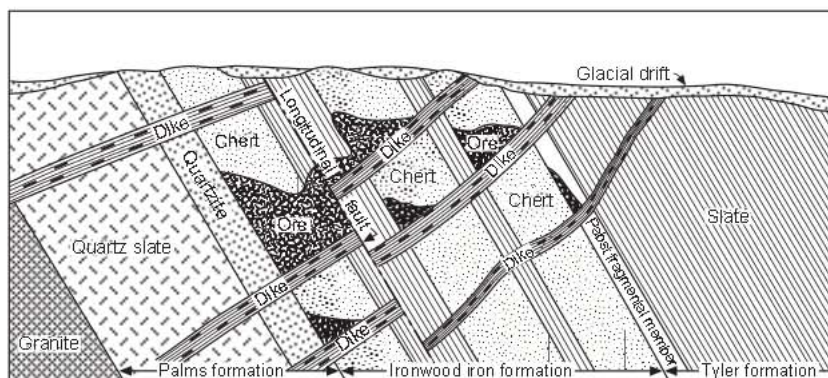


Fig. 8.5 Typical cross-section of the geologic structure of the Penokee-Gogebic Range, showing how ore deposits are located in trough-like structures formed by intersection of dikes with the iron formation.

The Pre-Cambrian iron formations in Minnesota were exposed to erosion during the Cretaceous period which resulted in the local development of a conglomeratic ore along the Mesabi Range in which the pebbles were derived from the iron formation or ores and are cemented by secondary limonite.

The Lake Superior region has been heavily glaciated and a mantle of glacial detritus covers essentially all of the area. The glacial deposits range in thickness from 0–90 m (300 ft).

8.21.1.2 Types of Iron Ore Iron ores of the Lake Superior region vary widely in mineralogy and chemical composition and physical characteristics. The ore types include (1) direct shipping ores and lump ores (commonly termed soft ore and hard ore, respectively), (2) beneficiated ores (material which can be upgraded easily by gravity methods), (3) magnetite taconite which is concentrated by magnetic methods, (4) hematite bearing jaspers which can be concentrated by flotation techniques and (5) potentially concentratable oxidized iron formations (ferruginous chert and semi-taconite). The term direct shipping ore is used to designate ore which is shipped as mined, without beneficiation. Until approximately 1950, iron ores of the Lake Superior region were restricted to the direct shipping ores, lump grade ores and beneficiated ores. Since 1956, magnetite taconite concentrates have contributed substantially to the production of iron ores from Minnesota and Michigan, and, since 1974, jaspers in Michigan have contributed important tonnage's to the production of non-magnetic iron ore concentrates. Magnetite taconite is a hard, dense, compact, fine-grained rock, commonly containing from 40–55% silica and 15–35% iron in the form of magnetite. Magnetite taconite ores are concentrated by magnetic methods after fine grinding. Jasper ore are concentrated by froth flotation methods.

8.21.1.3 The Mesabi Range The Mesabi Range, located about 105 km (65 mi.) north of Duluth in Minnesota, consists of a belt of iron formation about 193 km (120 mi.) long extending from the town of Grand Rapids near the west end to the town of Babbitt on the east end. Iron bearing rocks of the iron formation have been known in this area since about 1866, but commercial iron ore was not discovered until 1890. The first shipment of ore was made in 1892.

The iron ore deposits of the Mesabi Range occur in the Animikie Biwabik iron formation which is overlain by a thick slate series and underlain by quartzite, as shown on the diagrammatic section, Fig. 8.3. The iron formation ranges from about 120–230 m (approximately 400–750 ft) in thickness and is commonly called taconite. Where it is magnetic, it is termed magnetite taconite, and where it has been weathered and the magnetite, iron carbonate and iron silicates are largely oxidized to limonite and hematite, it is commonly termed oxidized iron formation or oxidized taconite. The structure of the rocks on the Mesabi Range is comparatively simple. Rocks generally dip gently to the south, commonly at an angle of less than 10°. In local areas the iron formation dips more steeply or is cut by faults.

The iron ore materials of the Mesabi Range are mainly magnetite taconites. The direct shipping ores of the Mesabi Range are generally soft, porous, blue, red, yellow or brown containing various mixtures of hematite and goethite. The present remaining natural ore operation is the Auburn Mine of U.S. Steel in Minnesota which ships about 400,000 tons/year of lump and fine ore; it will be depleted by 2000.

Magnetite taconites themselves can be considered as ore when they contain sufficient magnetite in grain sizes which allows their commercial concentration by magnetic methods following fine grinding. The fine sized magnetic concentrates must be agglomerated to produce a suitable blast furnace feed. See Section 8.5, Agglomeration Processes, for a description of pelletizing and sintering.

Magnetite taconites are concentrated and agglomerated at several locations in Minnesota. In 1997 about 41 million tons of pellets were produced at seven mine/concentrating/pellet plant complexes. The taconite pellets produced at these locations in 1997 had the compositions shown in Table 8.5.

8.21.1.4 Marquette Range The east trending Marquette Range is located in the northern part of the Upper Peninsula of Michigan with its eastern end 16 km (10 mi.) west of the Lake Superior port of Marquette. The range is approximately 49 km (30 mi.) long and 9.5 km (6 mi.) wide and

Table 8.5 Compositions of Pellets Produced from Concentrates in North America

Location	Fe	P	SiO ₂	Mn	Al ₂ O ₃	CaO	MgO	S		
Magnetic Taconites										
Minnesota	USS Minntac	63.58	0.012	4.25	0.09	0.18	3.52	1.10	—	
	Cliffs Northshore, acid	65.20	0.018	4.80	0.17	0.35	0.80	0.54	—	
	Cliffs Northshore, fluxed	63.30	0.017	4.25	0.16	0.36	3.60	0.86	—	
	LTVSMC	65.25	0.027	5.30	0.11	0.38	0.49	0.49	0.003	
	Eveleth	65.02	0.016	5.61	0.11	0.07	0.87	0.40	—	
	Hibbing	66.30	0.010	4.50	0.08	0.20	0.22	0.31	0.002	
	Inland Minorca	62.87	0.013	4.24	0.14	0.14	4.71	1.48	0.001	
	National	65.89	0.010	4.45	0.10	0.20	0.85	0.20	0.002	
Michigan	Empire, acid	65.10	0.015	5.57	0.07	0.45	0.35	0.37	0.001	
	Empire, fluxed, Viceroy	59.60	0.013	5.40	0.06	0.45	6.48	1.90	0.006	
	Empire, fluxed, Royal	60.90	0.013	5.50	0.06	0.45	4.95	1.55	0.005	
	Tilden, Magnetite	65.20	0.018	5.54	0.14	0.30	0.45	0.35	0.001	
	Tilden, Magnetite, fluxed	61.30	0.017	5.33	0.08	0.30	4.80	1.60	0.007	
	Hematite									
	Tilden, Hematite	65.40	0.036	5.15	0.07	0.45	0.42	0.25	0.001	
	Tilden, Hematite, fluxed	61.70	0.035	4.90	0.08	0.55	4.40	1.70	0.007	
	Canada	Specular Hematite								
		CCM, acid	65.00	0.017	5.35	0.03	0.53	0.60	0.25	0.003
CCM, fluxed		63.00	0.014	4.00	0.03	0.50	3.92	1.30	0.011	
CCM, low silica fluxed		65.10	0.010	2.50	0.02	0.45	2.25	1.50	0.008	
CCM, direct reduction		67.80	0.010	1.70	0.02	0.40	0.50	0.30	0.002	
*ICC, acid		65.60	0.008	4.75	0.11	0.27	0.50	0.30	0.002	
*ICC, acid, limestone		65.30	0.010	4.75	0.11	0.26	1.00	0.30	0.003	
*ICC, fluxed		61.90	0.010	4.75	0.11	0.30	4.30	1.80	0.015	
*ICC, fluxed, 4 % SiO ₂		63.50	0.010	4.00	0.11	0.30	3.60	0.70	0.010	
Wabush, acid, low Mn		66.00	0.010	3.25	1.20	0.40	0.40	0.12	0.010	
Wabush, fluxed, low Mn		63.25	0.010	3.25	1.10	0.40	2.90	1.30	0.010	
Wabush, acid, high Mn		65.20	0.010	3.25	2.00	0.40	0.40	0.12	0.010	
Wabush, fluxed, high Mn		62.40	0.010	3.25	1.95	0.40	2.90	1.30	0.010	

* ICC ore contains about 25% magnetite

includes the towns of Negaunee, Ishpeming, Palmer, Humboldt, Republic and Michigamme, see Fig. 8.2. Mining of natural ores was centered in the vicinity of Negaunee, whereas the mining of concentrating materials is in the vicinities of Republic, Ishpeming, Palmer and Tilden. Natural ores are no longer produced and all current production is from magnetic and nonmagnetic taconites. The Cleveland Cliffs Mather Mine, the last underground mine on the range, was closed permanently in 1979.

The Marquette Range is a large structurally complex synclinal basin comprised of metasedimentary and metavolcanic rocks which are collectively referred to as the Marquette Range Supergroup. These rocks have been tightly folded into a westward plunging syncline which opens toward the west. The Negaunee Iron Formation, the unit of major economic importance, attains thickness of 760 m (2500 ft) on the eastern end of the syncline near the city of Negaunee, but thins rapidly toward the west. The entire sequence has been faulted and cut by younger intrusives as shown in Fig. 8.4.

The metamorphosed Negaunee iron formation contains both specular hematite and magnetite facies. These are the present source of the iron minerals for the production of concentrates and pellets. Much of this iron formation requires fine grinding (up to 90% -0.019 mm or -500 mesh) for the liberation of the ore minerals. Concentration is either by selective flotation or magnetic methods or a combination of both. The concentrates are agglomerated into pellets ranging from 63.20–63.82% iron and 4.72–6.25% silica. In 1997 there were two operating mining and pelletizing operations which produced about 14.4 million tonnes of pellets.

8.2.1.2 Iron Ore Deposits in Other Parts of the United States

Iron ore mining had ceased by 1980 in the states of Alabama, Wyoming, Texas, New York, New Jersey, and Pennsylvania; the only other sites of potential current interest are:

The Pea Ridge Iron Ore Co. near Sullivan, Missouri has the only active underground iron mine in the country and one of the few in the world. The mine is on the northeast flank of the Ozark uplift and has proven reserves of 160 million tonnes of ore grading 55% magnetic iron. The mining and pelletizing complex was developed between 1957 and 1964. In January 1991, the company ceased pellet production and began concentrating on specialty iron oxide products, which had formerly been co-products. Production of direct reduction ore is being studied.

Geneva Steel of Utah maintains (but has not operated in recent years) two open pit mines, the Comstock and Mountain Lion, in the Pinto District of Iron County. The district, 32 km (19 mi.) west of Cedar City, has provided magnetite and hematite ores for blast furnaces in the Rocky Mountain region on an intermittent basis since 1923. Coarse ore and fines were shipped 370 km (220 mi.) to the Geneva Steel integrated steelworks at Provo.

8.2.2 Iron Ore Deposits of Canada

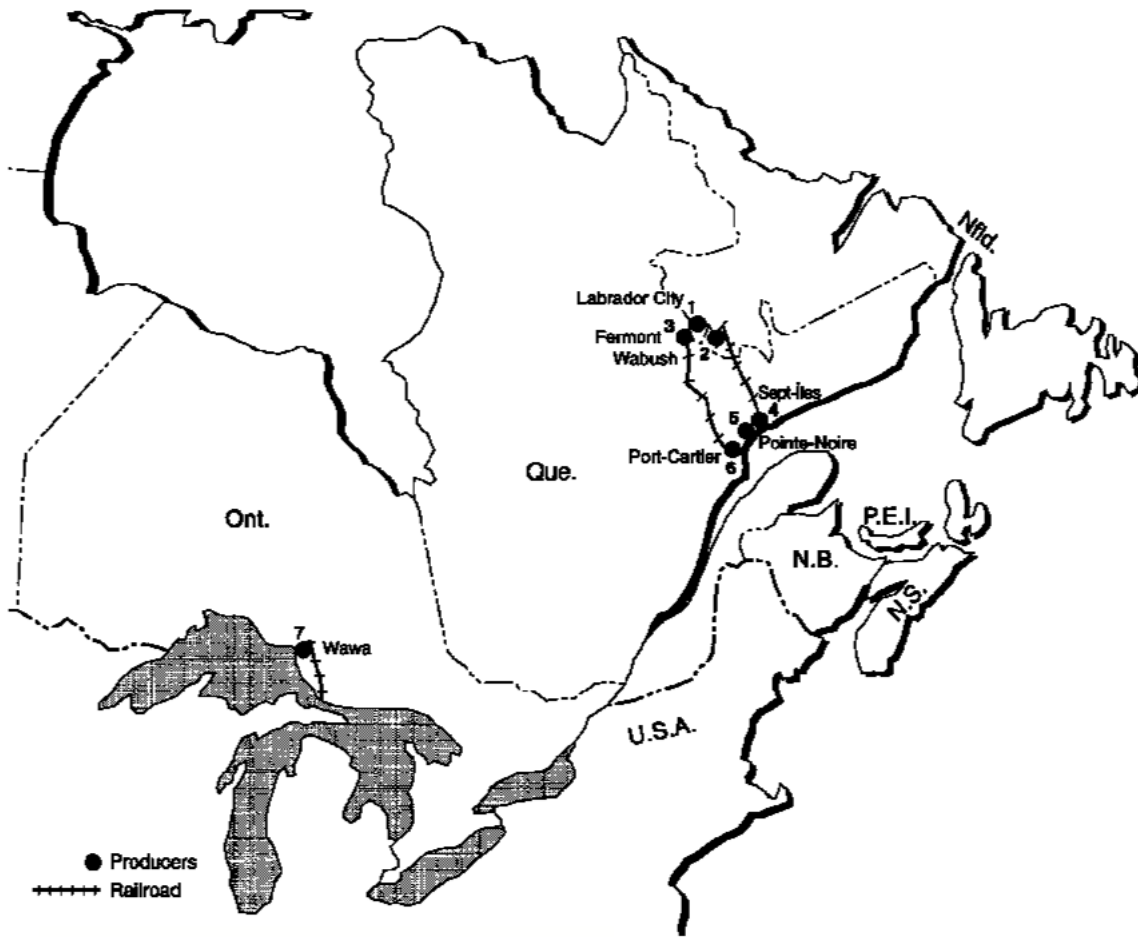
Canada ranked 8th in world iron ore production in 1996 with total shipments of 36 million tonnes. Of this tonnage, 27.9 million were exported, where Canada ranked 4th, after Australia, Brazil and India (Russia and the Ukraine combined would have exports exceeding that of Canada). Major export destinations were Europe, the United States and Japan.

All of the Canadian iron ore is concentrated at the mine sites and about two-thirds is pelletized. The grade of the concentrates and pellets ranges from 62–67%. The major companies offer concentrates, acid and fluxed pellets, all with very low concentrations of alumina and phosphorus. Some of the pellets are produced for direct reduction furnaces.

There are three mining operations in the Labrador Trough area of northern Quebec and Labrador, see Fig. 8.6, and these account for over 98% of Canadian iron ore production. These mines belong to the Iron Ore Company of Canada (IOC), Quebec Cartier Mining Company (QCM), and Wabush Mines. There are also a magnetite mine in Newfoundland, Lodestone Limited, and byproduct recovery of magnetite from two base-metal smelters in British Columbia. Although not included in the iron ore industry, QIT-Fer et Titane Inc. mines ilmenite, an iron-titanium ore, near Havre-St-Pierre, Quebec, and produces pig iron as a co-product of titanium slag. Employment in the iron ore industry is about five thousand.

In 1991, IOC became the first iron ore mine in the world to be certified under the International Organization for Standardization (ISO) ISO 9002 and in 1995, QCM became the first iron ore mine in the world to obtain ISO 9001 certification. ISO 9001 covers design (product development) in addition to production, installation and servicing defined for ISO 9002, which QCM obtained in 1992.

In December 1996, IOC announced a \$75M investment plan for its facilities in Labrador City and Sept-Îles, and the Quebec North Shore & Labrador Railway (QNS&L). A major part of the investment will be directed to producing iron ore pellets suitable for use in direct reduction furnaces. The mine, concentrator and pellet plant are all located in Labrador City. IOC operates the QNS&L to carry concentrate and pellets to its port at Sept-Îles on the Gulf of St. Lawrence. The port can



Numbers refer to locations on map above.

Producers

1. Iron Ore Company of Canada, Carol Lake Division (mine/concentrator/pellet plant)
2. Wabush mines (mine/concentrator)
3. Quebec Cartier Mining Company (mine/concentrator)
4. Iron Ore Company of Canada (port)
5. Wabush Mines (pellet plant/port)
6. Quebec Cartier Mining Company (pellet plant/port)
7. Algoma Ore, division of Algoma Steel Inc. (mine/concentrator/sinter plant)

Fig. 8.6 Iron ore mines of Canada. (Source: Natural Resources Canada)

accommodate cape-sized vessels. IOC's shipment levels in the 1995–1997 time frame were about ten million tonnes/year (Mt/y) of pellets and five million tonnes/year of concentrate for shipment to North America, Europe and Asia. The re-start of the idle Sept-Îles pellet plant is planned.

In February 1996, QCM purchased Normine's pellet plant for \$105M. QCM had been operating the plant since 1985 and since then has raised the production capacity from 6 Mt/y to 8.8 Mt/y, including a capacity for direct reduction pellets of 3.5 Mt/y. QCM operates its own railway to carry concentrate from the mine and concentrator complex at Mt. Wright to the pellet plant and port at Port Cartier, west of Sept-Îles. The port can accommodate cape-sized vessels. QCM's shipment levels in the 1995–1997 time frame were about 8.4 Mt/y of pellets and 7.5 Mt/y of concentrate for shipment to North America, Europe and Asia. In 1998 QCM began shipments of concentrate to the

United States for use in a rotary hearth furnace direct reduction process which in turn feeds hot DRI to a submerged arc furnace to produce liquid hot metal for EAF feed.

Wabush Mines increased its shipments of pellets in 1996 relative to 1995. The 5.3 Mt shipped during the year, mainly in North America and to Italy, was another step up from the 4.6 Mt/y operating level of the early 1990s. Wabush operates short-lines to carry concentrate from its mine at Wabush, Labrador to the QNS&L and from the south end of the QNS&L to its pellet plant and port at Pointe Noire, near Sept-Îles.

The chemistries of pellets produced at IOC, QCM and Wabush are shown in Table 8.5.

The Quebec-Labrador area contains extremely large reserves of concentrating ore and will continue to be Canada's prime producer for many years. The Labrador geosyncline extends from the northwest side of Ungava Bay southward to Knob Lake, Wabush Lake and then southwest to Lake Alabanel, a distance of 1600 km. This arcuate shaped structure is divided into three general zones, see Fig. 8.7.

- (I) The northern zone extends from northwest Ungava southward to Kuujuaq (formerly Fort Chimo). The iron formation of this area is characterized as a medium-grained hematite-magnetite quartz rock amenable to beneficiation. It occurs in long synclinal or overturned to recumbent folds with the iron formation beds repeated across the strike. The potential tonnage in this area is very large but there has been little definitive evaluation of the many known prospects.
- (II) The central area of the Labrador geosyncline extends southward from the vicinity of Kuujuaq to Knob Lake. Over 47 deposits have been investigated in the central area. Estimates indicate that over 2 billion tonnes amenable to open pit mining may exist. The central zone is characterized by Lake Superior type iron formations similar to the Mesabi Iron Range of northern Minnesota where rich hematite-goethite deposits occur within fine-to medium-grained, bedded,

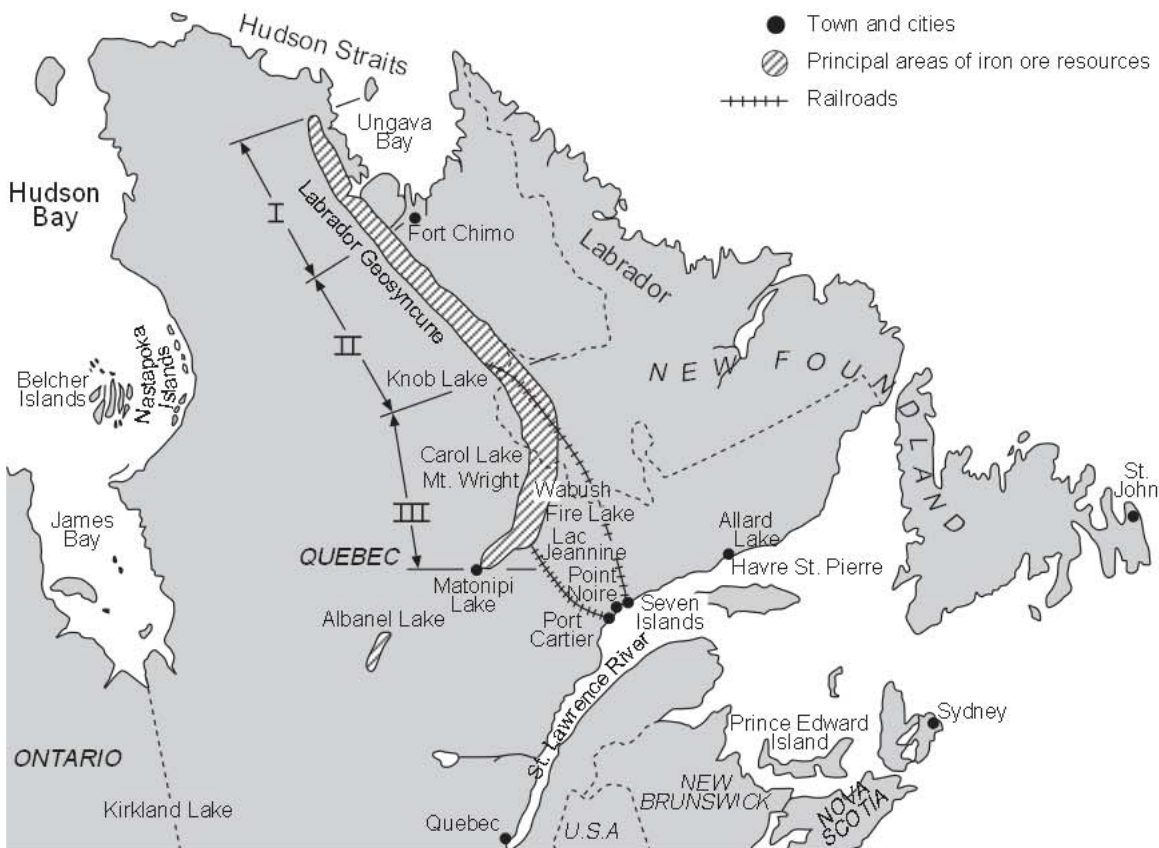


Fig. 8.7 Iron ore resources of Quebec and Newfoundland.

hematite, magnetite chert rock with iron silicates. Some of the ores are direct shipping, others are amenable to known methods of concentration such as magnetic, spiral and flotation. Deposits may contain up to 25% magnetite. The central area contains the former Schefferville/Knob Lake mine of IOC.

- (III) The southern zone extends from north of Wabush Lake to Mt. Wright and Fire Lake then southwestward to Matonipi Lake. The iron formations of this area lie within the Greenville Belt and are characterized by medium-to coarse-grained specular hematite, magnetite, quartz and minor iron silicates. They are all concentrating ores but due to their coarse grain size are all amenable to gravity concentration at around 0.6 mm or 28 mesh. Known deposits are highly folded. IOC, QCM and Wabush all have their operating mines in this zone.

Algoma Steel Corporation, Ltd. has mined siderite from various mines on the Michipicoten Range since 1939. Calcining the sideritic ore at Wawa, via the sintering process, on this range raised the grade from 35% to 50% iron. This operation was shut down in 1998.

Canada's iron ore reserves are substantial. Aside from the vast Quebec-Labrador region, there are large resources of concentrating magnetite-bearing quartzites in the Canadian Arctic on the Melville Peninsula, at Roche Bay in the Northwest Territories; on Ungava Bay, Quebec; at Schefferville, Quebec; in placer titanium-iron deposits near Natashquan, Quebec and in the Peace River area of Alberta. In Ontario, there are occurrences of concentrating ore across the province.

8.23 Iron Ore Deposits Of Mexico

There are more than 30 iron ore occurrences of more than one million tonnes each reported in Mexico; however, the principal iron ore occurrences are located in the Las Truchas, Pena Colorado and El Encino districts along the Pacific coast of Central Mexico and at the La Perla and Hercules localities in Northcentral Mexico, see Fig. 8.8. The deposits are mostly massive, irregular and dike-like

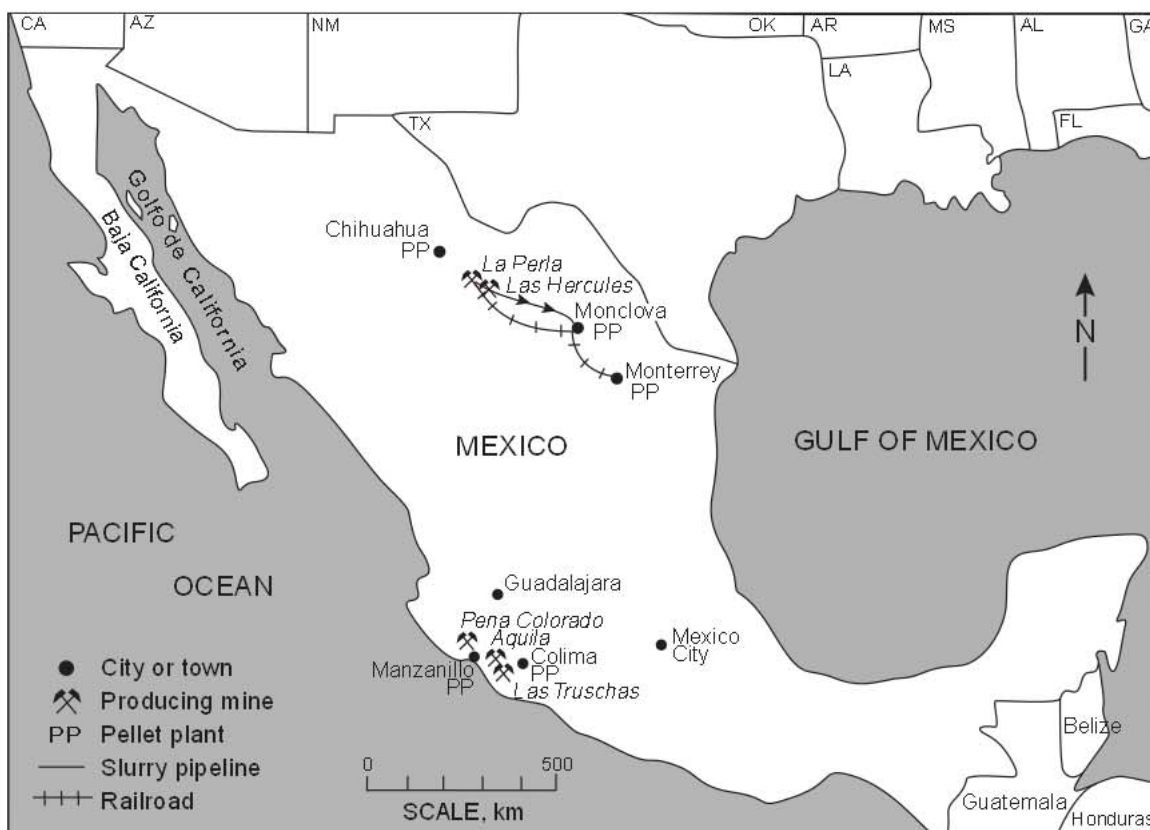


Fig. 8.8 Iron ore deposits of Mexico.

bodies in igneous and sedimentary rock and as metasomatic replacements in limestone's. They are composed of hematite, magnetite, goethite with minor pyrite and chalcopyrite.

Mexico's iron ore production was 12.91 Mt/y in 1996, an increase from the 10.6 Mt/y in 1995. In 1995 that production included 9.94 Mt/y of pellets and lump ore, all for domestic consumption. Pellet production sites include Monclova (AHMSA), Pena Colorada, Alzada and Lazaro Cardenas (Villacero). A pellet plant, ordered some time ago, but never completed, was started up in 1997 in Lazaro Cardenas by IMEXSA. The Grupo Acero del Norte (GAN) is Mexico's largest mining company. It acquired the state-owned Altos Hornos de Mexico (AHMSA) iron ore operations in 1991 which included the La Perla mine and the Hercules mine. A 380 km (228 mi.) slurry pipeline connects the Hercules and LaPerla mines to the AHMSA's sinter and pellet plants in Monclova. The GAN Cerro de Mercado Mine in Durango was restarted in 1994 following an eight year shutdown. Iron ore and steel production are expanding in Mexico with iron ore production expected to exceed 15 Mt/y by 2005. The utilization of natural gas is facilitating an expansion of direct reduction facilities but privatization has also rejuvenated the blast furnace based sector, as well.

8.24 Iron Ore Deposits of South America

8.241 Argentina

The principal iron deposits of Argentina, see Fig. 8.9, are located near Zapla and at Sierra Grande. Mining at Zapla ceased some time ago. The mine at Sierra Grande was intended to produce enough ore to yield 2.5 million tonnes of pellets. The pellet plant, owned by HIPASAM, at the port of Punta Colorada, started production in 1979. After many years of difficult operation, the pellet plant and mine were shutdown in 1991. Argentina's revitalized blast furnace and direct reduction steel sectors receive iron ore primarily from Brazil as Argentina no longer produces any iron ore. In recent years an organization called HIPARSA has been exploring ways of upgrading the Sierra Grande ore for use in alternative ironmaking technologies.

8.242 Bolivia

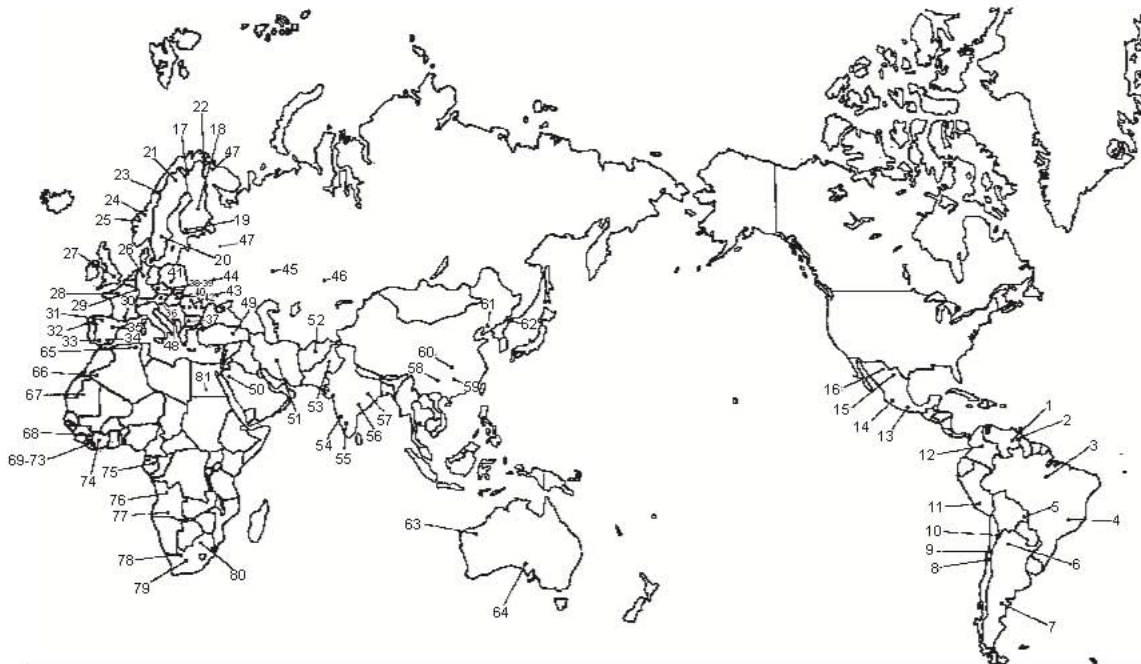
Bolivia is a small-scale iron ore producer but it does contain large iron ore resources which have at various times been proposed for development. The principal deposits, see Fig. 8.9, are located in the Cerro Mutun near Puerto Juarez in Southeastern Bolivia. Small amounts of iron ore of up to 80,000 tonnes per year have been shipped by barge to Argentine ports. Some mining operations began in 1990 with two concentrators with a capacity of 0.2 Mt/y available. The ore (sintering ore fines, 63–66% Fe) is trucked to Puerto Suarez and then to the Brazilian port of Puerto Ladario for barge transport to the Paraguay Company, Aceptar. The ore consists of bedded hematite with intercalated siliceous beds which have been enriched residually by weathering and the removal of silica. Ore grades are reported to vary from 45–55% Fe, 11–29% SiO₂ and 0.03–0.17% P. The indicated and inferred resources are reported to range up to 40,000 million tonnes of residual and detrital ore.

The latest study for the El Mutun ore deposit, conducted by the Corp. Minera de Bolivia (Comibol), could be facilitated by the availability of cheap natural gas which could enable an export-oriented direct reduction project.

8.243 Brazil

Iron ore production, whose estimated mine value in 1995 was US\$2,125 billion, represents about 18% of the mineral production in Brazil and constitutes the second most important mineral produced in Brazil, after crude oil. Brazil is the biggest iron ore producer, ahead of Australia and China, and shares with Australia the leadership in iron ore exports. Brazil's exports in 1995, represent 131,358 thousand tonnes, or 20.8% of the basic products exports, yielded US\$2,530 billion.

Although the average percentage of iron ore assay in Brazil is 53% of the measured reserves, the mines in operation produce iron ore with more than 65 % of purity. The varieties found in Brazil

**South America**

1. Cerro Bolivar, Venezuela
2. El Pao, Venezuela
3. Carajas, Brazil
4. Quadrilatero Ferrifero, Brazil
5. Mutun, Bolivia
6. Zapla, Argentina
7. Sierra Grande, Argentina
8. El Romeral, Chile
9. Algarrobo, Chile
10. El Laco, Chile
11. Marcona, Peru
12. Paz de Rio, Colombia

Central America

13. Las Truchas, Mexico
14. Pena Colorado, Mexico
15. Hercules, Mexico
16. La Perla, Mexico

Western Europe

17. Jussaro, Finland
18. Otanmaki, Finland
19. Rauturaara, Finland
20. Grangesberg, Central Sweden
21. Kiruna, etc., Northern Sweden
22. Sydvaranger, Norway
23. Rana, Norway
24. Fosdal, Norway
25. Rodsand, Norway
26. Salzgitter, Gifhorn, Peine-Ilse; Federal German Republic
27. Frodingham-Northampton-Lincoln-Wales; United Kingdom
28. Lorraine, France
29. Normandy, France
30. Pyrenees, France
31. Santander and Viscaya, Spain
32. Leon, Spain
33. Huelva-Sevilla, Spain
34. Granada-Almeria, Spain
35. Teruel, Spain
36. Erzberg, Austria

Eastern Europe

37. Kremikowtzi, etc., Bulgaria
38. Slovakia
39. Slovakia
40. Rudabanga, Hungary
41. Czeszochowa Klobuck, Poland
42. Romania
43. Ukraine, CISR

Eastern Europe (Continued)

44. Kursk, CISR
45. Urals, CISR
46. Kazakhstan, CISR
47. Kulo, CISR
48. Vares, Yugoslavia

Middle East and Asia

49. Divrigi, Turkey
50. Wadi Sawawin, Saudi Arabia
51. Choghart, Iran
52. Hajigarh Pass, Afghanistan
53. Chichali, Pakistan
54. Goa, India
55. Kudremukh, India
56. Mahya-Pradesh, India
57. Bihar-Orissa, India
58. Chichiang, Peoples Republic of China
59. Tayeh, Peoples Republic of China
60. Ninghsiang, Peoples Republic of China
61. Anshan, Peoples Republic of China
62. Musan, North Korea

Oceania

63. Hamersley Ranges, Australia
64. Middleback Range, Australia

Africa

65. Ouenza, Algeria
66. Gara Djebilet, Algeria
67. Kedia d' Idjil, Mauritania
68. Nimba, Guinea
69. Wologisi, Liberia
70. Mano River, Liberia
71. Bie Mountain, Liberia
72. Bong Range, Liberia
73. Nimba (Lamco), Liberia
74. Mont Klahoyo, Ivory Coast
75. Mekambo, Gabon
76. Cassala, Angola
77. Cassinga, Angola
78. Sishen, South Africa
79. Beeshoek, South Africa
80. Thabazimbi, South Africa
81. Bahariya, Egypt

Philippines

82. Santa Ines
83. Mindanao

Fig. 8.9 Outline map showing locations of the principal sources of iron ores outside North America.

are hematite, mainly in Carajás mine (state of Pará), with percentages varying from 60–68% of hematite iron, and itabirite mainly in Minas Gerais, with percentages varying from 50–60% of iron. It must be emphasized that Brazil has reserves of 20 billion tonnes, and estimated reserves of about 50 billion tonnes of iron ore. Its main reserves are found in Minas Gerais and Pará.

In Brazil, there are about 40 companies directly involved in iron ore mining, of which seven cover 95% of the production: Companhia Vale do Rio Doce—CVRD (formerly state owned company, privatized in May 1997); Minerações Brasileiras Reunidas S.A.—MBR; Samarco Mineração S.A.; Samitri S.A.; Ferteco Mineração S.A.; Companhia Siderúrgica Nacional—CSN; and Itaminas. Mines in Brazil are mainly located at the Iron Quadrangle (Minas Gerais), the Carajás region (Pará), and at Corumba (Mato Grosso do Sul). The main mining districts, mining companies, ports and railroads are shown in Fig. 8.10 and Fig. 8.11.

824.31 Iron Quadrangle Geology Generally speaking, the Iron Quadrangle may be divided geologically in three major units: Basement (Archean); Supergroup Rio das Velhas (Archean); Supergroup Minas (Inferior Proterozoic). The main iron mines are represented by layers of itabirite up to 250m (820 ft) thick, related to Supergroup Minas, more specifically to the Group Itabira (Formation Cauê). Itabirite show iron ore with oxidized characteristics, represented by hematite, magnetite or martite. In Gandarela Formation (Group Itabira), superimposed to Cauê Formation, there are various levels of itabirite, although smaller, associated to dolomite. The most economical ores are those resulting from the enrichment of ore caused by lateritic weathering. Iron ores in the Itabira district are basically high-grade hematite ores (67% Fe) and lower grade hematite ores amenable for WHIMS (wet high intensity magnetic concentration).

824.32 Carajás Geology The main group of deposits are found between North Mountains (Serras Norte) (N1 to N9), South Mountains (S1 to S45) and East Mountains (SL1 to SL3), geologically related to Group Grão Pará. The N4 deposit is the site of one of the largest operating iron mines in the world. It is hosted by the Late Archean Grão Pará Group, which is the lowermost stratigraphic unit of the Serra dos Carajás Volcano sedimentary Belt. The Grão Pará Group is composed of the

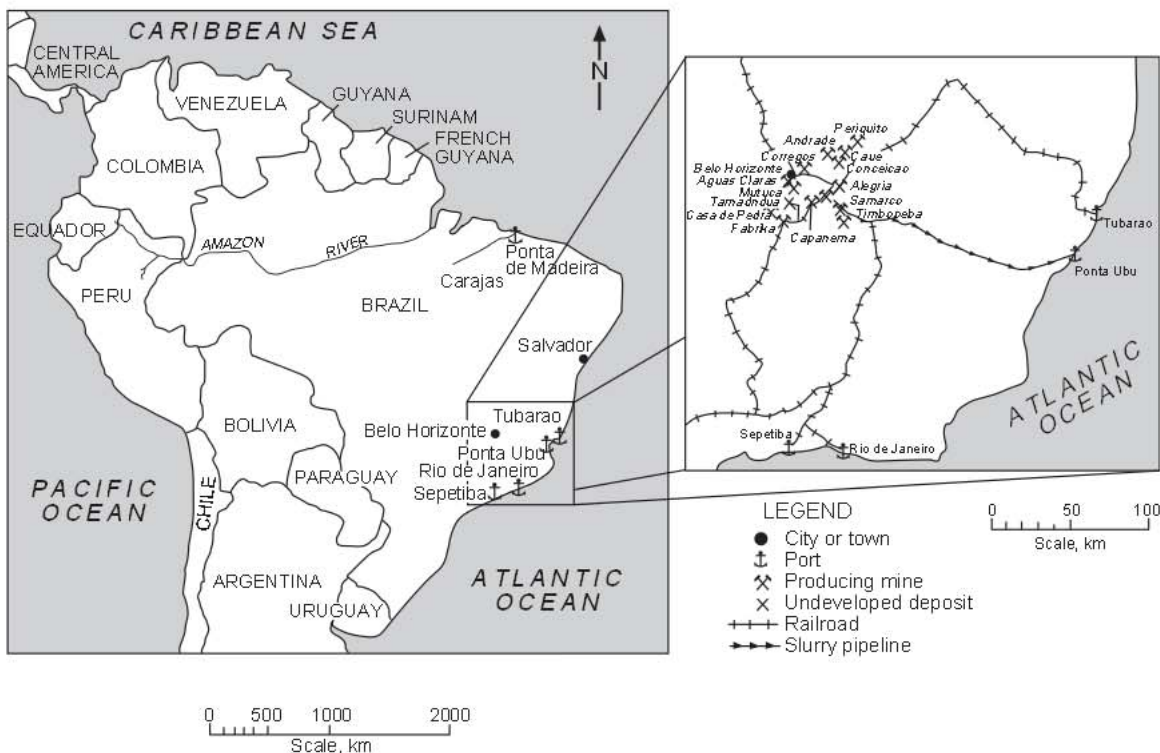


Fig. 8.10 Brazilian mining districts. (Source: Iron Ore Availability—Market Economy Countries, circular 9128, United States Department of Interior.)

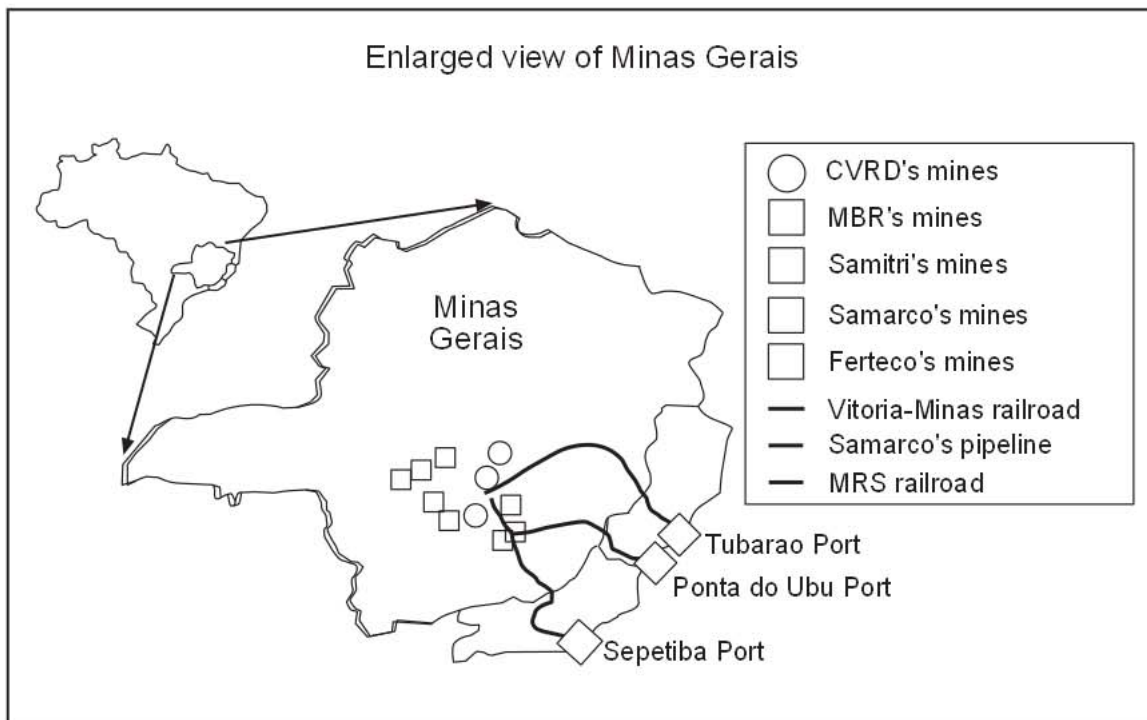
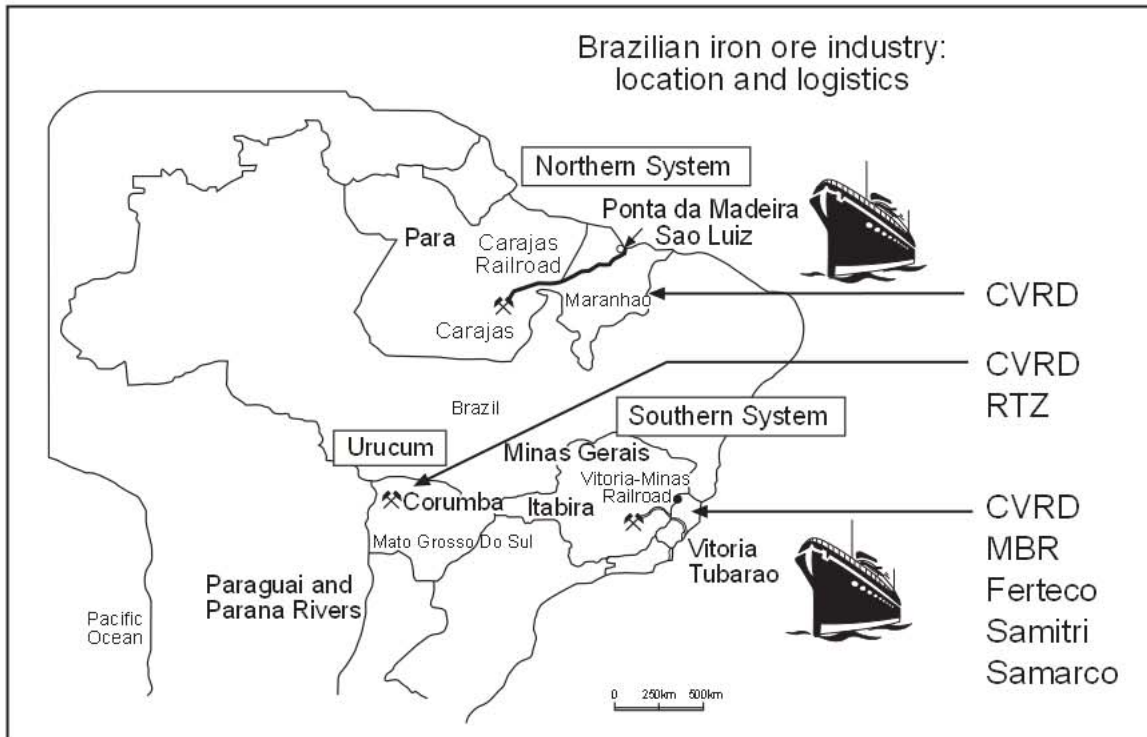


Fig. 8.11 Brazilian Iron Ore Industry: Location and Logistics. From Ref. 2.

predominantly volcanic Parauapebas Formation and the overlying Carajás Banded Iron Formation, the protone of the lateritic iron deposits.

The Grão Pará Group is divided into the Parauapebas Formation and the Carajás formation. The Parauapebas Formation consists of basic to intermediate metavolcanic rocks intercalated with sandstone and conglomerate. The extrusive rocks are greenish, fine-grained and generally porphyritic flows with localized vesicular zones and subordinate pyroclastic deposits. The Carajás Formation consists of a thick pile of chemical sediments starting with lenticular carbonate deposits (presently dolomitic) that grade upwards to an extensive and extremely regular jaspilitic banded iron formation (BIF).

8.24.3.3 Brazil Iron Ore Production—CVRD Companhia Vale do Rio Doce S.A. (CVRD) accumulated over 50 % of the total Brazilian production in 1997. In 1997, CVRD was the world's largest producer and exporter of iron ore and pellets, with production of 100.2 million tonnes and exports of 83.9 million tonnes (representing approximately 19.9% of the seaborne export market for iron ore and pellets). In 1997 approximately 70% of CVRD's shipments were made to customers in its exports markets, with 85% of these to Asian and European steelmakers.

CVRD operates two modern integrated iron ore mining and transportation systems in Brazil (the Southern System in the States of Minas Gerais and Espírito Santo and the Northern System in the States of Pará and Maranhão. Each incorporates a 900 km (540 mi.) integrated railroad network and automated port and terminal facilities designed to provide iron ore, freight and passenger rail transportation, bulk terminal storage and ship loading services to CVRD and third parties.

8.24.3.3.1 Southern System The Iron Quadrangle, situated in the State of Minas Gerais, has iron ore reserves estimated at approximately 1.4 billion tonnes, which can be processed using current technology. The reserves have a natural average iron content of 56.3% and are mined by open pit methods. Concentration operations are performed in on-site extraction facilities to improve the grade of products, as needed, to an average iron content of between 64% and 67%. The ore is then transported to port and terminal facilities or directly to certain domestic steelmaking customers via the company owned Estrada de Ferro Vitória Minas (EFVVM) railroad network for 540 km (324 mi.) from Itabira and 616 km (370 mi.) from Timbopeba to the Tubarão marine terminal, located near the Port of Vitória in the State of Espírito Santo. The Tubarão complex, which includes the Company and joint venture pelletizing facilities, covers nearly five square miles and can store up to 4.9 million tonnes of iron ore. The Tubarão port can accommodate vessels of up to 350,000 deadweight tonnes.

The Southern System iron ore mining operations accounted for aggregate production of approximately 55.5 million tonnes of iron ore products in 1997. The Cauê mine located in the Itabira district will be exhausted within four years, and CVRD expects to supply the Caue beneficiation plant with iron ore transported by truck from other CVRD mines in the area.

The Company also participates (in a joint venture with Japanese interests) in the Capanema iron ore mine located in Ouro Preto region of the State of Minas Gerais. The Capanema mine has a life until 2002/2003 and contains iron ore with an average dry iron content of 62.6%. The Capanema mine initiated operations in 1982 and produced 6.0 million tonnes of iron ore in 1997. The mine is linked by conveyor belt to the concentrator in Timbopeba. Other mineral deposits in the Southern System include over 6 billion tonnes of hematite and soft itabirite ore, which can be processed using current technology. An additional 3 billion tonnes of hard itabirite are present and CVRD is developing technology and conducting economic evaluations to determine the viability of production of this material. There are 13 billion tonnes of iron ore outside the main area, representing small deposits.

CVRD conducts pelletizing activities mainly to process fine and ultrafine iron ore in the Southern System designed to produce pellets for use in blast furnace or direct reduction steelmaking processes. CVRD operates six pelletizing plants at its Tubarão marine terminal complex, two of which are owned by the Company and four of which are owned by three separate majority-owned joint ventures with Italian, Spanish, Korean and Japanese steelmakers: Companhia Italo-Brasileira de Pelotização (Itabasco), Companhia Hispano-Brasileira de Pelotização (Hispanobrás), Kobrasco

(started up in 1998) and Companhia Nipo-Brasileira de Pelotização (Nibrasco). These plants have an aggregate annual capacity of 26 million tonnes of pellets. CVRD is planning a 6 MTPY pellet plant at Carajás.

824.33.2 Northern System The Carajás iron mines are located at the cities of Marabá and São Felix do Xingu, in the south of Pará. The Northern System has iron ore reserves estimated at approximately 1.6 billion tonnes and other iron ore mineral deposits near Carajás estimated at 17 billion tonnes, making it one of the world's largest deposits of high-grade iron ore. The iron ore mined at Carajás has a high average dry iron content of 66.2% and marketable sinter feed and lump ore can generally be produced through on-site crushing and sieving operations. The Carajás mining complex consists of an open pit mine with adjacent crushing and desliming facilities for the production of sinter feed (approximately 90% of production) and lump iron ore (approximately 10% of production). Carajás ore is transported to port and terminal facilities via the CVRD Carajás Railroad which extends for 892 km (535 mi.) to the Ponta da Madeira marine terminal located near São Luis in the State of Maranhão. The Ponta da Madeira complex has a storage yard for up to 2.2 million tonnes and can accommodate vessels displacing up to 365,000 deadweight tonnes. CVRD anticipates additional increases (up to a potential 60 Mt/y) could be achieved through selective investments in the Carajás Railroad without the need to construct a second line of track but more sidings.

824.33.3 Urucum Region The main iron ore and manganese mines of Mato Grosso do Sul are located in Corumbá and Ladário, near the international border of Brazil and Bolivia. The region is served by EFNOB, Brazilian Northwestern Railroad, connected to FEPASA, Paulistas Railroad, and thus is linked to Campo Grande, and São Paulo and Santos harbor. The Atlantic Ocean may be connected through the river Paraguay, with Corumbá and Ladário at its right bank. Transportation to customers in Paraguay and Argentina is only by rivers.

CVRD iron ore and pellet production in 1997 was as follows: Northern System—Carajás, 44.8 Mt/y; Southern System—Minas Gerais, 50.5 Mt/y; Urucum, 0.65 Mt/y; Capanema joint venture, 5.0 Mt/y; CVRD pellets production, 5.2 Mt/y; JV pellet production, 16.1 Mt/y.

824.34 Brazil Iron Ore Production—MBR Mineracoes Brasileiras Reunidas (MBR) is the second largest iron ore producer and exporter in Brazil and is 70% owned by CAEMI of Brazil and the balance by foreign interests. MBR's mining operations are located in the Iron Quadrangle in the State of Minas Gerais. Mining started with the Pico de Itabirito mine and expanded to the Mutuca mine. The Aguas Claras Mine project was initiated to exploit a high-grade hematite orebody in Nova Lima; the project also included an ocean terminal on Gauge Island in the State of Rio de Janeiro.

Initiation of mining is ongoing at the Tamandua, Capitao do Mato and the Capao Xavier deposit. These mines will ultimately replace the depleting deposits at Aguas Claras and Mutuca while still maintaining the production goal of 32 Mt/y which is expected by 2001. The Tamandua Mine production is expected to reach 14 Mt/y by 2012; the geological reserve is 327 million tonnes (153 million tonnes mineable) and 730 million tonnes of rich itabirites. The Capitao do Mato will reach 9 Mt/y by 2003; the geological reserve is 154 million tonnes (126 million tonnes mineable). The Capao Xavier Mine will increase to 6.5 Mt/y by 2008. The geological reserve is 169 million tonnes (133 million tonnes mineable) and 109 million tonnes of rich itabirites.

The Aguas Claras Mine, located 10 km (6 mi.) from Belo Horizonte, will have its capacity reduced 3.3 Mt/y in 2003, the projected final operating year. The Aguas Claras beneficiation plant has a capacity of 13.2 Mt/y of lump ore, sinter feed and pellet feed fines; the process includes crushing and screening, hydroclassification, cycloning and filtering. The Mutuca mine, located about 15 km (9 mi.) south of Belo Horizonte, will see its capacity decline from 6.5 to 2.4 Mt/y in the period 1996—2002. The beneficiation process is similar to that of Aguas Claras and produces mainly high-grade lump ore for direct reduction as well as blast furnace lump ore, sinter and pellet feed fines.

The Pico Mine, located 40 km (24 mi.) south of Belo Horizonte, has two beneficiation plants, one for hematite and the second for itabirite products which include ore for charcoal blast furnaces and siliceous (5% SiO₂) sinter feed. The hematite beneficiation plant includes crushing and screening, hydroclassification, cycloning, filtering and column flotation, while the itabirite process focuses on

crushing and screening and hydroclassification. The Pico Mine has a hematite geological reserve of 183 million tonnes (89.5 mineable) and a 550 million tonnes of rich itabirite geological reserve.

In 1997 a consortium which included MBR gained control over the railway linking their mines south of Belo Horizonte with the Guaibe Island and Santos (south of São Paulo) ocean terminals. The Guaibe Island terminal, expanded in 1996, can accommodate 300,000 deadweight tonne vessels. MBR sells about 10% of its ore products in Brazil and exports the following percentages: Europe, 31%, Japan, 23%, other Asia, 19%, North/Central America, 9%, and others (Middle East, Australia and Argentina), 8%.

824.35 Brazil Iron Ore Production—Samitri/Samarco SA Mineracao da Trindade (Samitri) operates four mines in the State of Minas Gerais. The ownership includes the Belgo Mineira group of Luxembourg. The largest mine is Alegria, started up in 1969; In 1997 it produced 7.1 million tonnes of sinter fines, concentrate and lump ore. The other mines and their 1997 production are: Morro Agudo, 3.8 Mt/y of sinter fines and concentrate; Corrego do Meio, 1.6 Mt/y and Andrade, 0.8 Mt/y. Over 90% of Samitri's overall output was fine ore for either sintering or pelletizing. Samitri also set up a screening operation to provide specially sized fine ore for the Nucor Iron Carbide plant (now shut down) in Trinidad in which Samitri has an equity interest. In 1997 Samitri produced 13.8 million tonnes of ore; about 30% was consumed in Brazil while the balance was exported to Belgium, Germany and France consuming about 70 % of the exports.

Samarco Mineracao S.A. (Samarco), is a joint venture between Samitri (51%) and BHP Minerals (49%) which has been operating since 1977. Samarco operations consist of mining enriched friable iron ore (itabirite/hematite) which is 50% iron and 23% silica. The mine and concentration plant are located in Mariana County in the State of Minas Gerais. The initial focus of mining was Germano; following the depletion of reserves at Germano Samarco leased the Alegria mine where the reserves are estimated at 800 million tonnes.

The ore is beneficiated to an upgraded concentrate (68% Fe) and then sent by a 396 km (235 mi.) slurry pipeline to a pelletizing plant and loading port complex at Ponta Ubu in Achietá County in the State of Espírito Santo. The concentrating process consists of grinding, followed by cyclones and then flotation using both cells and columns. The newest of the two pellet plants was started up in 1997 increasing the total pellet capacity to 12 Mt/y of which more than 50% will be direct reduction grade pellets.

In 1997 Samarco shipped 9.5 Mt/y of pellets and pellet feed concentrate. As the second pellet plant reaches full production and total pellet capacity reaches 12 Mt/y the shipment of concentrates will decrease as the total capacity of the slurry pipeline is 13.3 Mt/y. All of Samarco's output is exported with blast furnace pellets going mostly to Europe while direct reduction grade pellets are sent to the Middle East, the Caribbean area, Southeast Asia and Canada. Pellet feed concentrate goes to pellet plants in the Netherlands and Japan, where no local ore is available to feed pellet plants located at steel plant sites, as well as other pellet and sinter plants.

824.36 Brazil Iron Ore Production—Ferteco Ferteco, established in 1924, is owned by German steel interests and operates the Fabrica mine near Congonhas and the Feijao mine near Belo Horizonte. Reserves are estimated to be a billion tonnes of which less than 10% are from the Feijao mine.

The Fabrica ore body is composed of low-grade itabirite ores and high-grade hematitic and limonitic ores. The crude ore Fe content is 54% so extensive beneficiating equipment has been installed to upgrade to the level of 64–65% Fe. The Fabrica operation focuses mainly upon blast furnace and sinter plant products with a pellet plant capacity of 3.7 Mt/y.

The Feijao mine complex, located 40 km (24 mi.) west of Belo Horizonte, is a north dipping metamorphic ore body of predominantly hard and soft hematites with some limonitic and itabiritic ores. It is one of the richest ore bodies in the world with crude ore reserves at an Fe content of 66%, accordingly most of the products are destined for the direct reduction market. The processing steps consist simply of crushing and screening followed by cyclones. The finest concentrates, <0.1 mm,

are exported as pellet feed for direct reduction production. Ferteco expects to increase direct reduction lump ore shipments from the current 1.8 to 3.0 Mt/y by 1999.

In 1996 the Fabrica operation produced 10.4 million tonnes of ore, including 3.7 million tonnes of pellets, while the Feijao operation produced 3.4 million tonnes, including 1.9 million tonnes of direct reduction grade lump ore and 0.6 million tonnes of blast furnace lump ore. Exports from both operations via the port of Tubarao totaled 10.2 million tonnes while shipments within Brazil were 2.7 million tonnes. About 60% of the exports went to the German equity steel mill operations while the remainder were well distributed among blast furnace and direct reduction users in Europe, North America, Asia, the Caribbean area and the Middle East.

Ferteco's overall expansion plans include construction of a loading terminal at Sepetiba Bay capable of shipping 6 Mt/y in cape-size vessels. Overall ore shipments are expected to increase from 13 to 17.5 Mt/y by 1999 and then to 20 Mt/y by 2005.

824.37 Brazil Iron Ore Production—Others Other significant mining operations in Brazil are:

The major Brazilian steel company, Cia Siderurgica Nacional (CSN), operates the Casa de Pedra mine for its internal consumption. The mine currently supplies (1997 capacity in Mt/y) sinter feed fines (7.0 Mt/y), pellet feed (2.0 Mt/y) and lump ore (3.0 Mt/y) but CSN has been studying a pellet plant, also. CSN also became a part owner of CVRD in the recent privatization sale of CVRD.

The Corumba mine, owned by Rio Tinto, currently supplies about 0.8 Mt/y of direct reduction grade lump ore to Argentina. This ore is barged down the Parana River to the River Plate. With the prospect of a natural gas pipeline from Bolivia, Rio Tinto is considering expanding output to 4 Mt/y and using about 50% of this as feed for an on-site direct reduction plant.

The German steel company, HKM (Mannesmann) owns the Pau Branco mine which has an capacity of 1.2 Mt/y of fines and lump ore.

The Brazilian steel company, Itaminas, owns three mines, Femandinho, Sarzedo and Itacolomy, with an estimated total capacity of 4.5 Mt/y.

8244 Chile

The principal iron ore deposits of Chile are located along the western slopes of the Andes in a narrow 1000 km (600 mi.) long area extending northward from the Province of Coquimbo to the Province of Antofagasta, Fig. 8.9. All of the known ore deposits except El Laco are located relatively close to the coastal waters of the Pacific. The El Laco deposit is located about 300 km (180 mi.) inland from the port of Antofagasta and on the Andean Altiplano at elevations of 4300–4900 m (14,100–16,100 ft).

Most of the ore deposits occur as segregation and replacement bodies related to the intrusive Andean granodiorites. These ores are composed of massive magnetite-hematite with the gangue minerals of amphiboles and apatite. The El Laco hematite-magnetite ores have been described as being near surface magmatic intrusions, some of which may have broken through to the surface. In the Province of Arauco there are reported occurrences of bedded, finely laminated itabirites containing magnetite, hematite and quartz containing 30–40% Fe.

Total ore shipments in Chile in 1997 were 8.6 million tonnes of coarse ore, fines and pellets coming principally from open pit mining operations of the Compania Minera del Pacifico (CMP) mines at El Romeral and Algarrobo. Principal exports were to Japan, Korea and southeast Asia with lesser amounts to Europe and the United States. Approximately 7.9 Mt/y were exported with the balance being consumed domestically.

The Algarrobo mine will be exhausted by 1999, but its output will be replaced by expansion of Los Colorados East. Ores from these sources are shipped to a CMP pre-concentration plant and then about 86 km (50 mi.) to the Huasco Bay pellet plant. This pellet plant produced 4.2 Mt/y in 1996, mostly for export. The Los Colorados mine is a joint venture between CMP and Mitsubishi (50% each). The mineable reserves are estimated at 245 million tonnes and averaging 48.2% Fe.

The Romeral mine, located in the Coquimbo region, shipped 4.2 million tonnes in 1996 through the port of Guayacan, divided as follows: 2.2 million tonnes sintering ore, 0.9 million tonnes pellet feed fines, and 0.8 million tonnes lump ore. The lump ore was shipped to the Compañía de Acero del Pacífico (CAP) steel plant in Huachipato. The mineable reserves are 48.4 million tonnes with crude ore averaging 52.7% Fe.

The El Laco deposit has inferred reserves of plus 250 million tonnes of 65% Fe, high phosphorus ores. It is largely undeveloped although small amounts of high grade magnetite have been shipped to Argentina since 1993. CMP leased a portion of El Laco to Altos Hornos Zapla (Argentina).

8.245 Colombia

The principal iron ore deposits in Colombia, Fig. 8.9, are near Paz de Río, Boyacá, approximately 220 km (130 mi.) northeast of Bogotá. The deposits are bedded magnetite-type ores associated with sediments of Tertiary age. Ore grades average 44% iron, 11% silica, 1.0% phosphorus and 0.1% sulfur. Measured reserves of 73 million tonnes were reported in 1980. The ore is mined underground and is crushed and screened. Fines generated prior to 1968 and stockpiled are now being used as sinter feed. Production in 1996 was 580,000 tonnes of ore and concentrates.

8.246 Peru

The principal iron deposits of Peru, Fig. 8.9, are located along the coast about 400 km (240 mi.) south of Lima and along the contact zones of the Andean intrusive granodiorite with which they are believed to be genetically related. They occur either in tabular shaped ore bodies, as contact metamorphic replacements of calcareous zones within the enclosing rocks, or as disseminated magnetite in siliceous metasediments. The iron bearing minerals of these ore deposits are primarily magnetite and hematite with occasional pyrite and traces of copper. In the near surface zones (upper 25 m or about 80 ft), the ores have been oxidized to hematite(martite)-limonite, with a corresponding oxidation of sulfur to sulfates.

In 1997 the mineable reserves were 230 million tonnes of ore grading 58.6 % Fe. The deposits are located at an elevation of about 800 m (2600 ft) on the Pampa de Marcona, 15–20 km (9–12 mi.) inland from the port of San Nicolás.

The mining operation at Marcona is by open pit methods and transportation to the coast is by a 15 km (9 mi.) long, down hill conveyor. In 1963 a magnetic concentrator and pellet plant with an annual 1.2 Mt/y capacity were put into operation in St. Nicolás Bay and later expanded to 3.2 Mt/y by utilizing both magnetic and gravity concentration procedures.

The only iron ore company in Peru, Empresa Minera del Hierro del Perú, was purchased by the Chinese steel company, Shougang, in 1992. Total production in 1996 was only 4.7 million tonnes, mostly pellets with lesser amounts of sinter feed and pellet feed. Most of the output was exported to China with the balance exported to Japan, Korea, Mexico and the United States. Total ore production in Peru had been as high as 7.4 million tonnes in 1994. Shougang intends to restore productive capacity and to double pellet output with construction of a new pellet plant.

8.247 Venezuela

The Venezuelan iron ore deposits are associated with the itabirite-type rocks of the Sierra de Imatá which underlie a series of ridges lying south of and generally parallel to the Río Orinoco and which extend for about 500 km (300 mi.) from the Guyana frontier on the east to beyond the Río Cardón on the west, see Fig. 8.12. There are two types of ore bodies: the hard, massive, crystalline replacement ore bodies such as those of El Pao, and the residual, in-situ deposits such as those found at Cerro Bolívar and San Isidro. The replacement types are primarily compact ores, consisting of dense crystalline hematite and magnetite. The residual ores consist of granular hematite with surficial cavernous limonitic canga capping. Measured and indicated reserves of 1.7 billion tonnes of plus 55% Fe residual type ores are found within the Cerro Bolívar district to the west of the Río Caroní. Additional low grade reserves (<55% Fe) are estimated at 2.0 billion tonnes.

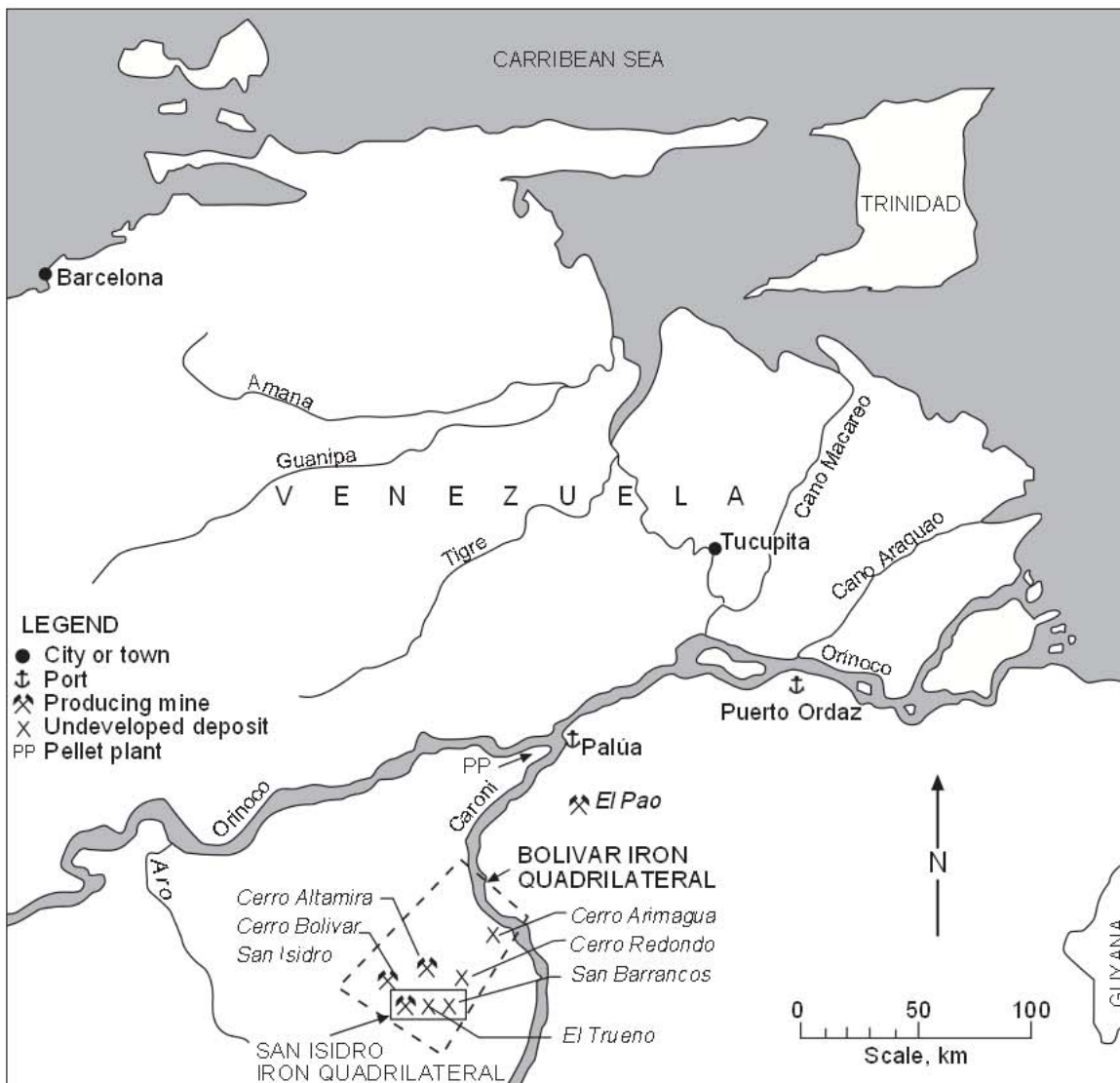


Fig. 8.12 Venezuelan iron ore deposits. (Source: Iron Ore Availability(Market Economy Countries, Information Circular 9128, United States Department of Interior.)

Mining is by open pit methods. The ore is moved by rail to separate deep water ports (Puerto Ordaz and Palua) on the Rio Orinoco where it is passed through treatment plants to produce various sized products for domestic use or export. The export products are loaded into ocean-going vessels and transported 273 km (164 mi.) down the Rio Orinoco to the Atlantic for transfer to vessels up to 220,000 DWT. The domestic products are shipped to a steel plant and to merchant direct reduction facilities. Product grades are +65 % Fe direct reduction pellets, and ore >67% Fe.

Iron ore production is currently controlled by Ferrominera Orinoco (FMO), owned by the state holding Corporacion Venezolana de Guayana (CVG). Total 1997 production was 18.7 million tonnes divided almost evenly between exports and domestic consumption. The export total is about two-thirds sintering ore fines with the balance divided between blast furnace pellets and lump ore and direct reduction grade pellets. Over 50% of the export tonnage went to Western and Eastern Europe with the balance going mainly to the United States, Japan and Trinidad.

Venezuela is also blessed with the availability of very low cost natural gas; this country has combined this low cost gas with its high grade iron ore to become the world leader in the production

of DRI (direct reduced iron) and HBI (hot briquetted iron). Most of the DRI is used in Venezuelan electric furnace steel facilities with the balance DRI/HBI exported. In 1997 installed DRI capacity totaled 6.2 Mt/y, spread among Midrex, HYL and Fior facilities. Additional DRI/HBI capacity is being built mainly for export to the United States to feed the explosive demand in electric furnace flat-rolled mini-mills, thus the majority of DRI/HBI production will be export-oriented in the near future.

Iron ore production is being increased to support the growth of the above DRI/HBI facilities. Iron ore production is expected to reach 25 million tonnes by 2001, however the export level will stay around 10 Mt/y as the additional production will be dedicated to the growth in DRI/HBI production. The current total pelletizing capacity of about 10 Mt/y (two pellet plants: FMO and Sidor) will be increased by 2 Mt/y by 2000 to help feed the DRI/HBI facilities.

8.25 Iron Ore Deposits of Western Europe

Historically and through the second world war, iron ore was primarily sourced from local or regional mines; frequently this ore was low-grade but options were limited. In the last four decades the sea borne trade of iron ore has grown dramatically with higher grade ore deposits being developed in Australia, Africa, South America, Canada, etc, while the construction of large vessels (Cape size) carrying greater than 120,000 tonnes has reduced shipping costs. The low delivered cost of high-grade ore, coupled with the sintering and blast furnace process benefits of such ore, gradually led to the closure of low-grade ore mining operations. These changes have been most pronounced in Western Europe and have led to closures of all iron ore mines in Finland, Germany, France, Spain and the United Kingdom. The sites of these are noted in Fig. 8.9. Sweden remains Western Europe's principal iron ore producer with Norway and Austria playing minor roles, the latter strictly for internal consumption.

8.25.1 Austria

Iron ore production in Austria is from the Erzberg mine near Leoben. The ore deposits are of hydrothermal origin (Bilbao type) and average iron content is 32%. Mineable reserves are about 10 million tonnes. Production in 1997 was 1.8 million tonnes, all for domestic consumption. This mine is expected to closed by the year 2003.

8.25.2 Norway

Up to the mid 1990s there were several iron mines in Norway producing both for export and domestic consumption. The largest was A/S Sydvaranger (mine and pellet plant) located near the Port of Kirkenes on the Barents Sea in arctic Norway. The next largest producer was Rana Gruber located near Moirana at the head end of the Rana Fjord in central Norway.

Only the Rana Gruber mine is still operating. The iron mines of Rana Gruber are located in the valley of Dunderlandsdalen, approximately 23 km (14 mi.) inland from the head of Rana Fjord in the north central part of Norway. A number of sedimentary magnetite-hematite deposits are associated with the Caledonian iron formation of northern Norway and are composed of bedded magnetite-hematite metasediments associated with garnet-quartz mica schists. Open pit reserves include ore grading 32–34% Fe, 30–32% SiO₂ and 0.2% P. The present concentration process produces a bulk gravity concentrate which is subsequently divided into a magnetic and nonmagnetic fraction. This plant treats ore of 33.1% Fe to produce about 0.5 Mt/y of material with 63.4% Fe and 0.017% P for sinter concentrates, all for export.

8.25.3 Sweden

The iron mines in Sweden are Kiirunavaara near Kiruna, and Malmberget near Gallivare, both in the northern part and operated by LKAB. The principal ore type is apatite bearing magnetite averaging 60% iron (Kiruna) and with 0.05–5.0% phosphorus. The largest of the ore deposits, located at Kiruna, is a steeply dipping tabular shaped body which has an overall length of 4 km (2.5 mi.), a

width of 100–200 m (330–660 ft) and drilled depth extensions of 1800 m (5900 ft). The ore is composed largely of magnetite. The titanium content is usually less than 1%. The Kiirunavaara mine, which started as an open pit operation, is now completely underground. Mineable ore reserves at Kiruna are 880 million tonnes of 60–65 % Fe and up to 2.0 % P.

The ore deposit at Malmberget is also mined by underground methods. Ore reserves at Malmberget are 500 million tonnes of 60% Fe and 0.7 % P.

The LKAB iron ore shipments in 1997 were 22.8 million tonnes, of which 15.1 million tonnes were pellets. Of the total, 14.8 million tonnes were delivered from Kiruna with 11.2 million tonnes being pellets. LKAB pellets are shipped for blast furnace use, mostly in Sweden, Finland and elsewhere in Europe, and for direct reduction use worldwide including the Middle East, Southeast Asia and North America.

8.26 Iron Ore Deposits of Eastern Europe

The break up of the former Soviet Union and the independence of the Eastern Europe countries from Moscow control produced profound changes in the iron ore and steel industries of both the former Soviet Union and Eastern Europe countries. The Ukraine and Russia have been and continue to be the principal suppliers of iron ore to steel plants in Bulgaria, Czech Republic, Slovakia, Hungary, Poland, Romania and the Balkan States of ex-Yugoslavia including Serbia and Bosnia-Herzegovina. Seaborne ore suppliers are increasing their presence accounting for about 8 Mt/y by the late 1990's. Each of these countries also had (see Fig. 8.9) small, local ore deposits, all of which are considered uneconomic; none are expected to be operational by 1999.

8.26.1 Former Soviet Union

With the economic dislocations surrounding the breakup of the former Soviet Union, iron ore production fell from nearly 250 Mt/y in 1988 to an estimated 120–130 Mt/y by the late 1990's. This was caused by a decrease in raw steel production as most ore was used domestically as higher cost iron ore and steel producers could no longer count on government subsidies to continue production. These operations were also affected by increased costs of rail freight, electricity, and taxes. Exports of iron ore fell from 43.1 Mt/y in 1988 to 30 Mt/y in 1996. Exports were also adversely affected by reduced steel production in Eastern Europe, the major customer area, quality problems in marketing to western Europe and elsewhere and transportation and infrastructure challenges within the former Soviet Union.

The total Soviet iron ore reserves in various categories exceed 100 billion tonnes averaging 34.8% iron. Of that total are 60 billion tonnes averaging 38% iron including 10 billion tonnes of ore averaging 55% iron. The total reserves are divided among: the Ukraine 31%, European Russia 24.4%, the Urals 15.7%, Kazakhstan 15%, Siberia 7.4%, northwest (Karelo-Kola) 3%, Soviet Far East 2.5% and all others 1%. Ore types range from natural soft ores to taconites from which magnetic and gravimetric concentrates are produced.

Iron ore production in the regions of the ex-Soviet Union can be described as follows.

8.26.1.1 Russia Russia is still one of the world's leading sources of iron ore reserves with production (1996 = 72.1 Mt) coming from 26 iron ore deposits. There are 49 open pit and underground mines in operation; five are expected to cease operation within five years while nine others will close within ten years. These iron ore deposits are generally poorer in quality (36% Fe), have complex mining and geological conditions and a severe operating environment. Deposits are relatively deep and overburden ratios, waste to ore, are high at about 2:1.

The main iron ore producing operations in Russia (with 1996 concentrate output in Mt/y as an indication of capacity shown in parentheses, followed by pellet output, if any) are:

- Mikhaylovsky (6.5, 5.0), Lebedinsky (9.4, 6.4), and Stoylinsky (7.0) in the Kursk Magnetic Anomaly, Kursk Region and Belgorod Region.

- Bogoslovsky (1.5), Kachkanar (3.0, 4.8, also 3.1 sinter), and Uralda (58.5, 4.1, also 2.7 sinter) complexes in the Sverdlovsk region, Urals
- Korshunovsky mine (4.7) in the Irkutsk Region,
- Kovdor (2.8) and Olenegorsky (7.0) complexes in Murmansk Region
- Kostamukshsky (6.9 pellets) in Karelia
- Sibruda (6.5) complex in the Kemerovo region, Siberia

Foreign investment is being sought to open up the high grade (65 (68 % Fe) mine at Yakolevsky in the Belgorod region. A direct reduction complex (HYL) process is starting up at Lebedinsky.

8.26.1.2 Ukraine The Krivoy Rog basin is the major iron production in the Ukraine. Production has decreased in the last ten years such that ore production is less than half of the 125 Mt/y capacity to 47.6 Mt/y in 1996. Typical aggro ore has an Fe content of 58% while typical concentrate has an Fe content of 65%. There are six open pit mining and beneficiation complexes and four underground operations. The latter account for 25% of the ore output.

The main iron ore producing operations in the Ukraine (with 1996 concentrate output in Mt/y as an indication of capacity shown in parentheses, followed by pellet output, if any) are:

- Inguletsky (14.4), Krivbassruda (0.4), Krivorozhsky Central (1.3, 4.2), Krivorozhsky Yuzhny (10.5, also 8.5 sinter), Novokrivorozhsky (1.6, also 8.9 sinter), Severny (3.7, 14.1), in Krivoy Rog in the Dnepropetrovsk region.
- Kamysh-Burunsky (0.5) in the Crimea
- Zaporozhstal (3.64 ROM) in the Zaporozhye region
- Poltavsky Komsomolsk mine (0.3, 9.7).

Krivoy Rog is receiving investment from the East Slovak Iron & Steel Works (VSZ) to secure pellet output. As transportation and infrastructure are improved, the Ukraine area should expand its role as an exporter to eastern and western Europe

8.26.1.3 Kazakhstan The Sokolovsky-Sarbay iron ore complex accounts for 75% of Kazakhstan's iron ore production and all of the pellet production. In 1995 the production was 4.3 Mt/y of concentrates and 5.3 Mt/y of pellets. Other mines are the Lisakovsky (1.6 Mt/y) mines in the Kustanai region and the Atasuisky mine (0.6 Mt/y) in the Dzhezkazgansky region. Run of mine ore averages between 36–46% Fe while concentrates vary between 49–66% Fe.

8.27 Iron Ore Deposits of Middle East and Asia

8.27.1 Afghanistan

In Afghanistan large, bedded iron deposits in excess of 1 billion tonnes containing 60% iron are reported to be located 140 km (87 mi.) west-northwest of Kabul near Hajigak Pass, Fig. 8.9. They are reportedly of Paleozoic Age. Other iron deposits in the country are located at Nish, Haji Alam and Pagmur although reserve data are not available.

8.27.2 India

India has vast mineral resources and is ranked among the top ten in the world in iron ore production and exports and steel production. Indian iron ore production has been on an increasing trend and over 66 million tonnes were produced in 1996. India's iron ore resources could be described as follows.

8.27.2.1 India – Hematite Ore Hematite is most important due to its higher grade and use in both blast furnace and direct reduction ironmaking. Indian hematite ore geologically belongs to the Pre-Cambrian iron ore series and occurs in banded iron formations (BIF) as iron-rich mineralization in



Fig. 8.13 Iron ore deposits of India. (Source: London Mining Journal)

forms varying from massive to powdery in nature. The major resources are distributed regionally as shown in Fig. 8.13, in five zones A(E). These zones are again sub-grouped in six sectors which contain a geological reserve of 12.2 billion tonnes and recoverable reserves of 9.6 billion tonnes as of January 1990. The major sectors of high grade (>65%) hematite, with amounts of reserves in millions of tonnes, are: Bihar-Orissa, 348; Bailadila, 511; and Bellary Hospet, 221.

8.27.22 India – Magnetite Ore Magnetite is the next principal ore type occurring as either of igneous origin or metamorphosed banded magnetite silica formations of sedimentary origin. Deposits of sedimentary origin are primarily in the state of Karnataka, Andhra Pradesh, Tamilnadu and Kerala, while those of igneous origin are in Bihar and Orissa. The geological reserves of magnetite are estimated at 10.6 billion tonnes comprising about 4.1 and 5.5 billion tonnes, respectively, of in-situ and conditional reserves. The Karnataka state has the largest reserves at 1.3 billion tonnes of metallurgical grade, +38% Fe, ore.

8.27.23 Current Production and Consumption Production of iron ore is achieved through the combination of large mechanized mines (mostly public sector) and smaller, less mechanized mines (mostly private sector). These operations are broadly grouped as follows:

- a. Captive production mines owned and operated by steel plants mainly for internal consumption.

- b. Mechanized mines owned and operated by Central and State governments mainly for export and internal consumption of merchant steel plants.
- c. Smaller mines privately owned and semi-mechanized for export and internal consumption.

By 1990 India's iron ore production had increased to about 55 Mt/y with about 40% consumed internally with the balance exported. After 1991 the liberalization of the economy allowed for additional private sector steel production; this promoted increased steel consumption which has increased the percentage of internal consumption of iron ore. In 1996 total ore production was 66.6 Mt/y of which 35.2 million tonnes (or 53% of production) were consumed internally.

India's main producing mines, with production capacity shown in Mt/y, are: Bailadila, 11.5; Dalli Rajahara, 6.5; Bansphani Sector-Keonjhar, 4.5; and the mines of Steel Authority of India (SAIL), Tata Steel (TISCO) and IISCO, 22.0; Bellary Hospet sector: private, 6.0, public 4.0; Goa sector, 18.0; and magnetite concentrate in Karnataka, 7.0. India expects to meet full expanded domestic demand and still export through 2000. Beyond 2000 expansion is required; this would occur through increased mechanization and improved efficiency at existing mines and exploitation of new deposits at Bihar, Orissa (Malangtoli, Daitri and Sundergarth, Keonjar), Bailadila and Bellary-Hospet..

Exported products included both lump, fines and pellets, mainly from the Goa area. The largest export market is Japan followed by Europe, China, Taiwan and Korea. The Kudremukh iron ore project in Karnakata, was completed in 1980. The design capacity is to produce 7.5 million tonnes per year of 67% Fe concentrates from 22.6 million tonnes of low-grade, 38–40% Fe, magnetite-hematite banded iron formation. The concentrates are moved in slurry form through a 67 km (40 mi.) long pipeline to a port at Mangalore, where a pellet plant produces about 3 Mt/y of blast furnace and direct reduction pellets. Other pellet plants are a smaller (0.8 Mt/y) plant operated by Mandovi and a new 3.0 Mt/y plant started up in 1996 at Essar.

8.2.7.3 Iran

Iran produced about 6.2 million tonnes of iron ore in 1996 for the expanding domestic steel industry. Iran is one of the worlds leaders in DRI production. Choghart near Bafqu in central Iran is the major producer. The ore is massive, high grade, high phosphorus, occurring as an intrusive mass similar to the Kiruna ores. This mine supplies about 4 Mt/y to the National Iranian Steel Company (NISCO) steel plants in Isfahan. NISCO operates pellet plants at Ahwaz and Mobarakeh with a total capacity of 9 Mt/y of direct reduction grade pellets. Also within the Bafqu area are the deposits of Chador Malu. With reserves estimated at 158 million tonnes the Bafqu area is the most important iron ore area of Iran. Other reserves such as those of the Arak area are small and low grade with many deleterious elements. Total reserves of iron ore in Iran are in the order of 250,000,000 tonnes.

NISCO has developed the Gol-e-Gohar mine in the Kerman Province with a production capacity of 2.7 Mt/y. Another recent project is the 1997 startup of the 5 Mt/y mine at Chadormalou in Yazd. Other potential projects include one at Sangan in Khorassan.

8.2.7.4 North Korea

North Korea produced an estimated 8 Mt/y of iron ore during 1996, of which a large portion came from the Musan mine in the northeastern part of the country, Fig. 8.9. The ore is described as Lake banded magnetite schists containing 40% iron from which 59–60% iron ore concentrates are made. Estimated reserves at Musan are 1.3 billion tonnes. Other producing iron ore mines are found in south Hamgyong Province along the eastern coast, in the provinces of North and South Hwanghae and in North Pyongang, along the western part of the country. Ores include both magnitnaya and residual types.

8.2.7.5 Republic of Korea

The Republic of Korea produced an estimated 0.6 Mt/y of iron ore in 1996, but this supplies only a small fraction of the needs of Korea's rapidly growing steel industry. The large seaborne access

greenfield steel plants of Posco at Pohang and Kwangyang import about 35 Mt/y of iron ore; almost half from Australia, with the balance from Brazil, India, Chile, Canada, South Africa and Peru, in that order. The mines in Korea include the Yeon Cheon Mine, 0.1 Mt/y; the Yeon Pyeong Mine, 0.35 Mt/y and the Seong Jin Mine, 0.2 Mt/y; all started up in the 1980s. Total capacity of these low-grade ore mines is only expected to reach about 2.0 Mt/y by 2005.

8.2.7.6 People's Republic of China

China's production of iron ore has increased dramatically from 154.4 Mt/y in 1988 to an estimated 246.0 Mt/y in 1996. However, the ore grades are very low: 30% Fe for major open pit mines and 36% Fe for major underground mines. After beneficiation, the concentrates average 62% Fe but some concentrates have as low as 52% Fe. Because steel production has increased by equally dramatic amounts in the same time frame, China has increased its imports of iron ore from 10.4 Mt/y in 1988 to 43.9 Mt/y in 1996. China is expected to increase its reliance upon imports in coming years as domestic mine production is hampered by low grade ore reserves, high capital costs, significant infrastructure barriers (transportation, electricity, etc.), taxes and other problems.

Reserves are reported to be 38,000 million tonnes of which the major portion is in the 30–35% Fe range. Approximately 25% of that total tonnage is in Pre-Cambrian banded metamorphic ores of magnetite-hematite containing 33% iron and 50% silica. The ores of this type are found at Anshan and in the northern and northeastern provinces, Fig. 8.9. Approximately 40% of total reserves are in bedded oolitic hematite-limonite ores which average 40% iron. The major deposits of these ores are the Hsuanlung (Sinian) Ninghsiang (Devonian) and Chichiang (Jurassic). Metasomatic skarn deposits containing high grade magnetite with associated sulfides of copper and cobalt are reported at Tayeh in central China. These five major deposits of three ore types represent almost 70% of China's total iron ore reserves.

Some major mining operations, with Mt/y of concentrate shown, are: Shoudu, 5.8; Tangshan, 1.1; Han-Xing, 2.0; Taiyuan, 1.0; Baotou, 3.0; Anshan, 10.0; Benxi, 4.4; Shanghai Meishan, 1.2; Manshan, 2.6; Wuhan, 2.4; Hainan, 3.3; Panzihua, 4.8; Jinquan, 1.4; and Chongqing, 0.2. In addition to lower Fe contents, many of these concentrates have deleterious impurities such as sulfur, phosphorus, rare earth's, etc. Also, the fine sizing makes these concentrates less desirable for sintering. As China relies extensively upon the sintering process the importation of quality sintering ores mainly from Australia has played a major role in improving sintering and blast furnace operations. In recent years, steel plants on or near coastal areas have increased their reliance upon imported ore from Australia, Brazil, South Africa, Canada, etc. China's pelletizing capacity is limited to five pellet plants producing about 12 Mt/y.

8.2.7.7 Philippines

There are numerous small iron ore occurrences reported throughout the Philippines, Fig. 8.9 but no significant production. In the late 1970s Kawasaki Steel started up a sintering plant, which relies exclusively on imported iron ores, for supply of sinter to Japan and elsewhere.

8.2.7.8 Saudi Arabia

Iron ores are reported at several localities in Saudi Arabia, Fig. 8.9. At Wadi Sawawin in the remote northwest region of the country there are indicated reserves of 350 to 400 million tonnes of 30(35% Fe in bedded magnetite-jaspillite Pre-Cambrian beds. At Fatima between Mecca and Jidah there is an oolitic hematite deposit containing 40 million tonnes of 45% Fe which reportedly can be beneficiated to 58% Fe.

8.2.7.9 Turkey

The principal iron ore producing mine is located at Divrigi in Sivas-Malataya province in eastern Turkey. The ore occurrences are described as contact metasomatic deposits of magnetite in limestone and of irregular size and distribution. Ore grades average 54% Fe and the proven reserves are 47

million tonnes. Apart from Divrigli another important hematite deposit is at Ateppe in the Kayseri region; the usable reserve, obtained by concentration is only 7.5 million tonnes. Another potential deposit is at Hasan Celebi where reserves total 685 million tonnes but only at 19% Fe. Another operating mine at Avnik has reserves of 40 million tonnes but the ore contains 1% P, so production is limited.

Total iron ore production in 1996 was estimated at 4.7 Mt/y including 1.5 Mt/y of pellets from the Divrigli pellet plant. The latter is part of the public sector Turkish Iron & Steel Works (TDCI); total TDCI production was 2.7 Mt/y including lump ore and concentrate. Private sector mines accounted for 1.9 Mt/y of output. Turkey now relies on imported ore for nearly 50% of its needs.

8.27.10 Other Asia

Malaysia at 0.30 Mt/y, Thailand at 0.12 Mt/y and Indonesia at 0.40 Mt/y continue to be small producers of iron ore in 1996. Japan had been producing small amounts of ore but stopped in 1995. Japan continues to be the leading importer of iron ore with 119 million tonnes imported in 1996.

The iron ore potential of Indonesia consists primarily of laterite deposits and iron sands with estimated total resources of 500,000,000 tonnes (492 million long tons).

Estimates of iron resources in Laos range up to 1000 million tonnes of 60% iron in contact metamorphic type deposits located in Xien Khoung province.

In Viet Nam exploration at the Thach Khe deposit is being undertaken by a consortium of foreign interests. The recoverable reserves total 320 million tonnes of magnetite, however, there is some concern about the Zn content.

The estimated iron ore resources of Pakistan are 500 million tonnes of which the largest deposits are the Chichali minette-type ores containing an indicated 335 million tonnes of 31–34% iron ore.

8.28 Iron Ore Deposits of Africa

The largest deposits of iron in Africa are associated with Pre-Cambrian formations and are mostly of the Lake Superior type. Countries bordering the Atlantic have been the biggest African producers and significant additional deposits are currently waiting to be developed. Summary descriptions of the more important producing and proposed iron mining operations are included below, see Fig. 8.9.

8.28.1 Algeria

The Ouenza iron ore mine which is situated in Algeria near the Tunisian border some 110 km (66 mi.) from the coast has been producing since 1921. The deposits are operated by Sonarem (Ste. Nationale Algerienne De Recherches Minieres, Algiers), which is owned by the Algerian Government. Reserves are estimated to be on the order of 70 million tonnes of ore grading 54% Fe, 3.6% SiO₂, 0.6% Al₂O₃ and 7% ignition loss. The mine capacity is estimated to be about 3 Mt/y although production in the mid 1990s was about 2 Mt/y. The product is mainly sintering ore fines for domestic consumption and for export through the port of Annaba.

The Algerian Government's Sonarem had been considering the exploitation of the Gara Djebilet iron ore deposit in southwest Algeria but the location together with the high phosphorus and sulfur contents of the ore have been major obstacles in bringing this project on stream.

8.28.2 Egypt

The principal iron ore occurrences in Egypt are located within and near the Bahariya oasis in the Western Desert. Total reserves are reported to be 250 million tonnes, of which 129 million tonnes of 54% iron ore are in the El Gedida deposit. In the mid 1990s the production from the El Gedida mine was about 2.5 Mt/y, mainly of lump ore which was rail shipped about 295 km (177 mi.) to the blast furnace plant located at Helwan near Cairo. This ore is also higher in silica and phosphorus.

The major growth in Egypt's steel industry has been in direct reduction (EAF based steelmaking so exploration for high-grade deposits have focused in the southern part of Egypt about 85 km (50 mi.) southeast of Aswan. So far about 480 million tonnes of oolitic hematite reserves have been identified with confirmation of 173 million tonnes.

8.283 Guinea

A proposed development located in the southeastern part of Guinea, is a northern prolongation of the Nimba range in Liberia where the LAMCO iron mining operations had been located. The Exploration studies have indicated over 600 million tonnes of crude ore grading about 65% Fe and 4% combined $\text{SiO}_2 + \text{Al}_2\text{O}_3$. Fine ore would be transported from the mine over a new 18 km (11 mi.) railway to connect with the existing LAMCO railroad in Liberia and thence to the port at Buchanan. The civil unrest in neighboring Liberia continues to delay this project.

8.284 Liberia

Liberia had been an active exporter of high quality iron ore to world markets until the civil war halted all mining activities and also resulted in the destruction of much equipment. At the present time, 1997, efforts are underway to restore mining activity mainly in the Nimba area.

The Mt. Nimba iron ore district is located in the north central part of Liberia adjacent to the international borders with Guinea and the Ivory Coast. It is about 290 km (174 mi.) northeast of Monrovia. The mine was operated rate by LAMCO JV Operating Company, which was jointly owned by the Liberian Government and foreign interests. Mining was done by open pit methods. The ore was crushed prior to being railed 274 km (164 mi.) to the port of Buchanan. The somewhat siliceous blue hematite ores (1% loss on ignition) of the main orebody were mixed on a 60/40 basis with slightly aluminous limonite brown ores (4% loss on ignition) from a secondary orebody producing three products: lump ore, sintering fines and pellet feed. Reserves in the main orebody were expected to be depleted by 1987 and LAMCO has been studying the feasibility of beneficiating low grade ores from its concession areas and other areas such as Tokadeh in order to mine in the future.

8.285 Mauritania

Mauritanian Government's Societe Nationale Industrielle et Miniere (SNIM) owns and operates the Tazadit, Rouessa and F'Derik mines in the Kedia d'Idjil area immediately east of Fort Gouraud in northwestern Mauritania. The ore is predominately hematite with minor limonite. Structurally the ore varies from massive to platy and granular. The ore grade is 65% Fe, 4.3% SiO_2 , 1.2% Al_2O_3 , and 0.03% P. Reserves of this type of ore are estimated to be 80 million tonnes. The ore is mined by open pit methods. transported by rail 650 km (390 mi.) to the loading port of Nouadhibou for export mainly to Europe.

The diminishing reserves in the Kedia d'Idjil area promoted development of the nearby Guelb deposits. The ore is a low grade Pre-Cambrian banded magnetite quartzite, which averages 37% Fe, 40.4–46.7% SiO_2 , 0.5–2% Al_2O_3 and 0.03–0.07% P. The ore is mined by open pit methods and concentrated by two methods: dry magnetic separation and wet gravity separation (startup in 1999). The ore is marketed as magnetite sinter feed (65.8% Fe) and magnetite pellet feed (63.5% Fe). Reserves are 530 million tonnes of ore grading at 37% Fe in the eastern Guelb deposits and an additional 980 million tonnes in the western Guelb deposits.

The M'Haoudat deposit of high grade hematites and itabarites was opened in 1994 and is located 30 km (18 mi.) east of Guelb El Rhein.

SNIM shipped about 11.4 million tonnes of sinter feed and lump ore in 1996 mainly to European customers. Production is expected to increase to over 12 Mt/y and then to 13.5 Mt/y by 2006. SNIM is studying construction of a pellet plant at Nouadhibou to serve mainly the direct reduction market.

8.286 South Africa

Sishen is the largest iron ore producing mine in South Africa. Its ore is located in two Pre-Cambrian geological units, dipping about 10° to the west in the Sishen-Postmasburg region of the Northern Cape Province. Iscor, Limited, which owns and operates both the Sishen and Thabazimbi mines, has available reserve of approximately 1500 million tonnes of hematite at Sishen with Fe content between 66 and 70% for about 50% of the deposit. A further 35% contains 63–66% Fe and the remainder has from 60–63%. Iscor has additional reserves of high grade hematite ore in the Sishen-Postmasburg region totaling about 300 million tonnes with about a third of these recoverable by open pit mining.

With completion of the export facilities at Saldanha Bay in 1976 the Sishen mine began to contribute significantly to the world market. Sishen currently has a crushing capacity of 30 million tonnes per year. Crude ore is beneficiated on site by dense medium separation for floating off shale and banded ironstone. Quaternary crushing and screening play a major part in ensuring flexible size gradings for supplying up to five different products to various customers.

Export production is transported 860 km (516 mi.) by rail to Saldanha Bay. The port capacity is designed to eventually accommodate ships of up to 350,000 deadweight tonnes. Sishen shipped 23.1 Mt/y in the period July 1995 to June 1996. Japan and China were the principal recipient of the export ore with lesser amounts going to Korea, Austria, Germany, Italy and the U. K. Iscor's various inland steel works consumed 6.1 Mt/y of Sishen iron ore.

Associated Manganese Mines of South Africa, Ltd. (ASSOMAN) operates an open pit iron ore mine at Beeshock, which is located about 10 km (6 mi.) northwest of Postmasburg in Cape Province, South Africa. Run-of-mine grade averages 64% Fe, 5% SiO₂, 2% Al₂O₃, and 0.08% P. Shipments totaled 4.5 Mt in 1996 for export markets through the port of Saldanha Bay.

The Thabazimbi mine is located approximately 500 km (300 mi.) northeast of Sishen in South Africa's Northern Province. The deposits occur in the banded ironstone and ferruginous chert forming the top of the Dolomite Series of the Transvaal System. Thabazimbi mine, with mineable ore reserves totaling approximately 88 million tonnes, is owned and operated by Iscor Limited for internal Iscor consumption (about 2.5 Mt/y). Ore is beneficiated by dense medium separation, producing both lump ore and sinter fines. Product grades average 63–64% Fe and 4.5–6% SiO₂.

8.287 Other Africa

Small amounts of iron ore are also produced (1996 production in Mt/y shown in parentheses) in Morocco (0.01), Tunisia (0.24), Nigeria (0.35) and Zimbabwe (0.35). Zimbabwe has potential for greater production particularly as several groups are studying direct reduction facilities in neighboring Mozambique which would utilize iron ore from Zimbabwe. Iron ore exploration activities have also been conducted in Angola, Gabon, Ivory Coast, Libya, Cameroon, Sierra Leone and Senegal. The Marampa mine in Sierra Leone had shipped about 1.0 Mt/y of sinter feed fines to export markets until it closed in 1975. In the Sula Mountains of Sierra Leone, the Consolidated Ventures Group of Canada is undertaking exploration activities. Production of more than 5 million tonnes of ore was reached in Angola during the early 1970s, but ore is not currently produced due to civil unrest. African mine and ore deposits are shown in Fig. 8.9.

8.29 Iron Ore Deposits of Oceania

8.291 Australia

Australia ranks along with Brazil as one of the leading iron ore producers in the world with annual production of 160 Mt/y and exports of 150 Mt/y, which is more than 1/3 of the total seaborne iron ore trade. Most of this production is concentrated in northwest Australia in Hamersley Province known as the Pilbara region. The three major mining companies are Hamersley Iron, a division of Rio Tinto; BHP Iron Ore; and Robe River, owned 53% by North Mining Group and 47% by Japanese interests. Domestic consumption is by BHP Steel at its plants in Port Kembla, Newcastle (sched-

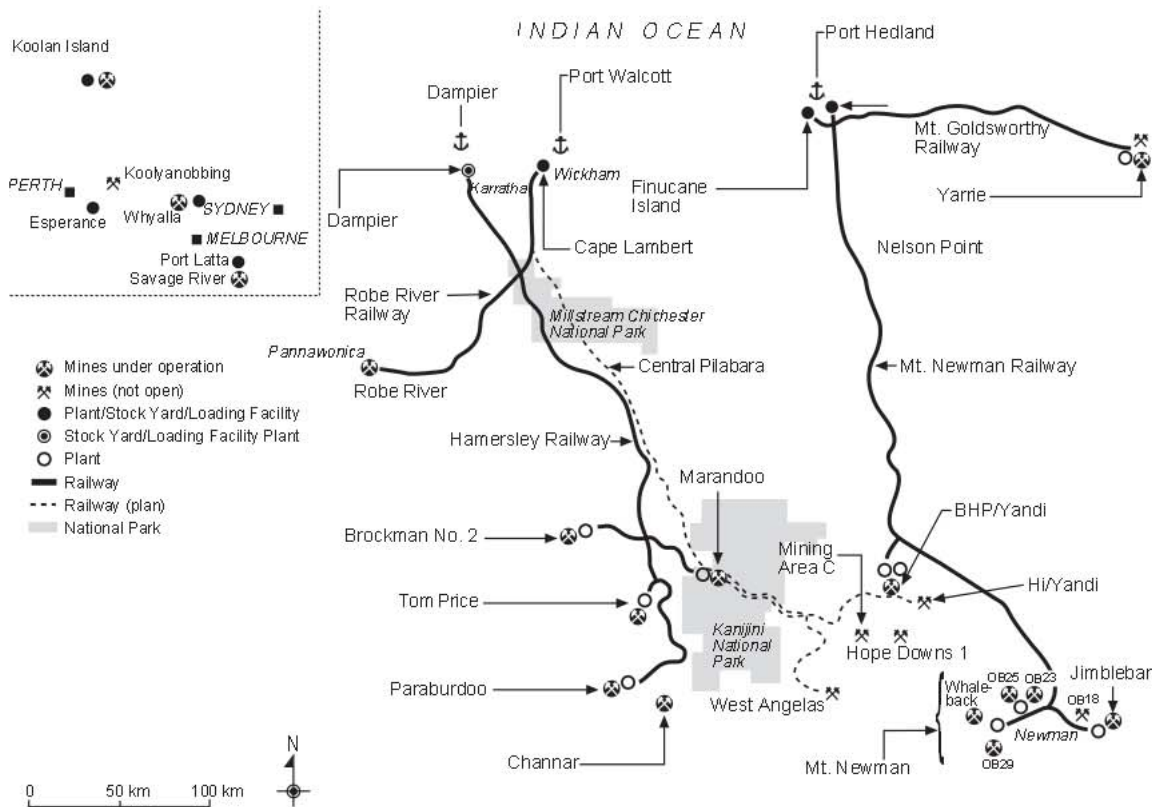


Fig. 8.14 Northwest Australia's iron ore operations.

uled for shut down) and Whyalla. Australian ore exports supply about 50% of the iron ore needs of the major Pacific Rim steel producers in Japan, Korea and Taiwan and a significant portion of the iron ore needs of China and Western Europe.

Over the last ten years the proportionate production of Brockman-type material, the source of the best lump ores, has decreased from 81 to 56 percent. Consequently, the lump portion diminished from 39 to 31 percent in the quantity produced and from 47 to 31 percent in the quantity exported. The growth in the Australian iron ore industry has been based on consumer acceptance of the pisolitic ores from Robe River and Yandi, which contain only a negligible portion of lump ore and today constitute more than 1/3 of the Australian production.

Our focus will be mainly on iron ore mining in northwest Australia.

8.29.1.1 Geology of Hamersley Province Three ore groups occur in the Hamersley Province: BID – Banded iron formation Iron Deposits; CID – Channel Iron Deposits; and DID – Detrial Iron Deposits. BID is the most abundant group; it consists of a banded texture with hematite and hematite-goethite mineralogy. This group includes the low P Brockman, Marra Mamba and high P Brockman types. Examples of the low P Brockman type are Mt. Tom Price, Mt. Whaleback and Paraburdoo locations. Marra Mamba ore types include Homestead/Nammuldi, Marandoo, Mining Area C (MAC), West Angelas and Hope Downs. High P Brockman types include Brockman No. 2, West Turner Syncline, Paraburdoo Western Range and Koodaideri.

The Mt. Tom Price and Paraburdoo orebodies at both localities were developed in-situ by the secondary enrichment of the Pre-Cambrian Brockman iron formation. The Mt. Tom Price has an overall length of 6.4 km (4 mi.) and a width of up to 1.6 km (1 mi.), average of 0.6 km.

The Mt. Whaleback orebody, consisting of hard hematite with minor magnetite and martite (64% Fe) is in an ore zone 5.5 km (3.3 mi.) long and 120 m (394 ft) wide, is the main segment of the Mt. Newman deposits which are included in a mineral lease covering 777 km² (300 mi²).

CID – Channel Iron Deposits, are characterized by a pisolitic texture with goethite-hematite mineralogy. Examples are Yandi and Mesa J. The Mesa J ore deposits at Pannawonica are 6–26 m (20–85 ft) thick capping of goethitic, pisolitic iron ore on 40–60 m (130–200 ft) high mesas, scattered along the broad valley of the Robe River. The ores are considered to have been deposited during Cretaceous times as a thick blanket of limonitic silt and mud in the broad estuary of the ancestral Robe River. The area was subsequently uplifted and eroded into the present day isolated mesas. The largest of the orebodies in this group contained about 50 million tonnes containing 57% Fe.

DID – Detrital Iron Deposits, have a clastic texture (broken pieces of older rocks) with a hematite-(goethite) mineralogy. An example is the Brockman No. 2 Detritals (B2D).

The resources of western Australian iron ore by type (in billions of tons) are estimated as follows:

Low-medium phosphorus Brockman	2.4, with Fe > 63 %
Marra Mamba	5.0, with Fe 60–64 %
Pisolite	6.0, with Fe 52–59 %
others (magnetites, etc.)	3.0

8.29.1.2 Hamersley Iron Operations Hamersley Iron shipped 58.4 Mt in 1997 from the port of Dampier which accommodates vessels up to 250,000 DWT. The port is connected by the Hamersley Railway (386 km) to the mine sites. The operating mines with capacity in Mt/y and reserves in Mt shown in parentheses are: Mt. Tom Price (30.0, 645), Paraburdoo (15.0, 430), Channar (15.0, 265), Marandoo (12.0, 335) Brockman No. 2 (4.0, 65) and Yandicoogina, started up in 1999 to produce 15.0 Mt/y of fines. All operations are 100 % owned by Hamersley except for Channar which is 40 % owned by CMIEC in China.

The Yandicoogina operation, known as Hamersley Iron Yandi (HIY) is connected by a 147 km rail line to the main railway. The ore is the CID type – solitic goethite-hematite with an Fe content of 58.5 %. Open pit mining is followed by on-site crushing, screening, stockpiling and train loading of a single fines product. HI ships lump ore and fines from all other properties.

Hamersley is investigating other mining developments all of which would use existing infrastructure. Hamersley also has built a demonstration plant for the HiSmelt smelting reduction process in Kwinana. A commercial HiSmelt plant could produce liquid hot metal from fine ore and coal.

8.29.1.3 BHP Iron Ore Operations BHP Iron Ore shipped 66.5 Mt in 1997 from Port Hedland which accommodates vessels up to 250,000 DWT. The port is connected by the Mt. Newman Railway (425 km) to the mine sites.

The Mt. Goldsworthy Railway (215 km) connects the Yarrie mine site to Funicane Island port (near Port Hedland). Most of the operations are conducted by the Mt. Newman joint venture which is owned 85% by BHP and 15% by Japanese and other interests. The Yarrie mine is 100 % owned by BHP. BHP ships lump ore and fines from all mines except for Yandi which supplies only fines. The ore is mined by open pit methods.

The operating mines with capacity in Mt/y and reserves in Mt shown in parentheses are: Mt. Newman (37.0, 2040), BHP/Yandi (30.0, 1800) and Yarrie (6.0, 100). The Mt. Newman operation consists of Mt. Whaleback, Orebodies 18, 23 and 25 (all Brockman BID), and Orebody 29 (Marra Mamba BID). The Yandi ore is a pisolitic goethite-hematite while Yarrie is a low P hematite BID ore.

BHP is investigating Mining Area C (MAC), a resource of 600 Mt of Marra Mamba BID and Detritals DID low P ore. It is located 35 km east of the existing Yandi rail spur. BHP has also started up in 1999 a 2.0 Mt/y FINMET direct reduction plant at Port Hedland that uses ore fines and natural gas to produce HBI (hot briquetted iron) mainly for electric furnace consumption.

8.29.1.4 Robe River Operations Robe River shipped 29.8 Mt in 1997 from the port of Cape Lambert which accommodates vessels up to 270,000 DWT. The port is connected by the Robe River Railway (196 km) to the mine site Mesa J, a mine with a capacity of 32.0 Mt/y with reserves of 2500n

Mt. The ore is mined by open pit methods and rail hauled to Port Lambert. Because the ore deposits are scattered, the central crushing station is located at the port site rather than at the mine. The ore is Pisolitic goethite-hematite CID averaging about 57% with nearly 10 % combined water. The product is mostly fines but about 2–3 Mt/yr are screened off as a special lump ore.

Robe River is investigating development of the West Angelas project. This resource consists of 750 Mt of Marra Mamba BID ore with a potential production capacity of 20 Mt/y of shipments from Cape Lambert. Robe River is also investigating rebuilding of a pellet plant at Cape Lambert that was shut down in the 1980's.

8.29.1.5 Middleback Range, South Australia Deposits of high grade (more than 60% Fe) hematite ore, manganiferous in part and associated with Pre-Cambrian banded hematite-quartz jaspillites have been mined by BHP since 1915 to supply its Whyalla, Newcastle and Port Kembla steel plants. Mining at the Iron Prince/Iron Baron and Iron Monarch mines is by open pit methods. The ore and concentrates are shipped 53 km (32 mi.) to a stockpiling and shiploading facility at Whyalla. The concentrates are pelletized in a 2.5 Mt/y pellet plant at Whyalla for consumption in the BHP steel blast furnace there.

8.29.1.6 Koolyanobbing Iron Ore Operations Koolyanobbing Iron operates the Koolyanobbing Iron Ore Project, 50 km north of the Southern Cross in Western Australia and the Cockatoo Island Iron Ore Beneficiation Project, 140 km north of Derby. Both ventures are owned by Portmann Mining in a joint venture with Anshan Steel of China. The lump and fine products are shipped mostly to China. The Koolyanobbing Iron Ore Project produced about 1.5 Mt in 1997 while the Cockatoo Island operation shipped about 0.7 Mt in 1997.

Hematite deposits occur as lenses in Pre-Cambrian metamorphosed sediments on Cockatoo and Koolan Islands in Yampi Sound, Western Australia. The ore at Koolyanobbing consists of hematite, goethite and magnetite and averages approximately 61.5% Fe, 3.5% SiO₂ and 0.14% P.

8.29.1.7 Future Developments in Australia Aside from the Hamersley, BHP and Robe River potential projects already mentioned, other potentially significant developments include:

Hope Downs—This resource of 800 Mt of Marra Mamba BID ore, located midway between Mt. Newman, West Angelas and Mining Area C, is being investigated by a joint venture of Hancock Prospecting and Iscor Mining, but faces infrastructure (port and rail) uncertainties.

SASE—The proposed South Australian Steel and Energy project would produce pig iron from South Australian magnetite and coal with the Ausmelt process

Western Australia DRI and Steel Projects—A number of projects have been proposed to add value to western Australian iron ore by producing DRI or steel products, with the aid of natural gas. Some projects would use iron ore from existing mines while others would develop mine projects such as the Mt. Gibson taconite deposits near Geraldton or the Fortescue magnetite deposits near Dampier. Australia has considerable reserves of taconite and magnetite which could be upgraded to produce DR quality ore. As of July 1999 only the BHP FINMET HBI plant in Port Hedland had come to fruition with no firm contracts even being signed for as many as ten other proposed projects.

8.29.2 Tasmania

There are several low grade ore bodies containing magnetite and pyrite along with minor chalcopyrite, which occur as steeply dipping lenses in an amphibolite sill intruded into an upper Pre-Cambrian metamorphosed basic volcanic succession of rocks of the Savage River area of Western Tasmania. The ore, mined by open pit methods, is crushed and magnetically concentrated prior to being piped in slurry form 85 km (51 mi.) to Port Latta. The concentrates are pelletized (capacity: 2.5 Mt/y) at the port to produce pellets (67.5% Fe and 1.30% SiO₂). The Port Latta shiploading berth, which is more than a mile off shore, can accommodate ships of up to 100,000 tonnes deadweight. The operation was halted in 1997 by Cleveland Cliffs but later in 1997 another company, ABM (Australian Bulk Minerals) re-opened the property and resumed pellet shipments in 1998.

8.2.9.3 New Zealand

On the west coast of New Zealand's North Island BHP mines two deposits of titanomagnetite sand. 1996 production was 2.6 million tonnes. The Waikato-North head mine, located 50 km (30 mi.) south of Auckland, has a reserve of 150 million tonnes of sand averaging 20% titanomagnetite. This property produces about 1 Mt/y of concentrate which is pumped in slurry form through an 18 km (11 mi.) pipeline to the BHP Glenbrook steel plant for use in a direct reduction process. The future of North Head is linked to the future of the Glenbrook steel plant which is currently in doubt.

The Taharoa mine, located 150 km (90 mi.) south of Auckland, has reserves of 300 million tonnes. In 1996 the concentrate shipments were 1.1 million tonnes at 57% Fe and 7.7% Ti. This concentrate was shipped mainly to Japan as a sinter feed. The Ti content, while detrimental to sinter properties, forms a protective layer in the blast furnace hearth, thus extending hearth life. Quality has been improved with addition of a spiral separation facility.

8.3 Discovery And Mining of Iron Ores

The first part of this section will be confined principally to a brief discussion of modern geophysical methods for iron ore exploration. The second part will discuss briefly the current methods used for mining iron ore.

8.3.1 Discovery Methods for Iron Ore

8.3.1.1 Geophysical Techniques

Present geophysical techniques and instrumentation, sampling methods, drilling procedures, and some methods of geological investigation will be discussed here, but only as they apply to the search for iron ore. Geophysics, as applied to iron ore explorations, is primarily a reconnaissance tool that provides information that must subsequently be complemented by geological mapping, petrographic studies, drilling and the evaluation of ore analyses and treatment tests. The geophysical techniques used in the search for iron ores, as in most geophysical mapping, are based upon the presence of measurable contrasts of physical properties between the ore minerals and the surrounding rocks. The physical properties used principally are magnetism (both permanent and induced) and density. Electrical methods (including polarization and electromagnetism) and seismic studies can sometimes be used in conjunction with magnetic or gravity surveys to obtain better definition of the ore bodies.

8.3.1.2 Magnetometers

The greater sensitivity and convenience of operation of modern magnetometers since 1950 have all but retired other methods such as the dip needle and Super-Dip from practical employment in exploration for iron ore. Magnetometers for this purpose have passed through several successive stages of development, the principal forms being known, in the order of their conception, as balance type, torsion type and flux gate magnetometers, followed in recent years by magnetometers that were conceived and developed in the field of atomic physics: these latter instruments include the rubidium vapor, proton-precession and optical absorption magnetometers.

All of the foregoing magnetometers are used to determine the strength of the earth's magnetic field or its vertical component at a given location. The earth's field is very weak, ranging from about 0.7 oersted at magnetic poles to about 0.25 oersted at some points on the magnetic equator. In geomagnetic studies, field strength is measured in a much smaller unit than the oersted, the gamma, which is equal to 0.00001 or 10^{-5} oersted. The shape of the earth's magnetic field is not uniform, but shows large scale regional irregularities due to variations in the shape and composition of the earth's crust and upper mantle. Variations on a smaller scale result from magnetic disturbances caused by concentrations of magnetic material near the surface and it is these local variations that are sought in searching for ore.

8.3.1.3 Magnetic Surveying

The airborne magnetometer is the primary geological tool used in the search for iron ores and iron bearing materials in large areas. It was first developed during World War II as a metal detecting device to locate submarines at sea and was later adapted to mineral and petroleum exploration. Airborne surveys with the magnetometer led to the discovery in 1947 of the Pea Ridge iron ore deposits of Missouri and in 1950 to the mineralized areas at Lyon, Nevada. It has since been used on a worldwide basis in the search for petroleum and minerals. The method of conducting an airborne magnetic survey is to install a flux gate or proton precession magnetometer in an aircraft which traverses the target area at a fixed altitude and along predetermined flight lines. The magnetometer measures the magnitude of the earth's magnetic field and these data are recorded electronically along with the position of the aircraft and its altitude. Improvements in the quality of the surveys in recent years have been brought about by refinements in the equipment, i.e., greater sensitivity and simplicity, multiple channel data recording, miniaturization of instruments and a more accurate positioning capability. The presentation and recording of the data in digital form permits the use of computers to carry out the necessary data reduction and plotting requirements needed for analyses and interpretation. Data from these records are plotted as a contour map, with lines connecting points of equal magnetic intensity on the map. The patterns formed by these lines indicate areas where magnetic anomalies (major local distortions of the earth's magnetic field) occur. The areas indicated by anomalies on the magnetic map may then be investigated in greater detail by geological surveys and by gravity measurements, electromagnetic studies or other geophysical techniques.

The detailed magnetic study of anomalous areas may involve using a magnetometer in a helicopter, or ground surveys employing hand-held or other portable magnetometers. A new electromagnetic prospecting technique known as AFMAG (audio frequency magnetics) has been used in areas where magnetic anomalies have been detected to attempt to differentiate between buried deposits of volcanic glass or low grade iron bearing intrusives and deposits with high remanent magnetization that represent potential ore bodies. The rubidium vapor magnetometer, likewise, may make possible the rejection of non-economic deposits by differentiating between magnetic deposits, high in magnetic susceptibility and electrical conductivity, and buried volcanic glass and low grade non-conducting iron bearing intrusives of low susceptibility which, however, are capable of producing attractive magnetic anomalies.

8.3.1.4 Sampling and Drilling

In the early period of iron ore discovery, most of the exploration of potential ore bodies was done by test pits and shafts. In recent years, correlation and evaluation of the detailed data from magnetometer or other surveys is usually followed by a carefully worked out drilling program to provide samples that, through geological and mineralogical studies, establish the kind, quality and extent of ore that may be present, and the nature and quantity of the overburden or rock formations associated with the ore.

Considerable attention is being given to the improvement of core drilling methods to provide better samples. The most complete and undisturbed drill sample possible at a reasonable cost is the ultimate goal of these studies. Diamond drills are employed especially in hard formations. The use of drilling muds with diamond drills has been adopted where samples of the highest quality from alternately hard and soft banded material are desired. Rotary down-hole drills and reverse circulation drills of several types can provide a rapid rate of penetration with satisfactory sample recovery in some sampling applications. Wire-line drilling is employed in about half of the core drilling operations in the United States.

Studies are continuing of the statistical evaluation of the results of exploration drilling to provide guides for planning drilling programs, especially with regard to the most economical spacing of holes and the most desirable degree of core recovery that would provide adequate sampling at the lowest cost.

8.3.2 Mining of Iron Ores

8.3.2.1 Planning and Development

The general occurrence, size and shape of an iron ore deposit is determined during the exploration phase, which is discussed above. Knowledge of the deposit is determined in more detail through development work. It is often necessary during the development of a mine to determine, in considerable detail, the position and nature of geological structures which affect ore distribution and availability. Currently most deposits being exploited in the United States are of low grade materials called taconites containing about 30% iron, all of which must be beneficiated or concentrated to produce acceptable shipping products. In such ore deposits, the results of laboratory concentration tests of drill samples, supplemented by pilot plant tests and by experience with commercial plant results, are used to determine the economics of ore treatment.

After sufficient detailed information is obtained, various combinations of operating plans are studied using maps and sections prepared for this purpose. These show the size and shape of the ore body, ore compositions and laboratory test results. From these graphic representations, the quantities of ores and waste materials are determined by the application of volume weight factors. Computers are commonly used in the preparation of tonnage estimates and in the preparation of detailed mining plans. Through the use of these systems, comparative evaluations of various mining methods and plans may be made to determine the most favorable plan for each particular deposit and to schedule the mining of the deposit.

8.3.2.2 Open Pit Mining

Inasmuch as open pit mining provides the lowest cost operation, it is employed wherever the ratio of overburden, either consolidated or unconsolidated, to ore does not exceed an economical limit. Nearly all the large iron ore mines in the world, with the exception of some in Europe, are worked by open pit methods. Fig. 8.15, Fig. 8.16 and Fig. 8.17 show examples of open pit mining on the Mesabi Range.



Fig. 8.15 Electric power shovel in an open pit mine loading iron bearing material into a diesel powered truck for transfer to a processing plant.



Fig. 8.16 Electric power shovel loading material from an open pit iron ore mine for transfer to an ore processing plant.



Fig. 8.17 Electric power shovel on caterpillar tracks, making a sinking cut and loading ore into steel dump cars for haulage from an open pit mine to a beneficiation plant. Diesel-electric locomotives handle the dump cars while a cable carries power to the shovel.

The depth to which open pit mining can be carried depends upon the grade of the ore, the nature of the overburden and the stripping ratio. The stripping ratio is the amount of overburden and waste that has to be handled for each unit of ore mined. The economic stripping ratio varies widely from mine to mine and district to district, depending upon a number of factors. In the case of direct shipping ores, it may be as high as 6:1 or 7:1; whereas, in the case of taconite, a stripping ratio of less than 1.5:1 may be the economic limit.

Overburden (stripping) may consist of unconsolidated material, rock, or lean ore material. In open pit mining, removal of overburden may continue through a large part of the life of a mine as the pit walls are cut back to permit deepening of the mine to recover ore in the bottom. Unconsolidated materials are excavated by power shovels, draglines or power scrapers, depending on local conditions. Other materials are generally excavated with power shovels.

Drilling and blasting is done to break consolidated materials into sizes capable of being handled by mining equipment and beneficiation facilities, and is also done to loosen ore banks ahead of power shovels to increase the efficiency of loading.

Taconite ore is loaded by power shovels equipped with buckets ranging in capacity up to 26.8 m³ (35 yd³). The ore is transported out of the pit by railroad cars, trucks, belt conveyors or combinations of these, to a crushing plant for size reduction and then to a beneficiation plant for fine grinding and concentration by magnetic, gravity or flotation techniques. The concentrates are usually agglomerated into 9.5 mm (1/4–3/8 in.) balls and fired into hard durable pellets which will withstand handling, shipping and furnace charging.

The mining of taconite poses special problems because of its extreme hardness, which necessitates considerable additional drilling and blasting and more specialized and rugged equipment, as compared with the techniques and equipment used in mining most oxidized ores. Also, the relatively low iron content of taconite makes it necessary to handle two to four times as much mined material to obtain the same quantity of iron-in-ore as from higher grade ore deposits.

Water causes a variety of problems in iron ore mining operations. Except in rare instances, such as in hilltop mining or mining under desert conditions, water must be collected in sumps, wells or underground workings and pumped out of the mine. Such drainage water is often utilized directly to make up for water losses in concentration operations.

8.3.23 Underground Mining

When the stripping ratio becomes too high for economical open pit mining, underground mining methods may be employed. In most cases, access to underground mines is obtained through inclined or vertical shafts sunk adjacent to the deposit but far enough away to avoid the effects of surface subsidence resulting from mining operations. Some deposits are so situated that shafts can be driven directly into them from hillsides or from open pit banks.

Underground mining requires a larger capital investment per ton of annual capacity than open pit mining because it depends upon costly shafts or tunnels, underground haulage and development workings, and elaborate pumping facilities. Moreover, the production of iron ore per man per day in an underground mine is only a fraction of that in open pit operations, whereas the cost of supplies, maintenance, hoisting, and pumping, are all higher.

In underground mining, several methods of ore extraction may be used. Among the most common, in order of increasing cost, are: block caving, sub-level stoping, sub-level caving, top slicing, and modifications or combinations of these. All of these methods involve: drilling; blasting; transportation within the mine by rail tramming, trackless shuttle cars, scrapers, or conveyor belts; and hoisting or hauling to the surface. On the surface, the ore may be crushed, sized or concentrated prior to shipment.

In general, the higher costs of underground mining has limited its use to ores requiring simple crushing or sizing, special ores such as open hearth lump ore, or low grade ores located so near a consuming market that transportation costs to the point of use were not significant. There is one

operating underground mine in the United States, located at Pea Ridge, Missouri, where a magnetite ore body is being mined at depths of +600 m (+2000 ft). The ore is crushed, concentrated and had been used as a pellet feed. However, the high cost of this operation led to discontinuance of pellet production; the mine still produces magnetite for non-ironmaking applications. Examples of successful underground iron ore mines are the LKAB operations in Sweden where high quality, economy of scale and proximity to markets overcome the economic challenges of underground mining.

8.3.2.4 Grading of Iron Ores

Furnace practices, as described elsewhere in this volume, require the production of natural ores and/or concentrates to meet the physical and chemical specifications required in ironmaking processes. Prior to the shift in the last two decades to the large scale production of iron ore concentrates and pellets, the natural ores were graded by the producers and shippers to meet furnace demands for particular and uniform chemical composition and structure. Iron ore merchant companies could satisfy grade requirements by purchase or exchange of ores, which were then mixed together in the correct proportions. Recognition of the importance of uniformity led to the use of elaborate ore blending facilities at some producing and consuming points, involving systematic layering in stockpiles and recovery for shipment or consumption by cross-cutting the layers, see Fig. 8.18. The blending, stacking and reclaiming process illustrated in Fig. 8.18 is prominently used to prepare a uniform feed blend for modern sinter plant operations.

In the last two decades in the United States, the annual production of natural ores has decreased to less than 0.5 Mt/y and there has been a reciprocal increase in the production of iron ore concentrates and pellets. On a worldwide basis, many iron ore districts continue to produce natural ores which are usually mined to supply a uniform quality of ore. Some producers ship natural ores along with sized products, concentrates and pellets while others ship only concentrates and/or pellets. In general, it has been demonstrated that the added cost of utilizing a uniform high grade iron ore product as furnace feed can result in significant economies in the cost of the resulting hot metal.

Of particular significance in grading of ores, aside from the iron content, is the content of silica, phosphorus, manganese and alumina. A high lime content makes some ores self-fluxing. Sulfur, copper, nickel, titanium, sodium, potassium and other deleterious constituents may require close

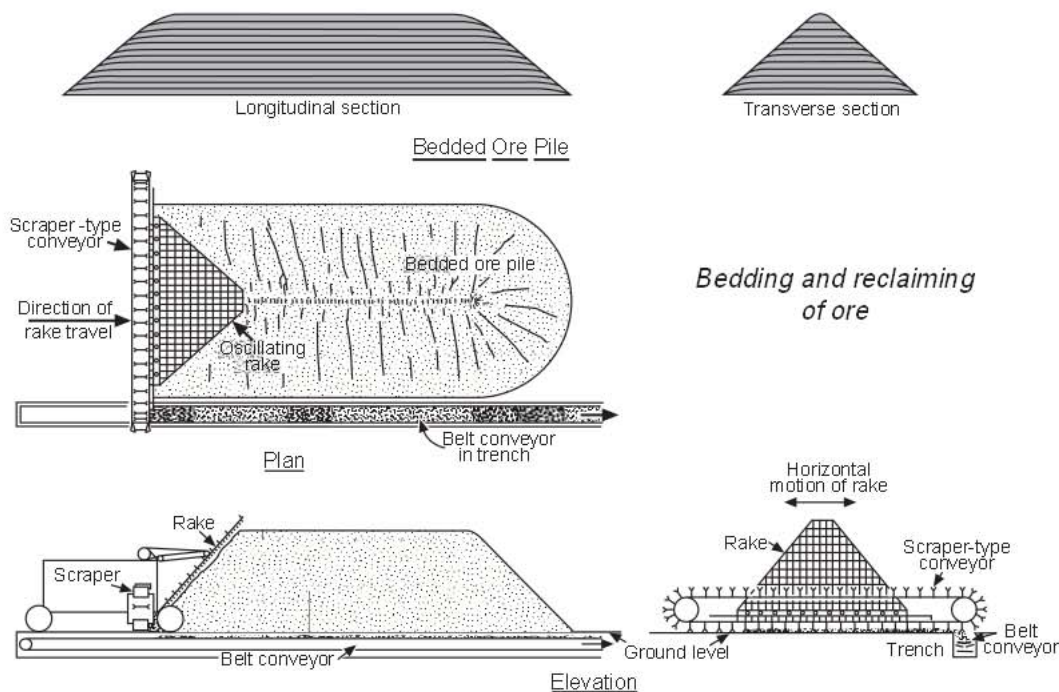


Fig. 8.18 Schematic representation of the principle of operation of a stacking and reclaiming system.

control in some producing areas. While ores are generally priced on the basis of natural iron content (that is, the amount of iron in the ore before the free moisture is removed), penalties or premiums may be applied for varying chemical and structural quality. Practices vary considerably in the various world iron ore markets.

8.4 Beneficiation of Iron Ores

8.4.1 Introduction

The term beneficiation in regard to iron ores encompasses all of the methods used to process ore to improve its chemical, physical or metallurgical characteristics in ways that will make it a more desirable feed for the ironmaking furnace. Such methods include crushing, screening, blending, concentrating and agglomerating.

Most iron ores fall within one of the three following categories. (1) Direct shipping, or high grade merchant ores, which contain enough iron to be charged to the blast furnace directly and may only require crushing, screening, and blending. (2) Associated low grade merchant ores which occur around the high grade ores that can be mined concurrently and which require minor upgrading by washing, or gravity separation techniques to increase their iron content. (3) The underlying iron formations, or taconite, from which most of these deposits have been derived; a hard, dense, low grade material that requires extensive crushing, grinding and concentration to produce an acceptable concentrate.

The iron ores that fall within these three categories have quite different processing requirements and discussion of the appropriate beneficiation steps have been grouped accordingly. The following brief and generalized descriptions are intended only to describe how the basic types of ore are beneficiated and are not to be interpreted as suitable for all ores.

8.4.2 High Grade Merchant Ores

8.4.2.1 Crushing and Screening

Iron ore of merchantable grade must be properly sized prior to charging to the blast furnace. Present blast furnace technology commonly requires crushing and screening of direct charge lump ore finer than 6 mm and coarser than 30 mm. The specific size selected is based on the characteristics of the ore and is specified so as to maintain high stack permeability and also allow sufficient time for reduction of coarser material. Consequently, crushing and screening are an integral part of ore producing facilities.

Crushing commonly involves a primary jaw crusher with secondary gyratory, or cone crushers operating in closed circuit with vibrating screens. Roll crushers, hammer mills, or vertical impact crushers have been used. Equipment selection is determined largely by the friability of the ore. Most of the screening operations on high grade ores are dry except when the fines fraction can be effectively upgraded by de-sliming.

The -6 mm (-1/4 in.) fines produced by crushing and screening are most commonly agglomerated by sintering, or sometimes reground and pelletized. The sinter produced is also crushed and screened to meet size specifications compatible with the other charge components.

8.4.2.2 Blending

The mining program at individual mines is developed to produce a uniform product. Although there are multiple handling steps involved in most loading and shipping systems they do not often provide enough mixing to meet quality assurance standards now required by industry, especially if both size consist and chemistry standards are specified. Sophisticated combined blending and loadout facilities are now almost universal in the industry.

Stacking and reclaim systems are used most commonly. Stacking results in layering of the ores, see Fig. 8.18. Each successive layer represents an ore that may differ in size consist or chemical composition from adjacent layers. The elongated pile is built up to a height limited by the stacking capability of the machine. The ore may then be reclaimed for use by bucketwheel excavators, front-end loaders, or a scraper-cross conveyor. Removal of ore from the face of the pile results in a stream of material that is a uniform blend of ore from all the layers. Variations of this method are used extensively for the stocking and reclaiming of iron ore pellets, as well as other bulk commodities used by the steel industry such as coal and limestone.

8.4.3 Low Grade Merchant Ores

The earliest iron ore beneficiation techniques were developed to upgrade the lower grade ores associated with direct shipping ores. The natural ore forming process produced layers of relatively pure iron oxides interbedded with partially decomposed silica rich layers. Ores in which the silica layers had been completely decomposed could be easily upgraded by simple washing techniques where the fine-grained friable silica particles could be separated from the heavier, denser, and coarse iron ore particles by hydraulic classification. Ores in which the silica-rich layers had not been weathered as intensely and were still relatively cohesive and had to be broken by crushing were upgraded by gravity concentration techniques such as jigging and heavy media separation with the finer fractions upgraded in spiral concentrators. The technology for beneficiating low grade ores was largely developed on the Mesabi Range in Minnesota in the 1950s and 1960s and applied world wide to similar deposits.

8.4.3.1 Washing

Washing is the simplest iron ore concentration process that takes advantage of the high specific gravity and comparatively coarse size of the iron bearing minerals to separate them from the finer, lighter, siliceous gangue which is predominantly quartz and clay minerals. The ore is prepared for washing by crushing in one or two stages finer than 50 mm (2 in.). The crushed ore is fed to log washers which were developed specifically for the wash ores of the Western Mesabi Iron Range. The intense agitation of the ore by the paddles (similar to a modern pug mill) combined with the counter flowing water efficiently commuted and removed the fine silica to leave a coarse residual iron-rich product. The log washer overflow was often retreated in rake or spiral classifiers to recover additional fine iron. Some washing plants employed spiral classifiers in one or two stages without a log washer on ores containing a minimum amount of sticky clay gangue.

Hindered settling classifiers of various types, hydrosizers, pocket sizers and Wilfley shaking tables were also used to recover fine iron before the development of the Humphrey spiral.

8.4.3.2 Jigging

Jigging is a more complex form of beneficiation than simple washing and is used on the more refractory ores that require crushing to break up the silica rich layers. Jigs used for iron ore beneficiation are basically horizontal screens which carry a bed of ore some 15–25 cm (6–10 in.) deep. The ore is fed at one end and is stratified by the pulsing action of water, either caused by an oscillating pump or by physical up and down movement of the jig screen itself. As the ore moves down the deck the pulsing allows the lighter silica rich particles to work their way to the top of the bed, while the heavier iron-rich particles segregate along the base. The two products are separated at the end of the jig, the lighter silica-rich particles over the top of the discharge weir and the iron ore concentrate under the bottom. Iron ore jigs worked best on the particles ranging from 25 mm to 1 mm (1 in. to 1/16 in.).

8.4.3.3 Heavy Media Separation

Heavy media separation devices were developed as a more effective alternative to jigging for the upgrading of the more refractory ores in the 1950s. Heavy media separation processes operate on

the sink-and-float principle. A suspension of fine, -200 mesh, ferrosilicon in water is used to create a fluid media with a specific gravity of about 3.0. Silica-rich particles with a specific gravity of about 2.6 will float on the surface of such a medium while the denser and heavier iron ore particles with a specific gravity over 4.0 will settle to the bottom. The conventional medium for concentrating coarse ore is ferrosilicon containing 15% silicon and 85% iron. Water suspensions containing 64–85% by weight of finely ground ferrosilicon have specific gravities ranging from 2.20–3.60.

The separation vessels for coarse ore, +9 mm (+3/8 in.) are commonly spiral classifiers, rake classifiers or rotating drums. Ore finer than 9 mm (3/8 in.) and coarser than 3 mm (1/8 in.) can be separated in heavy media cyclones where the high gravitational forces accelerate the settling of the heavy iron ore particles. Finely ground magnetite is used to make up the heavy media for the cyclone separators rather than ferrosilicon. The dynamics of the cyclone create the density and media fluidity required despite the lower specific gravity of the magnetite. Further the cost of magnetite is much less than ground ferrosilicon.

The medium, ferrosilicon and magnetite, is washed from the sink and float products on fine screens equipped with wash troughs and water sprays and is recovered from the wash water with magnetic separators and recycled.

84.34 Spirals

The Humphrey spiral, first developed for the treatment of beach sands, is used in iron ore concentration to treat -6 mesh \times 100 mesh ore. Efficiency below 100 mesh decreases rapidly and spirals are ineffectual on finer materials. Spirals are widely used for the supplementary recovery of fine iron from merchant ore types and are the primary concentration device for the specular hematite ores of the Labrador trough and similar ores that can be liberated by grinding no finer than 20 mesh. A typical concentration plant flowsheet for specular hematite ore is shown later in Fig. 8.27.

The spiral concentrator is a curved-bottom trough, wound around a vertical axis in the form of a helix, Fig. 8.19. When fed at the top with a slurry of iron ore and gangue, the less dense gangue, being more readily suspended by the water, attains greater tangential velocity than the iron minerals, and migrates toward the outer rim of the spiral trough. Wash water added along the inside rim helps wash away the lighter gangue. After a few turns, a band of iron mineral forms along the inner rim, and the gangue forms bands toward the outer rim. Ports are spaced along the inner rim to collect and remove the iron minerals. The gangue remains in the spiral and discharges at the bottom.

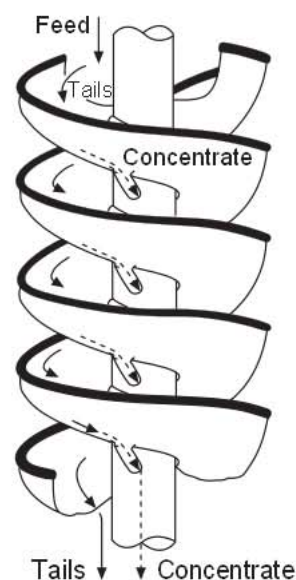


Fig. 8.19 Schematic of a spiral concentrator.

84.35 Reichert Cone

The principle advantages for the Reichert cone are capacity and the ability to recover fine heavy minerals efficiently down to about 325 mesh, finer than is attainable in spirals. A single Reichert cone has a capacity of up to 100 tonnes per hour and can be used effectively to recover specular hematite fines as well as merchant ore fines. De-sliming of the feed is desirable, and essential for merchant type ore fines.

The Reichert cone, Fig. 8.20, is a flowing-film concentrator. The denser particles concentrate at the bottom of a flowing film of slurry having a solids content of about 60% by weight. The separation mechanism is a combination of hindered settling of the dense particles and interstitial trickling of the fine particles. The separation element in the Reichert unit is an inward sloping 1.9 m (6.25 ft) diameter cone. Feed pulp is evenly distributed around the periphery of the cone. As the pulp flows by gravity toward the center, the fine and the heavy particles concentrate on the bottom and are

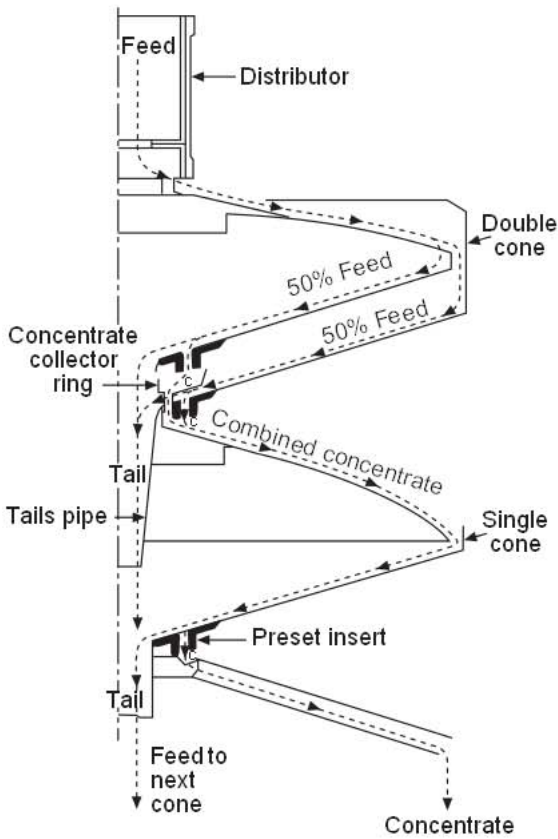


Fig. 8.20 Schematic of a section of a Reichert cone concentrator.

removed through an annular slot near the apex of the cone. The tailing flows over the slot and is collected at the apex or center of the cone. Because the efficiency of this separation process is relatively low, it is repeated several times within a single stacked arrangement of cones to increase the recovery. Generally, the highest grade concentrate is produced in the primary separation cone.

8.4.36 Wet High Intensity Magnetic Separation (WHIMS)

Wet high intensity magnetic separation machines, WHIMS, were developed to recover non-magnetic iron units. They can be effectively applied across a wide particle size range from 10 mesh to 500 mesh depending upon the matrix used. WHIMS applications include recovery of iron from natural ore fines, upgrading of spiral concentrates for direct reduction feed, and recovery of hematite from tailings.

In wet high intensity magnetic separations (WHIMS), electromagnets produce a very high-strength magnetic field that is applied to a matrix consisting of steel balls, spaced grooved plates, steel wool or pieces of expanded metal, Fig. 8.21. The matrix is contained in an annular ring that is rotated

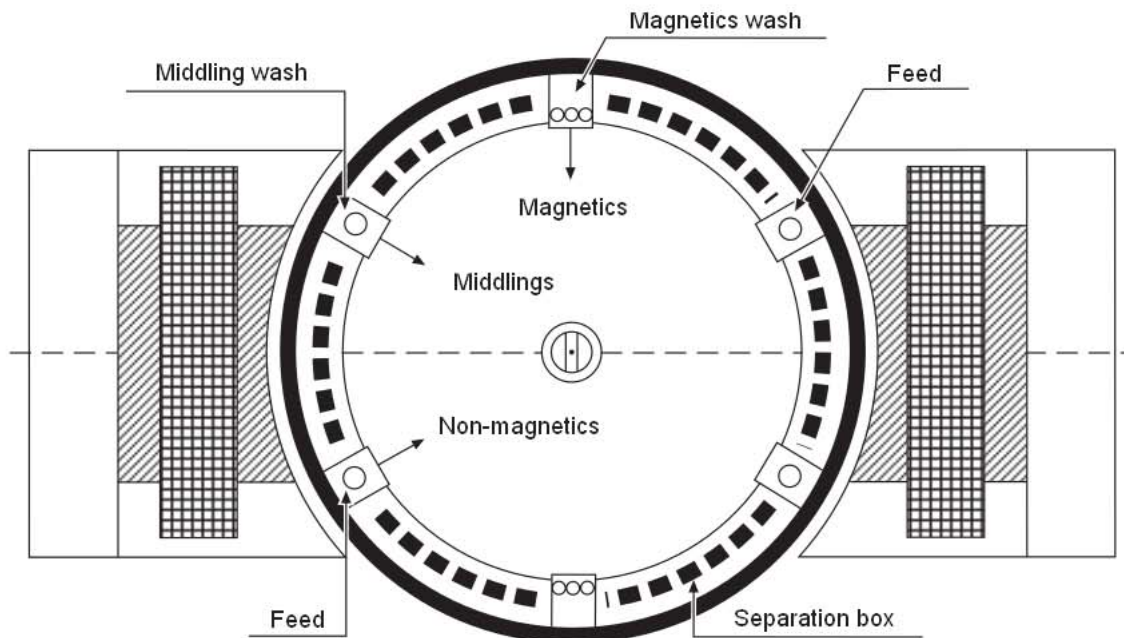


Fig. 8.21 Schematic diagram of a wet high intensity magnetic separator.

between the high intensity magnets. The iron ore slurry is introduced at a point where the matrix is in the field. The high magnetic gradients developed around the matrix hold the hematite while the siliceous gangue is washed through. The hematite concentrate is released and discharged as the matrix moves out of the magnetic field.

8.4.4 Primary Ores

The primary ores, iron formations from which most of the world's merchant ores have been derived by geological processes, represent almost unlimited iron unit reserves. These ores contain only 25–35% recoverable iron that is present as either magnetite or hematite. Typically the ore is very hard and the magnetite or hematite requires very fine grinding for liberation. Processing is complex and mining, crushing, grinding, and concentration costs are very high. Mining companies have to continuously develop new processing options to reduce costs and maintain product quality. However, the high quality of the pellets and sinter produced from the concentrates has revolutionized blast furnace ironmaking. Concentrates containing 4.0% silica are now the norm and the agglomerates produced, pellets, fluxed pellets or sinter, now dominate ironmaking in North America.

To produce a final product that is uniform in chemical and physical properties, blending of the crude ore from various shovel locations mining different grades of ore is accomplished by utilizing sophisticated computerized mine plans.

The greatest production at the present time is from the magnetite taconites of Minnesota and Michigan. There is also substantial production from the specular hematite iron formations of the Labrador trough. The discussion of beneficiation techniques will use these two iron ore types as models, however, similar iron formations are present on all of the continents and are being exploited, or will be in the future.

8.4.4.1 Comminution

8.4.4.1.1 Drilling and Blasting Comminution begins in the mine. The impact of fragmentation achieved in blasting on downstream comminution, crushing and grinding, is just beginning to be quantified. More companies now regard this as the first step in comminution and are willing to allocate more money to drilling and blasting to achieve finer fragmentation and reduce downstream costs.

8.4.4.1.2 Primary, Secondary and Tertiary Crushing Because of the hardness of the ore three, and sometimes four stages of crushing, are used in magnetite taconite plants to reduce the ore to rod mill feed size, Fig. 8.22. Primary and secondary crushing is almost universally by gyratory or cone crushers. Jaw crushers seldom have the capacity or the durability to serve as a primary crushing unit unless the ore is exceptionally soft. Tertiary crushing to a top size of 25 mm (1 in.) is almost universally by shorthed crushers operating in closed circuit with screens. A newly developed crushing system, the high pressure roller press (HPR) which has been successfully used for fine comminution in the cement industry is now being tested as an alternative to tertiary crushing, and rod milling. The HPR can reduce 60 mm (2.5 in.) crude ore to rod mill discharge size when closed with a screen. Power savings are significant and although the capital costs are high the metallurgical benefits are also high and HPR may replace both tertiary crushing and rod mills in some taconite plants.

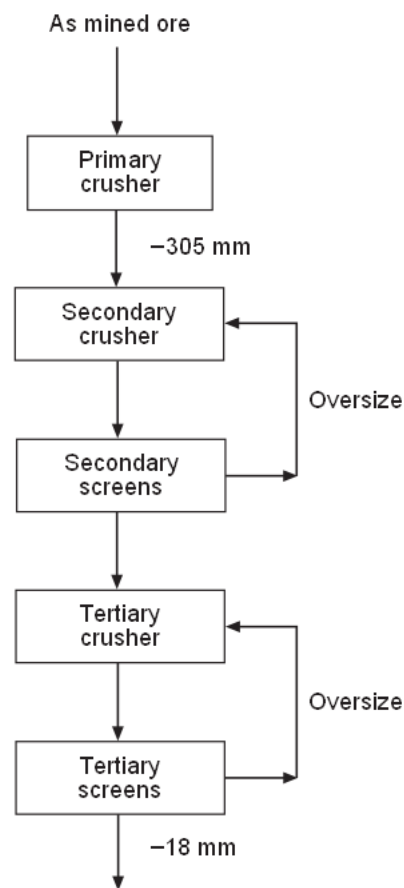


Fig. 8.22 Flow sheet of an iron ore crushing circuit.

844.13 Autogenous Milling Autogenous grinding is an alternative to multi-stage crushing. Autogenous mills use the ore as a grinding media. The crude ore is crushed to a top size of 305–457 mm (12–18 in.) in one stage of primary crushing. The tumbling mills have a high diameter to length ratio and the larger ore fragments are the grinding media. The benefit of the autogenous milling circuit is that it completely eliminates secondary and tertiary crushing required by conventional rod mill and ball mill plants. Metal consumption is lower because no steel grinding media is used, but the power input per ton of product produced is higher because of the low density of the natural ore grinding media.

The mill discharge is usually sized on a relatively coarse trommel screen at 3 mesh, and the over-size pebbles recirculated. This recirculating pebble load tends to build up in some circuits and eventually will curtail mill production. The most recent process improvement applied to autogenous milling circuits has been the addition of magnetic cobbing and pebble crushing to reduced the circulating load and significantly increase throughput. Three alternatives for pebble crushing have been or are being tested on a commercial scale. These are water flush crushing, vertical impact crushers, and the high pressure roller press.

The final product size from autogenous milling is controlled by cyclone classification of the trommel undersize. In some plants the autogenous mill grinds to final liberation size, –200 mesh. Other plants close the autogenous mills at a coarser size, –6 mm (–1/4 in.), and achieve the final grind in conventional ball mills or pebble mills.

844.14 Semi-Autogenous Milling Autogenous milling requires competent ore that will provide the coarse grinding media required to achieve effective breakage. Where such competent ore is limited, or the ore tends to break to a smaller size and the smaller fragments cannot provide the energy required for breakage, steel balls are added to the mill. This is termed semi-autogenous grinding. The other components of the circuit are essentially as described for autogenous milling.

844.15 Rod Milling Rod mills were designed to grind nominal –35 mm (–1.25 in.) feed, usually prepared by tertiary cone crushers, to –3 mesh. They are tumbling mills with a length to diameter ratio of 1.5 to 2.0. The grinding media are steel rods up to 100 mm (4 in.) in diameter. The ore is ground wet at about 68–80% solids. Rod mills are most commonly operated in open circuit. Product size is controlled by combinations of feed rate, rod charge characteristics, mill speed, slurry density and viscosity.

844.16 Ball Milling Ball mills are the principal means of fine grinding in the iron ore industry. They are tumbling mills like the rod mill, but usually with a smaller length to diameter ratio ranging up to 1.5. The grinding media are steel balls rather than rods. These mills are almost always operated in closed circuit with classification devices such as cyclones, spiral classifiers or density classifiers, commonly operated in combination with fine screens. Grinding efficiency is greatly affected by the classification efficiency and mill operating parameters such as mill speed, media charge, slurry density and viscosity.

844.17 Pebble Milling Pebble mills are also used for fine grinding. They are similar to ball mills except that they are charged with 25–100 mm (1–4 in.) pebbles rather than steel balls. Their principal advantage is that steel grinding media is not required and mill liner wear is reduced. The offset is the generally high power consumption per ton of product produced. The pebbles are most often obtained from an associated autogenous mill circuit where their diversion helps solve the primary mill recirculating load problem. However, they can also be obtained from a conventional crushing plant circuit.

844.2 Magnetic Separation

Magnetic separation is universally used for concentration of magnetite bearing iron ores and magnetite-taconite. Because of the layered nature of the taconite, quartz-rich layers interbedded with magnetite-rich layers, partial rejection of silica can be achieved at a relatively coarse size. A taconite plant may have as many as five magnetic separation stages at successively finer sizes before a final concentrate is produced.

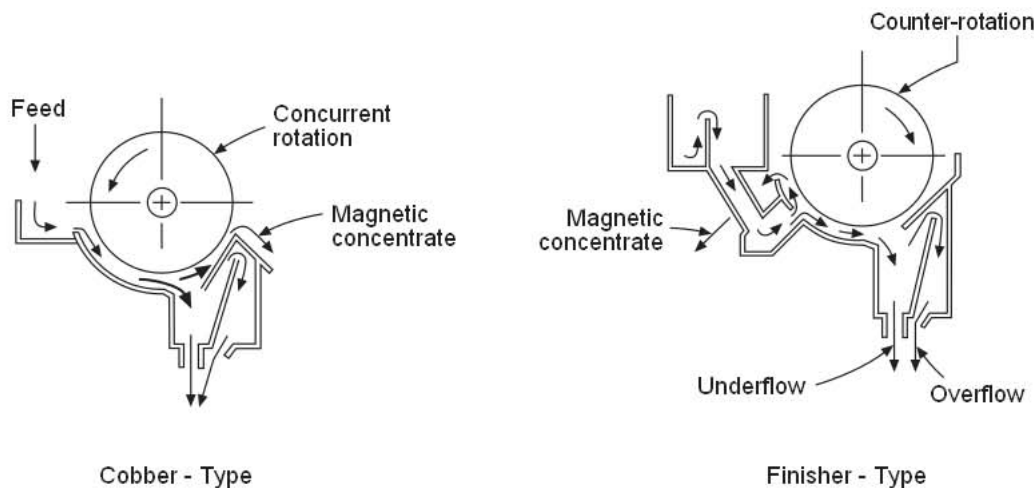


Fig. 8.23 Concurrent cobber type magnetic separator for coarse ore and counter rotation magnetic separator for fine ore.

8.4.4.21 Coarse Dry Magnetic Cobbing Coarse magnetic cobbing of tertiary crusher discharge at -25 mm (-1 in.), rod mill feed, has been practiced by several plants. Such separation is usually accomplished dry using a magnetic head pulley. Head pulleys with fixed permanent magnets, radial or axial configuration, have been used as well as fixed magnets inside a rotating drum similar to the wet magnetic cobbing drums described later. Rejection of 10–15 % of the ore while recovering over 98% of the magnetite is possible depending upon the grade of the feed. Magnetic separation at -75 mm (-3 in.) was also used at one mine to upgrade lean ore stockpiles.

8.4.4.22 Magnetic Cobbing of Rod Mill Discharge Magnetic separation of magnetic taconite at (3 mesh is a critical step in the process. At this size 25–45% of the ore can be discarded as a tailing which reduces downstream grinding and concentration costs. The magnetic cobbers, Fig. 8.23, generally consist of a fixed permanent magnet assembly inside a rotating stainless steel drum. The magnetic field strength at the drum surface is generally low, less than 2000 gauss. The magnetite is pulled against the drum and carried to the discharge lip as the drum rotates. Tailings drop to the bottom of the tank and are rejected through spigots. Drums of 4 ft diameter have a capacity of over 10 long tons per hour per foot of length.

8.4.4.23 Finisher and Cleaner Magnetic Separation These magnetic separators are used after ball mill or pebble milling to treat the circulating load, or between grinding stages, or to treat the final classifier product. Because of the finer grain size the tank configuration of finisher and cleaner magnetic separators and the feed and tailings discharge systems are different than coarse cobbers. The feed and tailings can be held in suspension so bottom spigot discharge is not required. Several different options for presenting the feed, and discharging the tailings have been devised, one of which is shown in Fig. 8.23. The magnetic field strength of the finisher and cleaner magnetic separators is generally lower than that of the cobbers to allow rejection of fine middlings and minimize free silica entrapment. Field strengths as low as 800 gauss have been specified for some plants. Capacity of 4 ft diameter separators treating fine material is also somewhat lower, generally less than 5 tons per hour per foot of width.

8.4.4.3 Hydraulic Separation

Hydraulic separation is an important step in the magnetic separation plant. It is applied most commonly to the final classification product, usually ahead of the finisher or cleaner magnetic separation steps. The feed is passed through a magnetic coil that causes the individual magnetite particles to coagulate by magnetic flocculation. The magnetic floccules settle very rapidly in a hydraulic separation tank and the silica slimes and some fine middlings will be rejected as a final tailings in the overflow. Dewatering in this stage is as important as the silica rejection and the densified classifier discharge then is fed to the final magnetic separators.

84.44 Classification and Fine Screening

The efficiency of fine grinding circuits is greatly affected by the efficiency of the classification system used to close the circuit. Numerous variations of rake, bowl, and spiral hydraulic classifiers were used before the introduction of hydrocyclones in the 1950s. Now cyclones are universally employed because of their low operating cost and minimal space requirement. Because of the high gravitational forces in the cyclone both particle size and particle specific gravity affects the size separation. This tends to increase the percentage of middling particles in the cyclone overflow and affects downstream processing. The addition of fine screens to treat the cyclone overflow can reduce this problem by allowing the cyclone to operate at a coarser size split and use the fine screens to control the final concentrate size. Either stationary slotted screens, or vibrating sandwich deck screens can be used to make separations about 325 mesh. The combination of cyclones and fine screens is almost universal in magnetite taconite plants, and some plants are operating circuits in which the cyclone is essentially eliminated and fine screens used alone. A recent development in the taconite industry is the testing of density classifiers as an alternative to cyclones because they can make a sharper, cleaner size split.

84.45 Flotation

Froth flotation is effective for the concentration of fine, -100 mesh, iron ores. It can be used for the supplementary upgrading of magnetite concentrates, as currently practiced at four taconite operations in Minnesota, or as the primary recovery method for hematite ores, as currently practiced at the Tilden mine in Michigan.

Flotation processes depend on the fact that certain reagents added to water suspensions of finely ground iron ore selectively cause either iron oxide minerals or gangue particles to exhibit an affinity for air. The minerals having this affinity attach to air bubbles passing through the suspension and are removed from the suspension as a froth product.

The reagents added to induce the preferential affinity for air are commonly called collectors or promoters; substances added to cause stable bubble or froth formation, are known as frothers; other substances added for control purposes such as pH adjustment, or to cause better dispersion or flocculation are known as modifiers, dispersants, and depressants.

Flotation collectors are of two general types; anionic and cationic. Anionic collectors ionize in solution such that the active species (that which attaches to the positively charged mineral surface) is negative charged. Conversely, the active ionic species in cationic flotation collectors is positively charged.

The main application of anionic flotation is to float iron bearing minerals away from gangue material. The most common collectors used are fatty acids or petroleum sulfonates. Fuel oil is often added along with the collectors to promote recovery of iron oxide particles finer than about 10 μm .

Conversely, cationic flotation is used to float siliceous gangue away from finely ground crude ore and to remove small amounts of gangue material from some magnetite concentrates. Cationic collectors are primary aliphatic amines or diamines, beta-amine, or ether amines, generally in acetate form.

84.45.1 Magnetite Taconite Concentrates Supplementary upgrading of magnetite concentrates is practiced at several taconite plants to lower the silica content for blast furnace pellets. It will also be an essential part of the flowsheet for the production of low-silica concentrates for direct reduction in the future. Cationic silica flotation is most commonly used for this purpose. The silica in the final concentrate may be reduced by as much 2 – 4% depending upon the efficiency of the magnetic separation plant and the characteristics of the crude ore.

Conventional mechanical flotation cells, 500–1500 ft³ capacity, are used in Minnesota taconite plants. Because of the carryover of fine, -500 mesh, free magnetite with the silica-rich froth, secondary froth treatment is essential. This may be complex and involves dewatering, cyclone classification and densification, regrinding and magnetic separation. One plant has pioneered the use of column flotation for froth retreatment because column flotation units recover -500 mesh magnetite more efficiently than the conventional mechanical cells.

8.4.4.5.2 Hematite Ores The basic selective flocculation, cationic silica flotation flowsheet was developed specifically to concentrate the ores of the Tilden Mine. Refer to the plant flowsheet shown as Fig. 8.28. Fine grinding of this somewhat soft ore produces a significant percentage of hematite slimes. These are flocculated by adding starch products to the slurry. This allows rejection of siliceous slimes by classification and retention of the flocculated fine iron minerals. The de-slimed ore is then concentrated by froth flotation using cationic collectors to remove additional silica. The separation is enhanced because the starch depresses (inhibits) flotation of the flocculated iron minerals.

8.4.5 Concentration Plant Flow Sheets

The type of beneficiation process depends on the ore and the ultimate destination of the iron concentrate, i.e. direct reduction feed requires a much lower silica content necessitating a more elaborate beneficiation flow sheet than does blast furnace feed.

8.4.5.1 US Steel Minntac

The flowsheet for U.S. Steel's Minntac taconite concentrator is shown in Fig. 8.24. Run-of-mine ore is crushed in three stages to 90% -18 mm (-3/4 in.) and is then ground in a rod mill to produce a 90% -3 mm (-1/8 in.) feed to the first stage (cobber) of magnetic separation. The magnetic concentrate is reground in the primary ball mill to -420 μm (-35 mesh) and sent to the second stage (rougher) of magnetic separation. The second stage concentrate is reground to 70% -53 μm (-270 mesh) and sent to hydroseparators where some fine silica is removed in the overflow. The hydroseparator underflow goes to the finisher stage of magnetic separation. Finisher magnetic concentrate is screened and the oversize returned to the secondary ball mill. The undersize at about 90% -53 μm (-270 mesh) goes to a cleaner stage of magnetic separation. The cleaner magnetic concentrate is sent to the flotation section where amine and frother are added to float additional silica and meet concentrate grade requirements. The final concentrate is pumped to the agglomerator for pelletizing. Minntac grinding mills and several stages of magnetic separation are pictured in Fig. 8.25.

8.4.5.2 Hibbing Taconite

Another method of processing taconite is shown in Fig. 8.26 for Hibbing Taconite Company. Run-of-mine ore is crushed to -230 mm (-9 in.) in a single stage and is ground in autogenous mills to -3 mm (-1/8 in.). The autogenous mill undersize is sent to the first stage of magnetic separation, while the oversize goes to a cobbing and crushing circuit. The magnetic concentrate is classified in hydrocyclones to produce an overflow containing about 80% -43 μm (-325 mesh) which goes to the second stage of magnetic separators. The coarse cyclone underflow returns to the autogenous mill. The second stage magnetic concentrate is screened at a 150 mesh cut using vibrating screens to remove coarse silica from the final product which goes to the agglomerator.

8.4.5.3 Quebec Cartier Mining Company

The flowsheet of Quebec Cartier Mining Company's Mount Wright concentrator is shown in Fig. 8.27. The ore contains specular hematite and quartz and is ground to -833 μm (-20 mesh) to liberate the hematite so that it may be concentrated by spirals. Run-of-mine ore is crushed to -305 mm (-12 in.) and is ground in an autogenous mill. The grinding mill product is screened in two stages to remove the +833 μm (+20 mesh) oversize, which is returned to the mill. The screen undersize is concentrated by three stages of spirals to make a concentrate which is then dewatered on horizontal vacuum filters. The concentrate enters world markets as a 1.0 \times 0.1 mm product and is used mainly as sinter feed or is pelletized at the company's Port Cartier pellet plant after being reground.

8.4.5.4 Tilden Mine

A flowsheet for the Tilden concentrator operated by the Cleveland Cliffs Iron Company is shown in Fig. 8.28. The crude ore is a jasper containing fine, disseminated hematite. Run-of-mine ore is crushed and then is ground in primary autogenous mills. The mill discharge is screened to remove

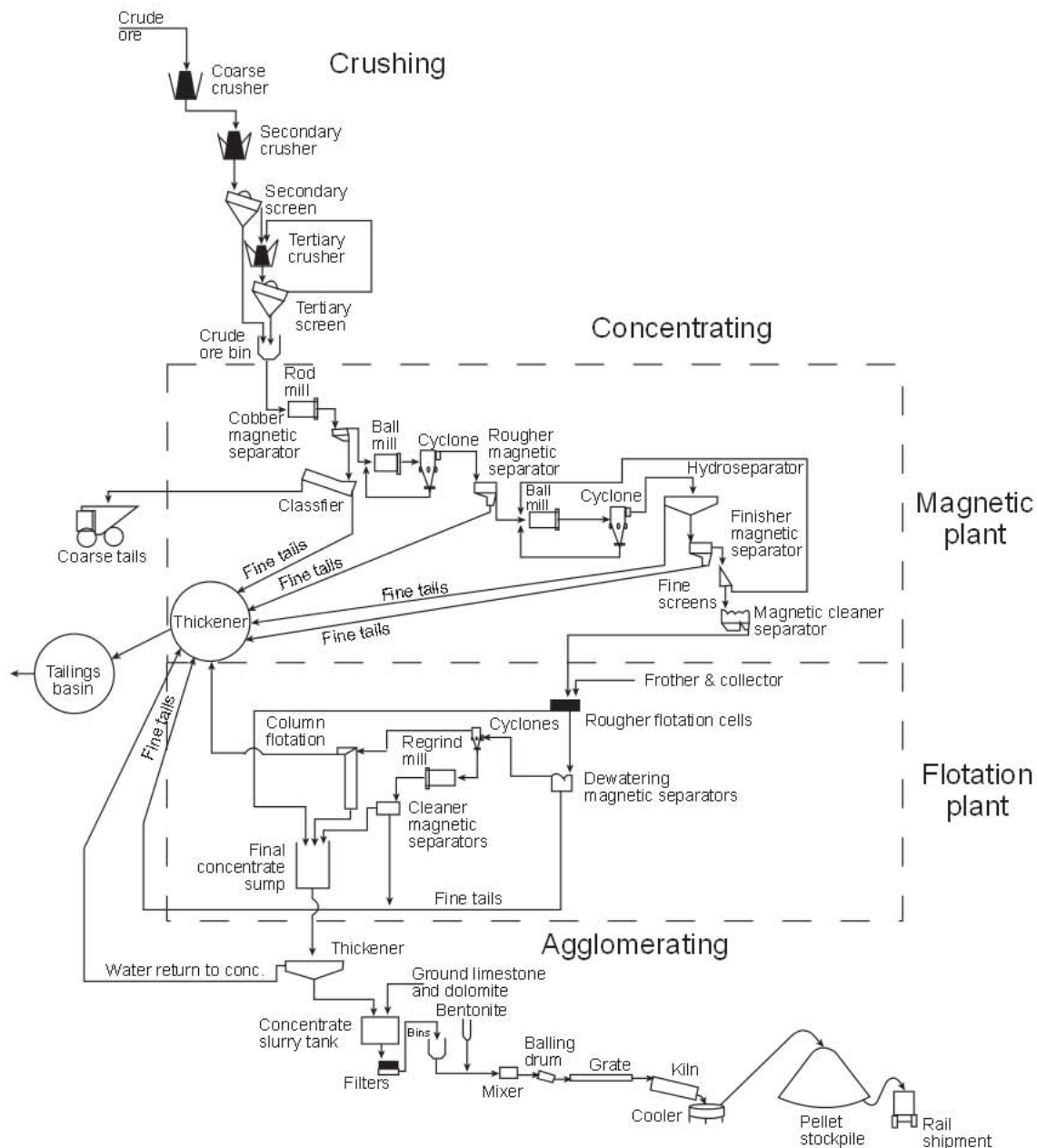


Fig. 8.24 Generalized flowsheet for U.S. Steel Minntac.

-2 mm (-8 mesh) particles, which are reground to 80% -74 μ m (-200 mesh) in pebble mills. Part of the screen oversize is used as grinding media in the pebble mills and the remainder returns to the primary mill. The 75 mm (3 in.) \times 32 mm (1 1/4 in.) fraction of the screen oversize is crushed before it is returned to the grinding mill in order to avoid an excessive and undesirable accumulation of this size fraction in the primary mill circuit. Reagents are added to the cyclone overflow from the pebble mill circuits to selectively flocculate the hematite. Removal of siliceous slime is then accomplished by overflowing it at the de-sliming thickeners. The de-slimed underflow goes to flotation, where the remaining silica is floated leaving the iron concentrate behind. The selective flocculation of iron oxides is accomplished by starch addition and the collector for silica flotation is a cationic amine.



Fig. 8.25 Flotation section in foreground, grinding mills and magnetic separation in the background at U.S. Steel Minntac

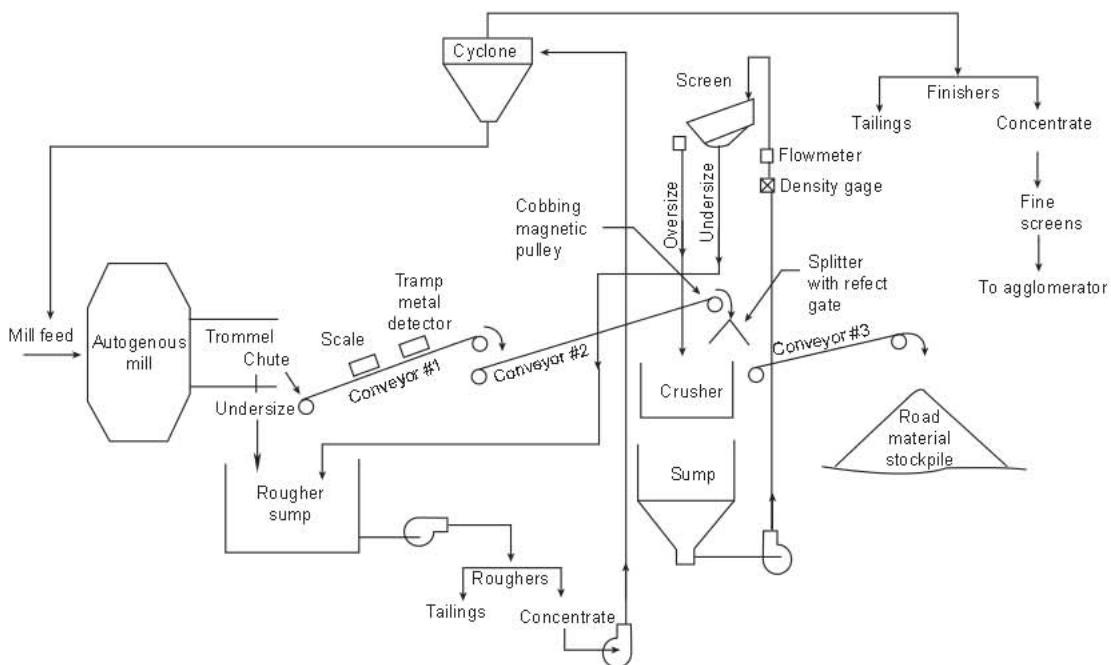


Fig. 8.26 Hibbing Taconite processing circuit, employing a cobbing and crushing closed circuit.

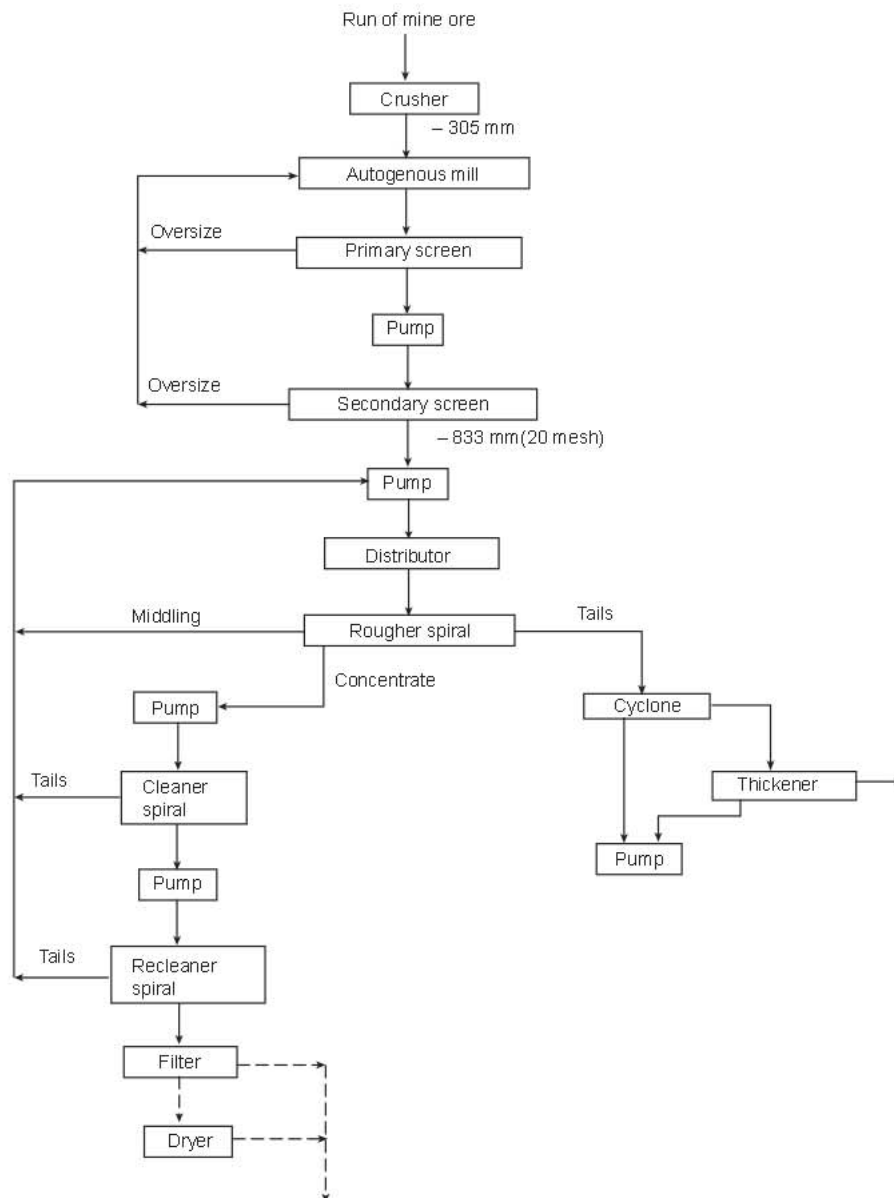


Fig. 8.27 Flowsheet for spiral concentration at Quebec Cartier Mining Company.

8.5 Agglomeration Processes

The blast furnace is a countercurrent gas-solid reactor in which the solid charge materials move downward while the hot reducing gases flow upward. The best possible contact between the solids and the reducing gas is obtained with a permeable burden, which permits not only a high rate of gas flow but also a uniform gas flow, with a minimum of channeling of the gas. The primary purpose of agglomeration is to improve burden permeability and gas-solid contact, and thereby reduce blast furnace coke rates and increase the rate of reduction. A secondary consideration is the lessening of the amount of fine material blown out of the blast furnace into the gas recovery system. Furthermore, in ironmaking furnaces, agglomerated materials, when they have the proper chemical composition, can substitute for lump ores used as charge ores.

The leading direct reduction processes such as Midrex and HYL are also shaft furnaces which rely on countercurrent gas-solid contact so the principles of burden sizing are similar to that of the blast

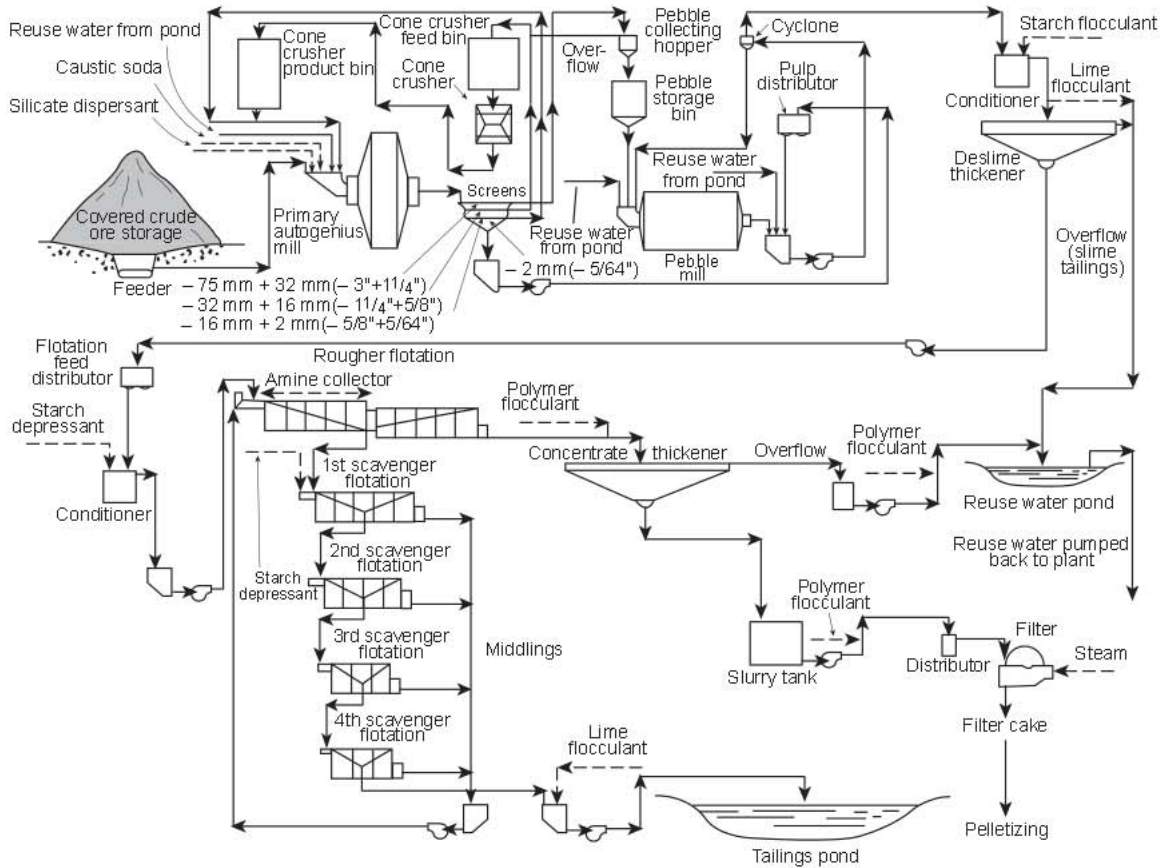


Fig. 8.28 Concentrator flowsheet of the Tilden Mine.

furnace but are even more important as the ferrous materials are the only solid materials in these shaft furnaces.

A good agglomerate for blast furnace use should contain 60% or more of iron, a minimum of undesirable constituents, a minimum of material less than 6 mm (1/4 in.) in size, and a minimum of material larger than 25 mm (1 in.). The agglomerate should be strong enough to withstand degradation during stockpiling, handling, and transportation to the furnace so as to arrive at the furnace skip containing a minimum of 85–95% of +6 mm (+1/4 in.) material. In addition, the agglomerate must be able to withstand the high temperature and the degradation forces within the furnace without slumping or decrimation. The agglomerate should also be reasonably reducible so that it can reduce at a satisfactorily high rate in the blast furnace. In the last several decades somewhat different standards have developed for the two leading agglomerate forms, sinter and pellets. A good summary of desirable sinter and pellet properties is presented in Table 8.7; a more comprehensive discussion is available in the reference for these tables.

Four types of agglomerating processes have been developed: sintering, pelletizing, briquetting, and nodulizing. Their individual products are known as sinter, pellets, briquettes, and nodules, Fig. 8.29. Only the sintering and pelletizing processes are of major importance as neither briquetting nor nodulizing has gained any substantial degree of commercial acceptance. Careful evaluation should be made of the processes, material to be agglomerated, and the product desired before arriving at a final decision on a commercial installation. Quite often the origin of the material to be agglomerated together with material handling and transportation considerations will dictate which process is chosen. Fine concentrates such as those made from magnetite taconite are not readily

Table 8.7 Desirable Sinter and Pellet Properties (Adapted from Ref. 3)

Sinter			
Chemistry		Physical Properties	
FeO	5.0–6.0%	ISO Strength (ISO 3271)	
Mn	≈ 0.2% (as low as possible)	> 6.3 mm	70–80%
P	≈ 0.04% (as low as possible)	Grain Structure	
SiO ₂	5.0–5.5%	< 5 mm or < 6 mm	max. 5%
Al ₂ O ₃	1.0–1.3%	< 10 mm	max. 30%
TiO ₂	– (as low as possible)	> 50 mm	max. 10%
Na ₂ O+K ₂ O	< 0.08% (as low as possible)	Metallurgical Properties	
CaO	8–10%	Disintegration in the Static Test	
MgO	1.4–2.0%	RDI	
CaO/SiO ₂	> 1.8	< 2.8 mm	max. 20–30%
		< 3.15 mm	max. 35%
		ISO 4696	
		< 3.15 mm	max. 30–33%
		Reducibility (ISO 4695)	1.4–1.6% min.
Conditions of the RDI and ISO 4696 method			
	RDI	ISO 4696	
Sample	500 g: 16–20 mm	500g: 10–12.5 mm	
Temperature	500°C	500°C	
Reduction Gas	30% CO; 70% N ₂	20% CO; 20% CO ₂ ; 2% H ₂ ; 58% N ₂	
Reduction Time	30 min	60 min	
Apparatus	Vertical retort; Ø 75 mm	Vertical retort; Ø 75 mm	
Evaluation of Results	Tumbling 900 revolutions drum: l = 200 mm, Ø = 130 mm two lifters	Tumbling 300 revolutions drum: l = 200 mm, Ø = 130 mm two lifters	
Expression of Results	% by wt > 6.3mm % by wt % by wt < 0.5 mm % by wt < 3.15 mm	< 3.15 mm % by wt > 6.3mm % by wt < 0.5 mm	
Blast Furnace Pellets			
Metallurgical Properties		Physical Properties	
Low Temperature Disintegration, dynamic test (SEP 1771/82)		Grain Structure	
> 6.3 mm	min. 80%	> 16 mm	max. 5%
< 0.5 mm	max. 15%	8–16 mm	min. 85%
		< 6.3 mm	max. 5%
Reduction Properties under Load (ISO 7992)		Cold Compression Strength, Pellets 10(12.5 mm (ISO 4700)	
80% degree of	max. 15 mm WG reductions	Average	min. 2500 N
Reducibility R40-value (ISO 4695)	min. 0.8 %/min	< 2000 N	max. 10%
		< 1500 N	max. 5%
Swelling (ISO DP 4698)	max. 20%	Tumbler Strength (ISO 3271)	
		> 6.3 mm	min. 95%
		< 0.5 mm	max. 5%

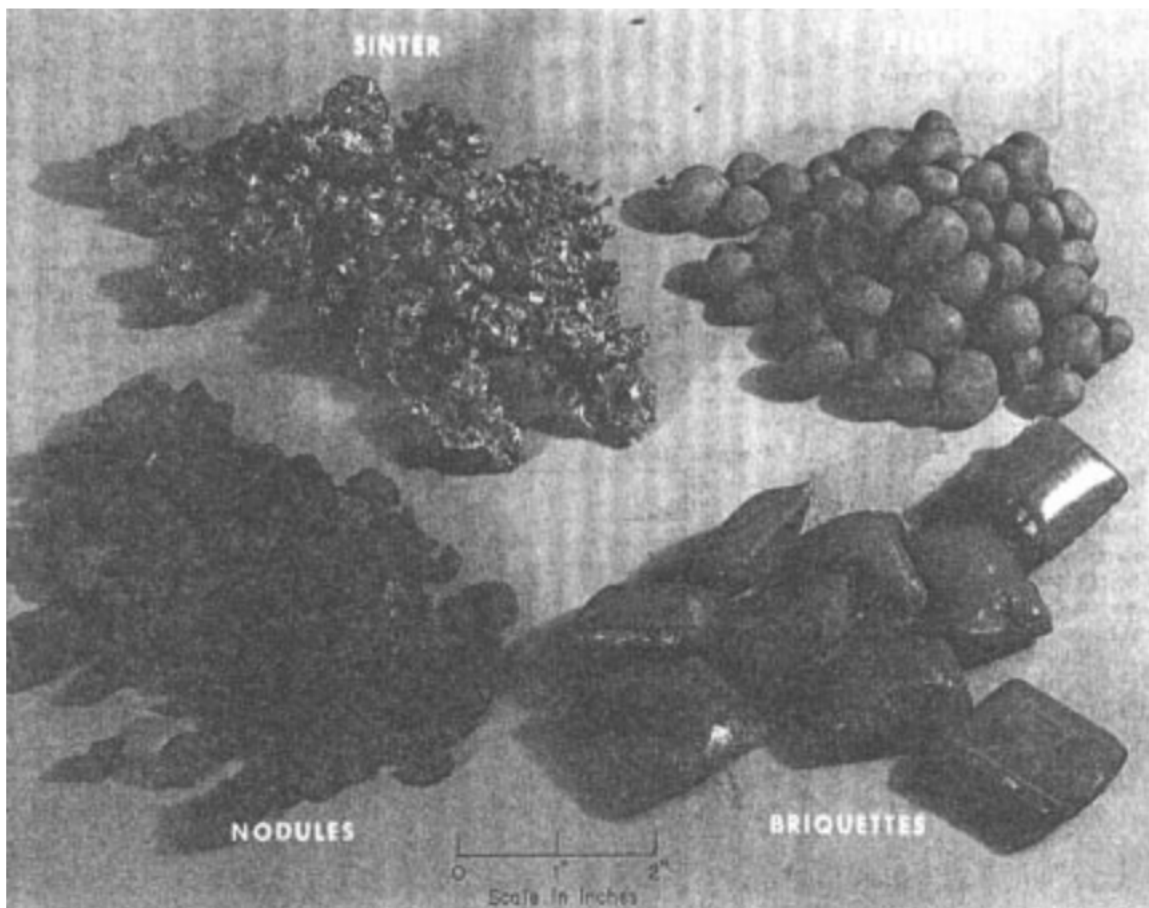


Fig. 8.29 Four types of iron ore agglomerates. The briquettes at the lower right were produced by hot ore briquetting.

shipped because of dusting and freezing problems but are readily made into pellets that are easy to handle and transport with minimal degradation. Consequently, if there is a considerable distance between the mine and the blast furnace it is preferable to locate pellet plants near the mine site. Materials that do not have the particle size distribution and characteristics required for pelletizing may be agglomerated by sintering. Typical sinter feed materials include fines generated during ore transport, steelmaking slag fines, flue dust, mill scale, and fine concentrates that are too coarse for pelletizing. Sinter plants tend to be located near the blast furnaces because sinter degrades badly during shipment and because the steelmaking facilities are the point of origin of many of the materials that must be agglomerated.

In North America and also in the Scandinavian countries, the availability of pellets from relatively modern pellet plants, the absence of coarse sintering ores and the environmental spending requirements for typically older sinter plants have made pellets the dominant burden material. Many sinter plants have been shut down and the remaining sinter plants mainly process steel waste oxides and a limited amount of concentrates and fine ores. However, in the rest of world sinter is still the dominant burden material as the abundance of coarse sintering ores, the flexibility of the sintering process and the desirable properties of sinter have generally overcome the environmental challenges to the sintering process.

Energy cost and the uncertain availability of fuels are important factors in all processes and have provided the incentive for development work to reduce fuel consumption and to utilize substitute fuels. Better utilization of hot gases and heat recuperation have recently resulted in lower fuel costs and conversion of oil and gas fired pelletizing operations to coal firing has resulted in a more reliable fuel source.

8.5.1 Sintering

Sintering has been referred to as the art of burning a fuel mixed with ore under controlled conditions. The flexibility of the process permits conversion of a variety of materials, including natural fine ores and ore fines from screening operations, flue dust, ore concentrates, and other iron bearing materials of small particle size into a clinker-like aggregate that is well suited for use in the blast furnace.

The continuous sintering process shown schematically in Fig. 8.30 is carried out on a traveling grate that conveys a bed of ore fines or other finely divided iron bearing material, intimately mixed with approximately 5% of a finely divided fuel such as coke breeze or anthracite. Near the head or feed end of the grate, the bed is ignited on the surface by gas burners, Fig. 8.31, and, as the mixture moves along on the traveling grate, air is pulled down through the mixture to burn the fuel by downdraft combustion. As the grates (or pallets) move continuously over the windboxes toward the discharge end of the strand, the combustion front in the bed moves progressively downward. This creates sufficient heat and temperature, about 1300–1480°C (2370–2700°F), to sinter the fine ore particles together into porous clinkers. That location along the traveling grate where the combustion front touches the bottom of the bed is called the burnthrough point.

Although simple in principle, sintering plants require that a number of important factors in their design and operation be observed to attain optimum performance. Intimate mixing of the feed materials is one of the most important. In most modern sinter plants, a bedding and blending operation, as shown in Fig. 8.18, is used to pre-mix the sintering ores, steel plant waste oxides, fluxes, and some solid fuels. This blended feed is then supplemented by small trim amounts of flux and solid fuel. This total feed mixture is the subject to a water addition within a mixing device such as a balling drum or disc, Fig. 8.32 and Fig. 8.33, or pug mill. These mixers are operated to produce small rice size nodules that significantly improve the permeability of the sinter bed. Improved permeability, in turn,

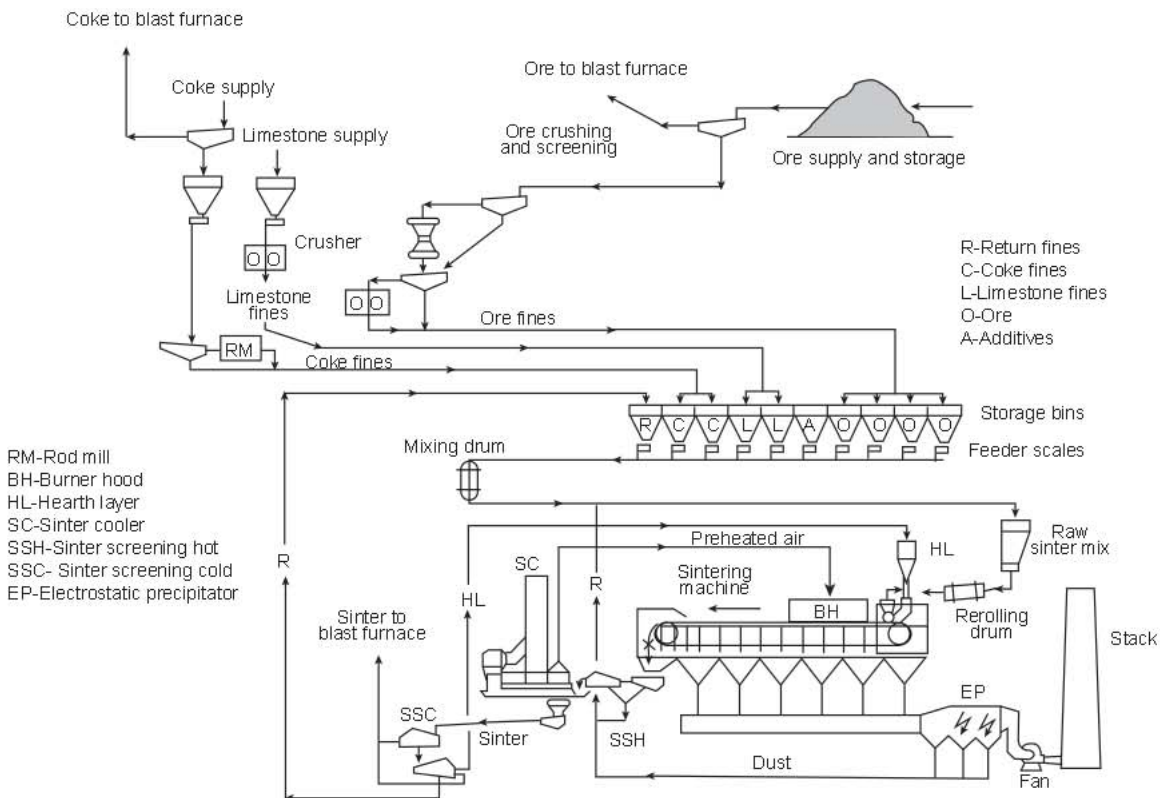


Fig. 8.30 Schematic flow diagram of continuous iron ore sintering process.



Fig. 8.31 Sintering machine in operation. The ignition furnace in the center background ignites the fuel in the surface layer of the sinter mix. As the bed of sinter progresses into the foreground, air is pulled down through the bed to cause the burning zone to move downward through the bed by igniting fuel in deeper and deeper zones of the mix. By the time the discharge end of the machine is reached, sintering will have taken place throughout the depth of the bed.

results in more rapid and uniform sintering. Desirable mixer retention times vary from about one minute for sticky hematite ores to four minutes for more difficult to ball ores.

In transferring the prepared mix from the mixer to the grate of the sintering machine it is essential to feed the material carefully to provide a uniform, homogeneous bed and to prevent compacting of the bed. To avoid a direct drop of feed onto the grate, a hearth layer of about 25–50 mm (1–2 in.) of already sintered material is fed first onto the traveling grate. Feeding devices typically include a roll feeder in conjunction with chutes which act to avoid compacting the feed material. Design of surge bins and feeders for distributing the prepared mix into these bins is equally important because, if the prepared mix is compacted or segregated during handling and loading onto the grate, all of the advantages gained through good feed preparation may be lost. Once the feed is charged onto the grate, metal bars or rods already inserted longitudinally along the grate for a distance of about 2–4 m (6–13 ft) help to loosen up the mixture to enhance permeability.

Proper ignition of the sinter bed is also important. Poor ignition results in spotty burning and may leave unsintered material over the surface of the bed. Conversely, too intense an ignition flame can result in slagging over the bed and reduced sintering rates. The radiant hood ignition furnace provides good ignition. Replacing part of the solid fuel with gaseous fuel results in sinter having a slightly improved strength and reducibility without affecting sinter production rate. This practice is termed mixed firing. Where a shortage of solid fuel exists, and gas is available, use of increased amounts of gaseous fuel should be desirable. Plants using increased ignition (extended firing) have approximately 25% of the length of the sinter bed covered by a gas fired ignition type hood. The

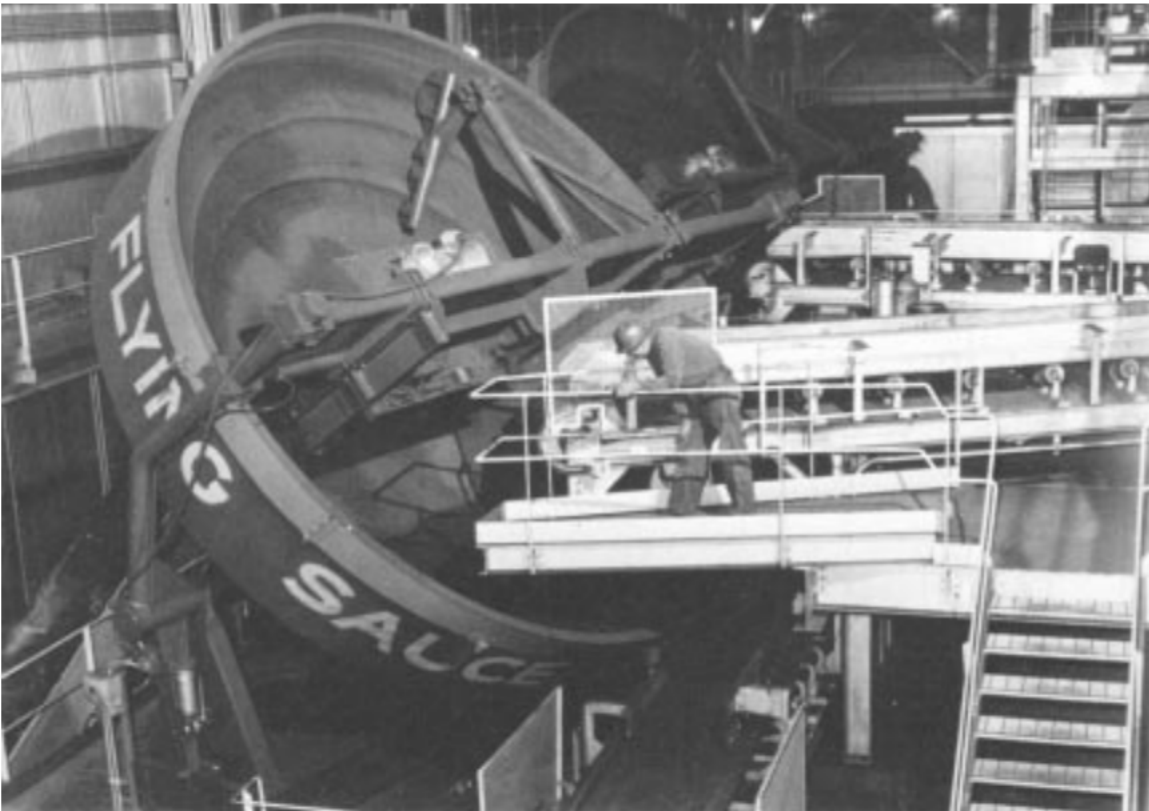


Fig. 8.32 Two disc-type pelletizing machines. Ore fines are fed to the discs by the belt conveyors (behind the operator). As the discs rotate, there is a balling action that causes the fines to agglomerate into pellet-like masses that are discharged from the discs over their lip at the bottom onto the belt conveyor shown at floor level that carries the pellets to the bins of the sinter machine.



Fig. 8.33 Balling drum mixer.



Fig. 8.34 Induced draft rotary or circular sinter coolers, shown in process of construction.

temperature in this hood ranges from about 1150°C (2100°F) in the first section where ignition begins to approximately 800°C (1500°F) at the exit end of the hood. Depending upon the characteristics of the ore materials and the sintering conditions, daily average production rate of 22.4–42.9 tonnes/m²/day (2.3–4.4 net tons/ft²/day) of grate area are expected, and individual daily rates in excess of 48.8 tonnes/m²/day (5 net tons/ft²/day) have been attained.

Cooling of the sinter below 150°C (300°F) so that it can be handled on conveyor belts is an important part of the operation. Sinter coolers, such as the rotary type, Fig. 8.34, are usually used; it is desirable to avoid a water quench as the quench adversely affects sinter properties. The exhaust air from these coolers is normally at too low a temperature to permit the economical recovery of heat, although such systems have been installed in countries with high energy costs as in Japan.

Sinter represents an improved blast furnace material as compared to lump ore or acid pellets as follows. Improvements have been obtained (1) by incorporating the blast furnace flux into the sinter rather than charging it separately to the top of the furnace, as was formerly done, (2) by use of sized sinter and (3) by virtue of improved high temperature properties. The available data on the use of fluxed sinter, sometimes called self-fluxing sinter, indicate that for each 200 lbs of limestone per net ton of hot metal removed from the blast furnace burden and charged into the sinter plant to make a fluxed sinter, approximately 9.1 kg (20 lb) of metallurgical coke per net ton of hot metal are saved. The coke savings results primarily from calcining of limestone on the sintering grate rather than in the blast furnace. Limestone in the form of fluxing fines for the production of sinter is made by crushing and screening methods that result in a product meeting size specifications.

Use of sized sinter is desirable because iron production rates in the blast furnace are further increased. Plant tests have demonstrated significant increases in iron production rate as a result of screening out small-sized material in sinter before it is charged to the furnace. Other tests have shown that sized sinter, which contains 85–90% of 25 mm × 6 mm (1 in. × 1/4 in.) material as compared with 60% in unsized sinter has a much higher permeability than unsized sinter and performs as well as pellets of comparable size. It also appears that crushing to (25 mm (1 in.) size at the sinter plant yields a more stable sinter because the smaller size fractions are more resistant to degradation.

In the last several decades researchers have shown that fluxed sinter (and also fluxed pellets) have superior high temperature properties in the blast furnace as compared to lump ore and acid pellets. These improvements include higher softening and melting temperatures and higher levels of reducibility.

The above description of sintering only provides an introduction to this topic. The earlier (before 1980) references are useful for North American and former Eastern bloc sinter plant operations, most of which were built in the 1950s and 1960s. Some more recent references describe advances in sintering relevant to large, modern sinter plant operation which are predominant in Europe and the Asia-Pacific area.

In North America and in the Scandinavian countries it has been demonstrated that fluxed pellets; fluxed with either limestone/dolomite mixtures or olivine, and also properly sized, can achieve blast furnace performances comparable to that of fluxed, sized sinter.

8.5.2 Pelletizing

Pelletizing differs from sintering in that a green unbaked pellet or ball is formed and then hardened by heating. Experimental work, started many years ago by E. W. Davis and his associates at the University of Minnesota on the concentration and agglomeration of low grade iron ores, showed that it was possible to ball or pelletize fine magnetite concentrate in a balling drum and that if the balls were fired at sufficiently high temperature (usually below the point of incipient fusion) a hard, indurated pellet, Fig. 8.29, well adapted for use in the blast furnace, could be made. Consequently, despite the unquestioned benefits of sinter on blast furnace performance, intense interest in the pelletizing process had developed because of the outstanding performance achieved by steel producers

in extended operations with pellets as the principal iron bearing material in the blast furnace burden. In North America this interest was further promoted by the absence of coarse sintering ores coupled with the opportunity to effectively utilize abundant reserves of low grade taconite ore.

In general, the pelletizing process is desirable for agglomeration of finely divided concentrates because they are normally of such fine size that they will form into a green ball with little difficulty. Concentrates and high grade ores that are not suitable in size for pelletizing are in some cases ground to the required size when pellets are desired as the final product.

The balling drum and the disc pelletizer are the most widely used devices for forming green balls. Compared with the balling drum, the disc has the advantages of lighter weight and greater possibility for adjustment. Its inherent design averages out the effect of instantaneous fluctuations in the feed, whereas the drum cannot. Also, the classifying action of the disc promotes discharge of balls of more uniform size, which simplifies screening of the product. However, the capacity of the discs is low and discs generally require closer control than drums. Best control of ball size is achieved when the balling device is in closed circuit with a screen to remove and recycle the undersize material.

Binders, such as bentonite, clay or hydrated lime, are generally used to raise the wet strength of green balls to more acceptable levels for handling. Bentonite consumption at the rate of 6.3–10 kg (14–22 lb) per ton of feed is a significant cost element and adds to the silica content of the final product. Considerable effort has been directed to reducing bentonite usage and to development of cheaper substitutes. The ballability and strength of green balls are influenced by the additives and by the moisture content and particle size distribution of the concentrates. Optimum moisture content for good balling is usually in the 9–12% range. It appears that balling characteristics are relatively independent of the chemical composition of a concentrate, but are strongly affected by its physical properties. For example, specular hematites are more difficult to ball than magnetite concentrates because of the plate-like structure of the specular hematite particles. In any case, satisfactory pellet formation is usually achieved by regrinding to about 80–90% $-43 \mu\text{m}$ (-325 mesh). Normally, any material considered for pelletizing should contain at least 70% $-43 \mu\text{m}$ (-325 mesh) and have a specific surface area (Blaine) greater than 1200 cm^2/gram for proper balling characteristics.

Both the drop and compressive strengths of green pellets are important but because dried pellets are not required to withstand much handling, their compression strength is considered most important. The strength of fired pellets is important in minimizing degradation by breakage and abrasion during handling and shipping, and in the blast furnace. Strong bonding in pellets is believed to be due to grain growth from the accompanying oxidation of magnetite to hematite, or recrystallization of hematite. Although slag bonding may promote more rapid strengthening at slightly lower firing temperatures, pellet strength is normally decreased, especially resistance to thermal shock. Fired pellet strength is most commonly determined by compression and tumble tests. Compressive strengths of individual pellets depend upon the mineralogical composition and physical properties of the concentrate, the additives used, the balling method, pellet size, firing technique and temperature, and testing procedure. The compressive strengths of commercially acceptable pellets are usually in the range of 200–350 kg for pellets in the size range of -13 mm $+9$ mm. In the tumbler test 11.4 kg (25 lb) of $+6$ mm pellets are tumbled for 200 revolutions at 25 rpm in a drum tumbler (ASTM E279-65T) and then screened. A satisfactory commercial pellet should contain not more than about 5% of -0.6 mm (-28 mesh) fines, and 94% or more of $+6$ mm size, after tumbler testing. A minimum of broken pellets between 6 mm and 0.6 mm in size is also desirable. Other important properties of fired pellets to be used for blast furnace feed are reducibility, porosity, and bulk density. With some concentrates these can be varied within certain limits.

The flow sheet of a pelletizing process is similar in many respects to the sintering process, particularly in the materials handling area. Usually the associated mining, concentrating, and grinding installations are operated as a feed preparation section of the pellet plant. A typical pelletizing plant is shown in Fig. 8.35. The three most important pelletizing systems are the traveling grate, the grate-kiln, and the shaft furnace. Each system has been used commercially to make acceptable quality pellets and thus, capital and operating cost factors are usually involved in choosing one or the other. Fuel requirements for pelletizing by these systems vary from about 500,000 to 1,000,000

kJ per tonne (Btu/long ton) of pellets depending on the feed material. Oxidation of magnetite to hematite during pelletizing will provide a significant proportion, about 400,000 kJ per tonne (Btu per long ton), of the heat requirement in all of the systems. For pelletizing of hematites, the use of coke breeze (or some carbon source) in the pellet feed mixture has become a common practice to provide the additional indurating energy normally provided by magnetite oxidation. Pelletizing processes are being improved constantly and further details on their technology and development may be found in the references at the end of the chapter. The production of self-fluxing pellets is an example of an innovation that has been accepted on a commercial scale and has led to major advances in blast furnace performance. A brief description of important differences in the major pelletizing systems are pointed out in the discussion that follows.

8.5.21 Traveling Grate

The traveling grate system for producing pellets, illustrated in Fig. 8.36, is essentially a modification of the sintering process. The green balls are fed onto the grate continuously to give a bed depth of about 300–400 mm (12–16 in.) and are dried in the first few windboxes by updraft air recuperated from the firing zone, followed by downdraft drying using recuperated air from the cooler. This arrangement of hot air flows limits pellet damage resulting from condensation of moisture in the bed. Following drying, the pellets are preheated by downdraft air from the cooling zone. Firing is done downdraft in the combustion zone by burning fuel oil or natural gas with hot air from the cooling zone. The cooling zone follows the combustion zone and uses updraft fresh air.

Fuel consumption in the traveling grate system is about 350,000 to 600,000 kJ per tonne (Btu per long ton) of pellets produced from magnetite and up to 1,000,000 kJ per tonne (Btu per long ton) when pelletizing hematite. The system offers good temperature control in the firing zone. Pellet consistency throughout the bed may be achieved by recirculating some fired pellets to form hearth and side layers on the grate. The largest grate machines are 4 m (13 ft) wide and are capable of producing more than 3 million tonnes of pellets per year. Circular grate machines have also been designed and one such machine is in operation.

8.5.22 Grate-Kiln System

The grate-kiln system depicted in Fig. 8.37, consists of a traveling grate for drying and preheating the pellets to about 1040°C (1900°F), a rotary kiln for uniformly heating the throughput to the final induration temperature of 1315°C (2400°F), and an annular cooler for cooling the product and heat recuperation. Heat for firing is supplied by a central oil, gas, coal or waste wood burner at the discharge end of the kiln. Hot gases produced in the kiln are used for downdraft preheating of the pellets. Hot air from the cooler is used to support combustion in the kiln and is also recuperated to the traveling grate for drying and tempering preheat.

The grate-kiln system offers excellent temperature control in all stages of the process and produces a consistently uniform product. Fuel consumption is 300,000 to 400,000 kJ per tonne (Btu per long ton) of standard pellets produced when using magnetite ore, and up to 700,000 kJ per tonne (Btu per long ton) of standard pellets produced when the feed is hematite. These fuel consumption numbers will increase by 250,000 kJ (BTU per long ton) when producing fluxed pellets. Power consumption, from balling to pellet loadout, is 23 kWh per long ton. Grate-kiln systems can be designed for production tonnage's up to 6 million tonnes per year per line.

8.5.23 Vertical Shaft Furnaces

Vertical shaft furnaces are not as common as the traveling grate or grate-kiln systems. There are several variations in shaft furnace design but the most common is the Erie type, shown in Fig. 8.38. Green balls are charged at the top and descend through the furnace at a rate of 25–38 mm (1–1 1/2 in.) per minute countercurrent to the flow of hot gases. About 25% of the total air enters the furnace through the hot gas inlet at temperatures from 1280°C (2340°F) to 1300°C (2375°F). Pellets in this zone of the furnace reach temperatures of 1315°C (2400°F) or higher because exothermic heat is released when the magnetite oxidizes to hematite, increasing the temperature. The remaining 75%

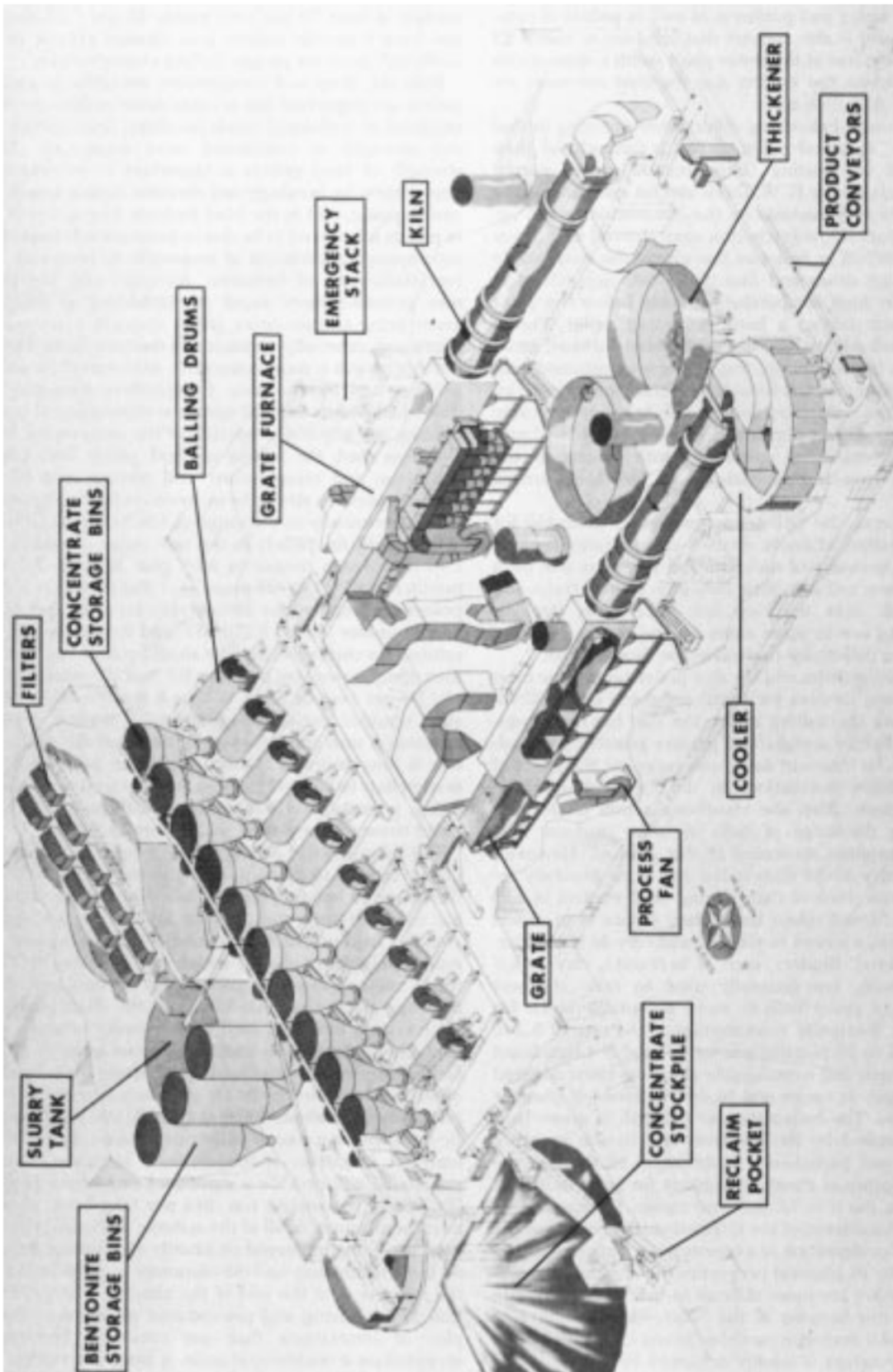


Fig. 8.35 Schematic diagram of U.S. Steel's Minntac agglomerator. Magnetic concentrate is filtered from slurry, mixed with bentonite binder, rolled into green balls in the balling drums and fired to the grate-kiln furnaces to make taconite pellets

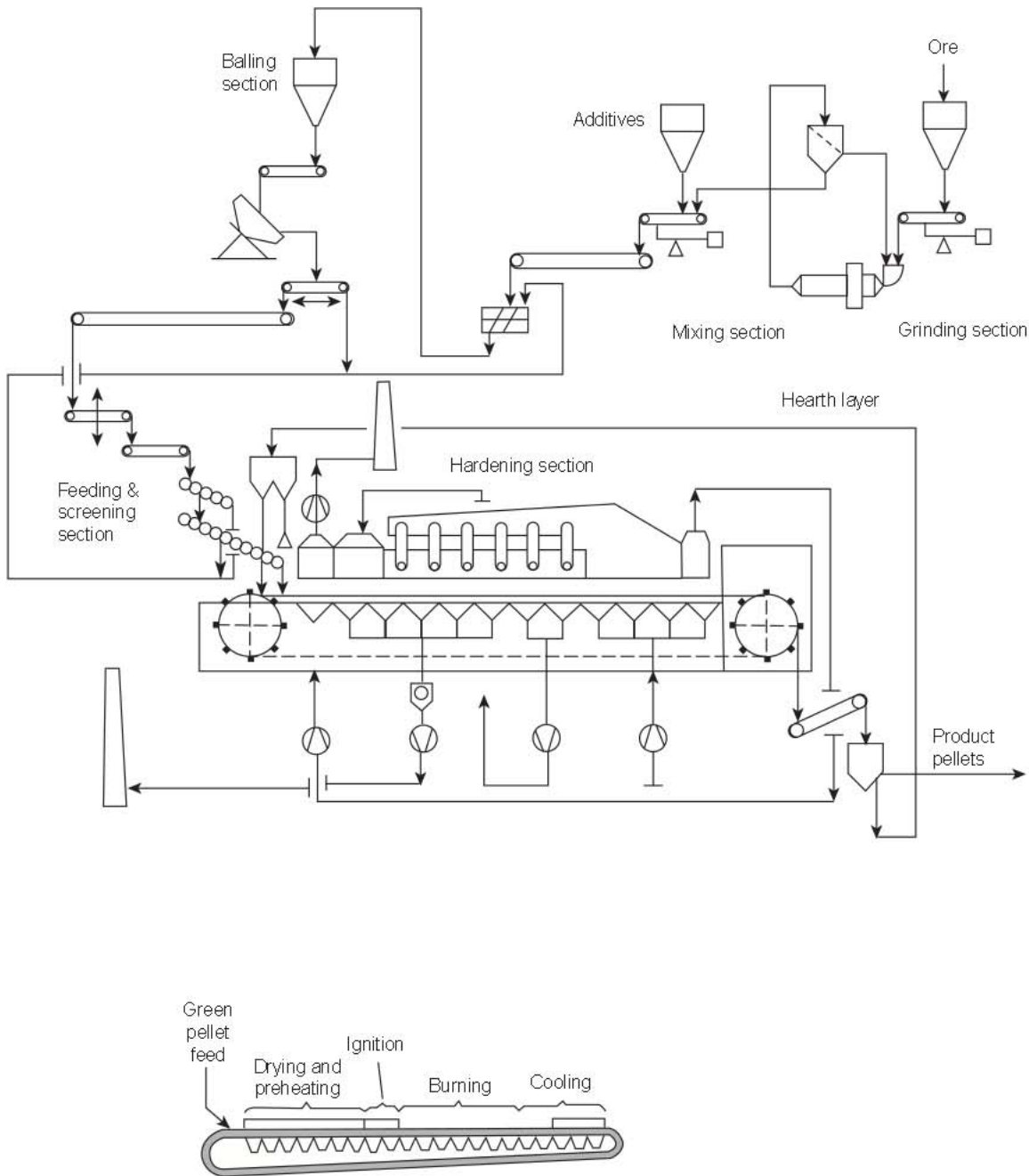


Fig. 8.36 Schematic diagram of the traveling grate system for producing pellets.

of the furnace air enters via the cooling air inlet. Pellets discharge at about 370°C (700°F), and top gas temperature is about 200°C (400°F). Typical furnace capacities are 1000 to 2000 tonnes per day. Shaft furnaces are more energy efficient than the traveling grate or grate-kiln systems. The shaft furnace is well suited for pelletizing magnetite, but not hematitic or limonitic materials.

Disadvantages of shaft furnaces are low unit productivity and difficulty in maintaining uniform temperature in the combustion zone. Hot spots may occur which cause pellets to fuse together into large masses, producing discharge problems. It is also very difficult to produce fluxed pellets in a shaft furnace.

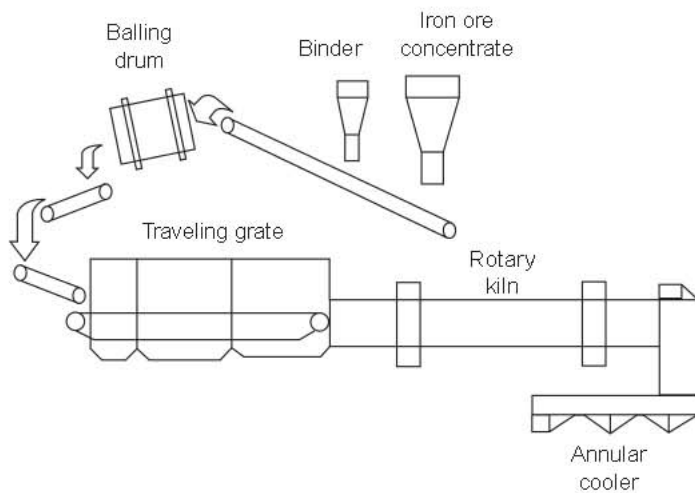


Fig. 8.37 Schematic diagram of the grate-kiln system for iron ore pelletizing.

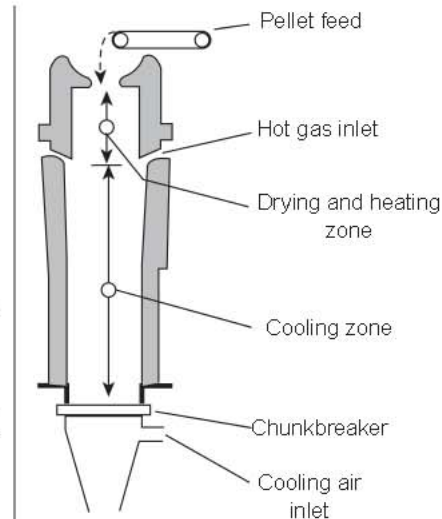


Fig. 8.38 Schematic diagram of the shaft furnace system for producing pellets.

As with sintering, the above description only provides an introduction to the pelletizing process. The reader is encouraged to look in the Bibliography for a more comprehensive treatment as well as updates on recent advances.

8.5.3 Nodulizing

In this agglomerating process, fine iron bearing materials moving through a rotary kiln are formed into nodules or lumps, Fig. 8.29, by the rolling of the charge heated to incipient fusion temperatures. This process has been used at various places throughout the world to agglomerate fine iron bearing materials but is now of very little importance due to the developments in sintering and pelletizing.

8.5.4 Briquetting

Briquetting is an old art that has been used to agglomerate or form small or large lumps of regular shape from a wide variety of materials, including wood, coal, lignite, chars, cokes, ores, and flue dust. Various designs of punch and roll presses are or have been used. However, briquetting of cold or unheated material had not been successful as a means for producing satisfactory agglomerates for the blast furnace until recently. Briquettes are usually formed with the use of a binder and do not possess the strength resulting from the high temperature heating that is developed in pellets and sinter. The shut down of sinter plants in North America and Scandinavia has motivated improvements in briquetting technology to recycle waste oxides. Such briquettes, as described in the Bibliography, can be used at 3–10% of the furnace burden without difficulty; the absence of high temperature properties precludes higher consumption levels.

8.6 Transportation of Iron Ores

8.6.1 North America

Historically, since the development of high capacity iron and steelmaking complexes, the avenues of commerce for steelmaking raw materials such as iron ore, concentrates, and pellets have been by rail and water. The Great Lake Superior Iron Ore District has occupied a very strategic location with respect to water routes along the Great Lakes to the steel centers on Lake Michigan and Lake



Fig. 8.39 Great Lakes vessel *Edwin H. Gott*, 305 m (1000 ft) in length, being loaded with pellets at a modern conveyor loading dock.

M.V. CANADIAN NAVIGATOR

Manager: Seaway Self Unloaders
 Registry/Flag: Toronto
 Type: Great Lakes, Self-Unloading Bulk Carrier
 Class: Lloyds \geq 100A1
 Great Lakes and St. Lawrence River Service..

Principal Particulars
 L.O.A.: 729.4' 222.20m
 L.B.P.: 714.3' 217.60m
 Beam: 75.9' 23.12m
 Depth: 40.5' 12.35m

Design Cargo Deadweight
 @ 8m 26,000 tonnes

Cubic Capacity
 32,000m³

Self-Unloading Equipment
 Single belt gravity system with single loop belt. 79m discharge boom at aft end luffing to 18° and slewing to 90° P. & S. Remote controlled basket-type unloading gates. Designed discharge rate of 4,000 tonnes/hour through gravity feed, in combination with two front shovels.

Machinery
 Doxford, type 76JT4
 7120 kw (9,600 b.h.p.)
 Bow Thruster 750 kw (1,000 h.p.)

Fig. 8.40 Newly converted *m. v. Canadian Navigator* of the Seaway Self Unloaders fleet shown at a discharging berth. (Source: *Skilling's Mining Review*.)

Erie and via water to rail transfer to facilities in the Pittsburgh area. As much as 96 million tons in one year have moved by rail to Great Lakes ports in Minnesota, Wisconsin, Michigan and Ontario, and thence by vessel to lower lake ports. There are now over 75 American and Canadian Great Lakes ore vessels in service or available for service ranging in capacity per trip from 20,000 long tons to 60,000 long tons. Vessels of this type are shown in Fig. 8.39 and Fig. 8.40.

Discovery and development of large deposits of high grade ore close to deep water ports outside the United States has led to the utilization of ocean going vessels for transporting iron ores to steel centers on the coast or via rail transport to inland steel centers. On the Great Lakes, ore carriers with deadweight capacities of more than 60,000 long tons have been constructed to realize the economy of size. These vessels, 305 m (1000 ft) in length and 32 m (105 ft) in beam, are designed to take maximum advantage of the Poe Lock in the St. Marys River at Sault Ste. Marie, Michigan and are restricted by their size to service on the four western Great Lakes. The maximum size vessel capable of transiting the Welland Canal to Lake Ontario and the St. Lawrence Seaway is 223 m (730 ft) in length and 23 m (76 ft) beam. Some ocean going vessels unload their cargoes in Contrecoeur, Quebec for trans-shipment on laker sized vessels to lower Great Lakes receiving ports.

Transfer of iron ores from railroad cars to vessels had been accomplished in the Great Lakes ports by unloading into dock pockets from which ore is discharged by gravity through chutes lowered into the holds of vessels. In the more modern Great Lakes vessel loading installations constructed to accommodate larger vessels, ore is unloaded from railroad cars into storage bins or stockpiles from which it is recovered by shovels or ore reclaiming equipment and transferred by conveyor belts for discharge into the vessel's holds, Fig. 8.39. At receiving ports, the ore has historically been removed from the vessels' holds by unloading rigs or Hulett unloaders and transferred to stockpiles or to railroad cars for shipment inland. Recent trends have replaced shore based unloading equipment through the use of self-unloading conveyor systems located onboard the vessel that transfer the ore to stockpiles or hoppers shoreside, Fig. 8.40. The ore is then conveyed for utilization within the steel mill or reshipment by rail to steel mills inland.

By 1998 only several North American steel plant and commercial ore docks still maintained Hulett unloaders; the use of self-unloader vessels has become predominant.

The Great Lakes shipping season has successfully been extended into the winter months when traditionally the vessels were laid up due to ice conditions. Typically shipments are made through December (or in some years early January) and then resume in March. Transportation of iron ores in modern integrated ore trains has also been accomplished.

8.6.2 International Iron Ore Trade and Transportation

As noted in an earlier section, historically and through the second world war, iron ore was primarily sourced from local or regional mines, but in the last four decades the sea borne trade of iron ore has grown dramatically with higher grade ore deposits being developed in certain countries while the construction of large vessels (Cape size) carrying greater than 120,000 tonnes has reduced shipping costs. The low delivered cost of high grade ore, coupled with the sintering and blast furnace process benefits of such ore, gradually led to the closure of low grade ore mining operations. The following tables indicate the leading countries with respect to iron ore production, exports and imports in 1996, as compared to 1985.

Inspection of the data in Table 8.8 indicate how the dominant role of Australia and Brazil has increased further in the eleven year period of 1985 to 1996 such that these two countries account for nearly 60% of the world trade in iron ore. The role of these two countries is best illustrated by the world trade map shown in Fig. 8.41. Australia is the dominant supplier in Asia while Brazil is the dominant supplier in Europe but both countries export significantly to the other's principal market region as well.

Other countries such as India, Canada and Sweden have maintained their roles as producers and exporters. It is noteworthy that China, although one of the leading producers, has also become the

Table 8.8 Seven Leading Countries in Production, Export and Import of Iron Ore, Mt/y

Production			Exports			Imports		
	1996	1985		1996	1985		1996	1985
1. Brazil	179.9	128.2	1. Australia	135.7	88.0	1. Japan	119.2	124.5
2. Australia	147.2	96.2	2. Brazil	129.7	92.3	2. China	43.9	10.0
3. ex USSR	128.5	247.6	3. India	31.7	28.8	3. Germany	39.4	45.1
4. China ^(a)	116.2	62.1	4. ex USSR	30.3	43.9	4. Rep. of Korea	34.4	13.2
5. India	66.6	44.2	5. Canada	27.9	32.3	5. United King.	20.4	15.4
6. U.S.	62.1	49.5	6. South Africa	19.3	10.2	6. France	18.4	16.2
7. Canada	36.8	40.4	7. Sweden	16.1	18.2	7. U.S.	18.4	16.0
Others	143.5	172.0	Others	44.2	62.1	Others	136.7	147.1
World	880.8	840.2	World	434.9	375.8	World	430.8	377.5

(a) Gross iron ore production converted, so that its %Fe content is about equal to that on average in the rest of the world.

second leading importer both as a result of its expanding steel industry and its low quality of local ore. Although iron ore production dropped by nearly 50% in the former Soviet Union, overall world iron ore production still increased from 1985 to 1996. We also observe that combined United States and Canadian production actually increased somewhat in this period in spite of the rationalization of the North American steel industry.

Looking ahead to the future the major factors affecting iron ore demand are overall economic conditions which affect steel demand, continued regional shifts in steel production towards developing nations and the growth of electric furnace scrap based steelmaking. Although the EAF is scrap based, the need to maintain quality for the production of higher quality steel products, mainly flat rolled, is accelerating the growth of ore based direct reduction facilities in North and South America, and elsewhere. This growth in direct reduction has also helped to increase iron ore demand.

8.7 Iron Ore Quality

In this section we supplement the data on iron ore resources in Section 8.2 with data on the chemical and physical properties of the leading producers in each region of the world. We also differentiate by product: sintering ore fines, lump ore, blast furnace pellets and direct reduction pellets.

8.7.1 Sinter Feed

8.7.1.1 Chemical and Physical Attributes

Because sinter is the predominant worldwide burden material we will briefly summarize the importance and desired levels of the chemical and physical attributes of sinter feed materials as follows.

Iron – Iron content is to be as high as possible; > 60% is preferable, 50–60% is adequate, and < 50% is low grade. High Fe increases the iron content yield of the sinter and reduces transportation costs.

Silica – The normal range for SiO₂ is 4.50–5.50% to match the desired SiO₂ level of sinter product; > 5.5% is considered high; < 4.5% is helpful to balance out higher SiO₂ components, but large amounts of very low SiO₂ (< 1.0%) ore require use of siliceous ore or olivine to restore normal sinter SiO₂ level. Excessive SiO₂ raises the blast furnace slag volume and the coke rate.

Alumina – An increase in Al₂O₃ content improves sinterability by improving balling characteristics. It also allows an increase in CaO/SiO₂ ratio in sinter which improves the sinter strength and

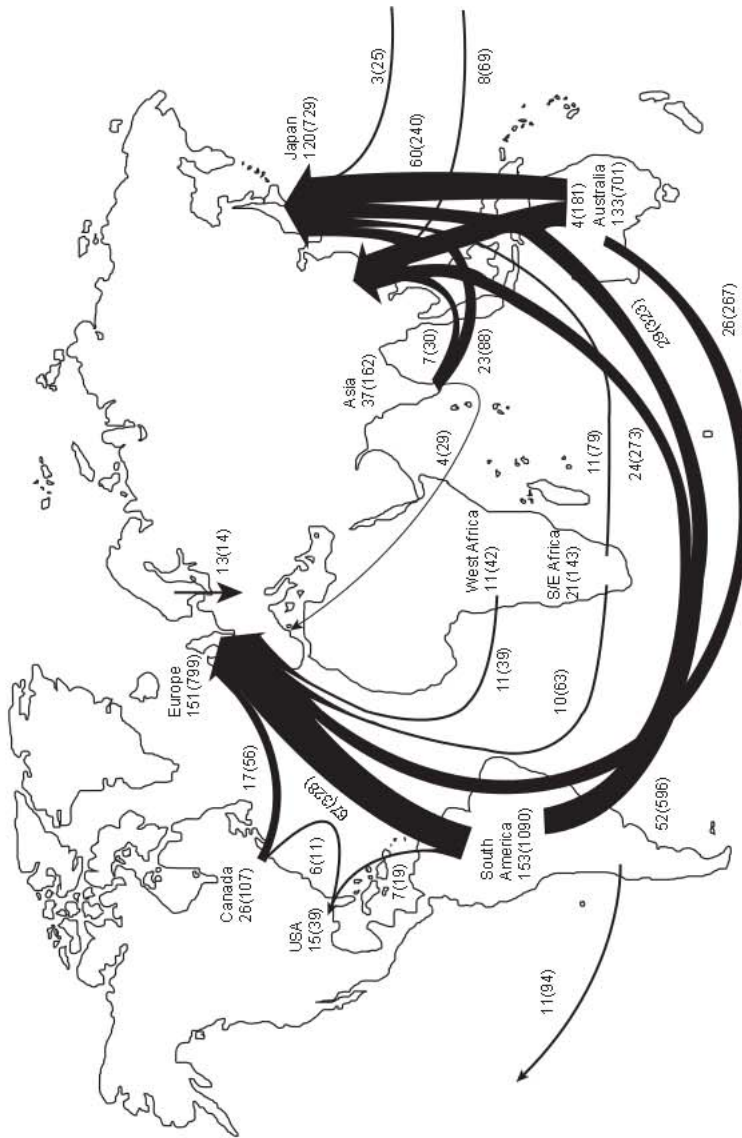


Fig. 8.41 Iron ore sea borne trade in 1995. Main inter-area movements in million tonnes. (Billion tonne-miles in parentheses.) Only main routes are shown. Area figures are totals including smaller routes not shown separately.

also increases the CaO/SiO₂ ratio in the blast furnace slag, which reduces hot metal Si content. However, an increase in Al₂O₃ decreases the RDI strength of the sinter.

Phosphorus—Phosphorus is undesirable for steel properties. Increased phosphorus increases steel-making slag volumes and reduces the ability to recycle BOF slag. The target level is < 0.030% P.

Sulfur—An increase in sulfur increases the blast furnace sulfur load, the blast furnace flux requirement, blast furnace slag volume and coke rate, and increases hot metal desulfurization costs. The target level is < 0.010% S.

Manganese—An increase in manganese will increase the blast furnace coke rate and the steel-making slag volume, but may improve BOF lance skulling. The target level is < 0.050% Mn.

Titania—High TiO₂ levels, > 1.0%, cause undesirable sinter properties; however, some TiO₂ is useful for blast furnace hearth protection

Basic Oxides—The basic oxides CaO and MgO at moderate levels (up to 2–3%) are not a problem, aside from reducing Fe content, as these flux materials need to be added to the sinter mix.

Alkalis—The alkalis Na₂O and K₂O should be minimal, total less than 0.1%, as they cause blast furnace operating problems such as scab formation, coke deterioration, etc.

Vanadium and Copper—These impurities should be at very low levels, < 0.010%, for steel product quality reasons.

Moisture—An increase in moisture content will increase handling problems in winter, sinter fuel requirements and transportation costs, but some moisture does reduce dusting problems

Sizing—According to modern sintering theory, sinter strand permeability and productivity is enhanced by sinter feed material ease of granulation to form large pseudo particles. These large pseudo particles are formed when coarse sinter feed materials (> 0.7 mm) form nuclei onto which fine sinter feed materials (< 0.2 mm) will be adhered. Materials in the intermediate size range (0.7–0.2 mm) will neither be nuclei nor adhering materials and may impede sinter mix permeability. Hence the ideal sinter feed material has minimal intermediate particles and is distributed between coarse and fine particles.

87.1.2 Brazilian Sintering Ores

The Brazilian ores, shown in Table 8.9, are the predominant sinter feed materials in European sinter mixes and play a major role in Far East sinter mixes. The CVRD Carajás and MBR are distinguished by their very low (< 1.0 %) SiO₂ content. The Al₂O₃ content of Carajás and MBR is less than 1.0% which is helpful in Far East sinter mixes where the Carajás and MBR ores play a key role in reducing SiO₂ and particularly Al₂O₃ content in Far East sinter mixes where Australian ores are always predominant and also in European sinter mixes where Australian ore is usually used. The P and Mn levels are moderate but the basic oxides, CaO and MgO, are very low for Brazilian ores. The alkali levels and the levels of S, V and all other impurities are very low.

As for sizing, all Brazilian ores are characterized by at least 50% or more of coarse particles, >1 mm, which contributes to sinter blend permeability and productivity. These ores have a high percentage of ultrafines (< 180 microns) but these become adhering particles.

In summary, the Brazilian ores, with high Fe content, very low impurities, and coarse sizing, are the predominant European sinter feed and are a very important Far East sinter feed.

87.1.3 Other South American Sintering Ores

The ores from other South American countries, shown in Table 8.10, have many of the attributes of Brazilian ores. However, these ores have some chemistry deficiencies: higher Al₂O₃, Mn and P levels in the Romeral and CVG ores and also higher levels of impurities such as CaO and MgO, alkalis, S, Cu and V in the Romeral ore. The Hierro Peru sinter feed has major chemistry deficiencies: very high alkali and S levels, and high basic oxides, CaO and MgO.

Table 8.9 Brazilian Sintering Ores

Chemistry	CVRD SSF	CVR Carajás	MBR Sinter Feed	Samitri			
				Fabrica Sinter Feed	SAAL	SAMA	Pau Branco
Fe	64.2	67.2	68.3	64.7	64.5	65.2	67.0
SiO ₂	5.10	0.60	1.30	4.00	4.20	4.20	0.84
Al ₂ O ₃	1.00	0.94	0.90	1.10	0.70	0.80	1.18
TiO ₂	0.08	0.03	0.04	0.03	0.07	0.09	—
CaO	0.02	0.01	0.03	0.05	0.02	0.03	0.00
MgO	0.03	0.02	0.04	0.05	0.04	0.05	0.00
Na ₂ O	0.005	0.010	0.006	0.020	0.006	0.006	—
K ₂ O	0.008	0.010	0.004	0.010	0.006	0.007	0.020
Mn	0.200	0.450	0.229	0.200	0.070	0.070	—
P	0.045	0.037	0.030	0.040	0.057	0.040	0.050
S	0.007	0.010	0.005	0.005	0.006	0.006	—
V	—	—	0.006	—	—	—	—
LOI	1.50	1.40	0.61	0.05	2.30	1.50	—
Sizing, % +							
8 mm	2	2	6	2	20	21	1
4 mm	8	7	24	7	14	12	25
2 mm				20	12	5	
1 mm	31	48	26	30	12	9	41
500 µm			10	13	10	10	10
250 µm			8	11			10
180 µm	22	27	4	4	13	17	4
90 µm	12	4	6	5	4	7	
63 µm	10		15	8	3	5	4
-63 µm	15	12			11	11	5

Table 8.10 Other South American Sintering Ores

Chemistry	Hierro Peru Sinter	Romeral FeedFines	CVG Cerro Bolivar Fines	CVG El Pao Fines	CVG San Isidro Fines
Fe	65.4	64.4	64.8	64.3	65.8
SiO ₂	4.20	4.80	1.30	3.34	1.15
Al ₂ O ₃	0.51	2.00	1.00	1.63	0.80
TiO ₂	—	0.23	0.10	0.03	—
CaO	0.78	0.88	0.05	0.05	0.05
MgO	1.12	1.03	0.03	0.13	0.02
Na ₂ O	0.155	0.280	0.010	0.010	0.003
K ₂ O	0.120	*	0.010	0.010	0.003
Mn	0.020	0.210	0.050	0.300	0.050
P	0.020	0.100	0.085	0.050	0.070
S	0.900	0.060	0.030	0.030	0.050
V	—	0.430	0.020	0.020	—
Cu	0.016	0.050	0.040	0.030	—
LOI 0.05	—	1.40	5.30	2.50	4.0
Sizing, % +					
8 mm		1	8		7
4 mm	1	30	10	14	
2 mm				20	14
1 mm	8	29		17	
500 µm	22	10	30	14	
250 µm	28	6			
180 µm	11	5	28	11	49
90 µm	31	7	2	4	10
63 µm		7	8	10	10
-63 µm		5	20	10	10

* Na₂O total includes Na₂O and K₂O

8.7.1.4 South American Concentrates, Pellet Feed

These concentrates are used mainly as pellet plant feed except for MBR and Samitri concentrates which are also used as sinter feed. Some pellet feeds including MBR are also used in the NKK hybrid pellet-sinter (HPS) process in Japan. The chemistry, shown in Table 8.11, for all except for Hierro Peru is excellent, low in SiO_2 and Al_2O_3 , low in basic oxides, alkalis, S, V and Cu. The finer size makes these concentrates best suited as pellet feed.

8.7.1.5 Australian and New Zealand Ores

The Australian ores, Table 8.12, are characterized by higher gangue content, SiO_2 and Al_2O_3 , and particularly higher Al_2O_3 content. These are all coarse ores, with $> 50\%$ + 1 mm and have excellent granulation properties. These technical reasons and their abundance and low cost make Australian ores the prime sintering ores in the Far East and important sintering ores in Europe, as well. The major limitations on the use of Australian ores are the Al_2O_3 content which adversely affects sinter properties and to a lesser extent, the P content, which raises hot metal pre-treatment costs. Typically ores from the Atlantic basin, mainly from Brazil, complement Australian ore significantly with their low Al_2O_3 contents. The ironsands ore is high in TiO_2 which limits its use in sinter mixes; it is also high in Al_2O_3 and P content.

Table 8.11 South American Concentrates, Pellet Feed

Chemistry	CVRD pellet feed	Samitri SACT	MBR pellet feed	Hierro Peru pellet feed	Romeral pellet feed	Ferteco		
						CVG nat. pellet feed	Fabrica	Feijao
Fe	68.6	68.1	67.5	69.0	67.0	67.3	67.8	68.0
SiO_2	1.20	1.40	1.30	1.71	1.90	1.10	1.20	1.40
Al_2O_3	0.30	0.30	0.70	0.27	0.45	0.70	0.50	0.30
TiO_2	0.05	0.03	0.04	—	0.15	0.03	0.03	0.03
CaO	0.02	0.02	0.03	0.40	—	0.01	0.05	0.05
MgO	0.03	0.03	0.04	0.62	—	0.08	0.05	0.05
Na_2O	0.004	0.003	0.006	0.170	0.150	0.01	0.020	0.020
K_2O	0.005	0.002	0.004	0.070	(a)	0.01	0.010	0.010
Mn	0.050	0.030	0.229	0.015	—	0.11	0.300	0.300
P	0.017	0.035	0.036	0.010	0.040	0.040	0.030	0.030
S	0.003	0.003	0.003	0.200	0.045	0.020	0.005	0.005
V	—	—	0.006	—	0.750	0.020	—	—
Cu	—	—	—	0.016	—	0.030	—	—
LOI	0.30	0.70	0.67	0.05		2.0	0.8	0.6
Moisture		7.0	9.2				8.6	8.0
Sizing, % +								
8 mm						6 max.		
1 mm	1							
500 μm		4					1	2
250 μm		4						
180 μm	11	10	6 max.	2				
90 μm	8	13		4		40 max.	9	13
63 μm	15	21		28			40	45
-63 μm	66	48	57 min.	65	75 min.		50	40

(a) Na_2O total includes Na_2O and K_2O

Table 8.12 Australian and New Zealand Ores

Chemistry	Hamersley high grade fines	BHP Mt. Newman	BHP Marra Mamba fines	BHP Yandi ore fines	Robe River sinter fines	Gold's worthy fines	BHP New Zealand ironsands
Fe	62.7	62.5	61.0	59.5	57.2	62.8	56.8
SiO ₂	4.21	5.60	3.30	5.03	5.60	6.10	4.40
Al ₂ O ₃	2.57	2.60	1.80	1.25	2.75	1.50	3.80
TiO ₂	0.13	0.11	0.07	0.05	0.22	0.10	7.80
CaO	0.06	0.05	0.28	0.04	0.07	0.04	—
MgO	0.05	0.11	0.23	0.02	0.07	0.06	—
Na ₂ O	0.009	0.040	—	—	0.017	0.015	—
K ₂ O	0.009	0.030	0.020	0.008	0.001	0.015	—
Mn	0.070	0.050	0.100	0.037	0.100	0.120	—
P	0.071	0.069	0.069	0.039	0.040	0.046	0.180
S	0.015	0.007	0.039	0.013	0.028	0.009	0.001
V	0.001	—	0.006	—	0.007	—	—
Cu	0.002	0.005	0.002	—	0.002	0.002	—
LOI 0.05	2.8	1.9	7.00	8.3	9.3	1.8	—
Sizing, % +							
8 mm				8	3	4	
4 mm	7	3		21	12	16	2 mm
31	43			17	15		
1 mm	16	12		26	15	15	
500 μm	10	10		15	15	12	
250 μm	11	10		13	10	11	
180 μm		3		7	8	5	
90 μm	8					5	
63 μm	7	8		5	5	6	
-63 μm	10	10		5	5	10	

Table 8.13 India and Goa Ores

Chemistry	Dempo sinter fines	Kudremukh conc.	Bandekar fines	VM Salaocar sinter feed	Sesa Goa fines	Bailadila fines	Donimalai fines	Chowgule fines
Fe	62.6	67.0	62.0	60–62	63.0	63–65	63–65	62.0
SiO ₂	2.35	4.00	4.00	4.00m	4.00	3.00m	—	4.00
Al ₂ O ₃	1.94	0.50	6.00	2.5–3.5	2.20	3.00m	—	2.30
TiO ₂	0.08	0.08	0.30	0.25m	0.25	0.10	—	0.30
CaO	0.03	0.01	—	0.10m	0.15	0.12	—	—
MgO	0.05	0.03	—	0.10m	0.08	0.15	—	—
Na ₂ O	0.012	0.010	—	0.040m	0.016	—	—	—
K ₂ O	0.011	0.040	—	0.050m	0.030	—	—	—
Mn	0.320	0.100	—	—	1.50	—	—	—
P	0.064	0.025	0.100	0.100m	0.070	0.040	0.080	0.100
S	0.048	0.010	0.100	0.050m	0.050	0.008	0.050	0.100
V	—	0.010	—	—	—	—	—	—
Cu	0.002	0.005	—	0.050m	0.010	0.050	—	—
LOI	5.6	1.5	—	5.0m	—	—		

m = maximum

8.7.1.6 India and Goa Ores

The listing of ores from India and Goa, Table 8.13, (chemistry only) contains most of the ores exported except for Fomento which is similar to Chowgule. The major chemistry problem for these ores is the high Al_2O_3 content which impairs sinter properties. The major exception is the Kudremukh concentrate which is mainly used as a pellet feed at the Kudremukh pellet plant although it is sold as a sinter feed in the Far East.

8.7.1.7 African Ores

In Table 8.14 we have focused on ores sold in the world market and have ignored (do not have data available) ores which are captive to steel companies in North Africa (Egypt, Algeria, Tunisia, etc.), Nigeria, Zimbabwe, and South Africa. The SNIM ores from Mauritania are sold mostly in Europe and, although higher in SiO_2 , have good sizing and granulation properties. The Guelbs concentrate, on the other hand, is finer in size and is a magnetite which reduces sinter plant energy consumption. Ores from Liberia such as Nimba had been major factors in Europe and North America until the civil war virtually halted shipments. The Nimba ore is characterized by reasonable good sizing and chemistry. The South African Sishen and Assoman ores have good sizing and reasonable chemistry with the major drawback of high K_2O levels, which severely limits the percentage of these ores in sinter mixes.

Table 8.14 African Ores

Chemistry	SNIM Guelbs conc.	SNIM TZF fines	Nimba washed fines	ISCOR Sishen fines	Assoman fines
Fe	65.7	63.2	64.3	65.5	64.2
SiO_2	7.30	7.00	4.25	3.50	4.95
Al_2O_3	0.30	1.20	1.34	1.60	2.22
TiO_2	0.05	0.06	0.04	0.07	0.09
CaO	0.40	0.01	0.02	0.04	0.06
MgO	0.40	0.02	0.01	0.03	0.03
Na_2O	0.080	—	0.020	0.020	0.060
K_2O	0.020	0.020	0.020	0.200	0.100
Mn	0.040	0.023	0.080	0.050	0.190
P	0.015	0.035	0.066	0.050	0.032
S	0.012	0.008	0.008	0.014	0.024
V	—	—	0.002	0.006	—
Cu	0.005	—	0.002	0.001	—
LOI	+ 2.8	1.1	2.2	0.8	—
Sizing, % +					
8 mm		8			1
4 mm		19	17	4	13
1mm	7	14	25	80	62
500 μm	13	15	8		20
250 μm	25		11		2
180 μm	18	13	7	10	1
90 μm	20	12	7		
63 μm	5	10	5		
-63 μm	12	10	10	6	1

Table 8.15 European Ores

Chemistry	LKAB Kiruna B Fines, KBF	LKAB Malmberget MAF	Mo i Rana Conc.	Voest Alpine Erzberg	Krivoi Rog Conc.	Olenogorsky Conc.	Kovdorsky Conc.
Fe	69.8	70.7	66.0	32.3	64.2	65.3	63.3
SiO ₂	1.20	0.60	2.70	4.80	9.00	7.06	1.18
Al ₂ O ₃	0.18	0.25	0.80	1.07	0.25	0.30	2.01
TiO ₂	0.49	0.30	0.50	0.040	0.04	—	0.81
CaO	0.53	0.18	0.80	7.80	0.17	0.40	0.63
MgO	0.47	0.40	0.30	4.10	0.30	0.70	5.10
Na ₂ O	0.030	0.030	0.100	0.330	—	0.040	0.020
K ₂ O	0.080	0.020	(a)	0.360	—	0.010	0.040
Mn	0.070	0.050	0.015	1.97	0.08	0.09	0.35
P	0.044	0.030	0.020	0.016	0.020	0.014	0.014
S	0.020	0.007	0.010	0.045	0.070	0.044	0.220
V	0.118	0.124	0.010	—	—	—	0.062
Cu	0.002	0.001	0.002	—	0.005	—	0.007
LOI	0.2	0.1	—	32.0	—	—	—
Sizing, % +				59			
8 mm							
2 mm	21	2					
1 mm	17	15		2		1	
500 μm	11	35	8			1	
250 μm	9	26	22				16
180 μm	5	7	20				
90 μm	15	10	37	11	17	80	36
63 μm	6	2	8		16	7	20
—63 μm	16	3	5	2	67	11	28

(a) Na₂O total includes Na₂O and K₂O

8.7.1.8 European Ores

The ores of most interest are the LKAB ores from Sweden which are used extensively in Europe. The Kiruna and Malmberget fines are much coarser than typical concentrates but not as sinterable as prime materials such as the Brazilian ores. The V levels of both fines are high. The LKAB ores are primarily magnetite which provides energy to the sintering process. The Mo i Rana concentrate is slightly higher in most impurities, basic oxides, alkalis, P, S and V.

The Voest Alpine Erzberg ore is one of the few remaining low-grade local ores in Europe. It is characterized by a very low Fe level mainly due to the high levels of carbonates of Ca and Mg which contribute to an LOI of 32. Other impurities are also very high such as alkalis, Mn and S. The low value-in-use of this ore is indicative of why imported, high grade ores have replaced local, lower grade ores in most of the world.

Ores from the former USSR have been the principal suppliers to Eastern Europe. Some Russian and Ukraine ores of which chemical and physical data are available are those shown in Table 8.15 which are either in the Ukraine region (Krivoi Rog) or the Kola region (Olenogorsky and Kovdorsky) near Finland. The concentrates shown are finely sized and have higher levels of gangue.

8.7.1.9 North American Ores and In-Plant Revert/Recycle Materials

The Canadian concentrates, QCM and IOC, are used in sinter plants in Europe, North America and Far East mainly for their chemistry value, high Fe, low levels of Al_2O_3 , P, Mn, V and other impurities which allow blending with other ores with specific chemistry limitations. However, the total amount of any concentrate in any given sintering mix is limited by permeability so concentrate use is complimentary with use of coarse, natural sintering ores.

The Minnesota ores are limited to the USX Auburn property which ships about 400,000 net tons/year. This ore is characterized by low Fe levels and high levels of SiO_2 , Mn and P. The ore is very coarse but can be muddy and hard to handle.

We included the in-plant revert (recycle) materials which play a prominent role in North American sinter mixes, but these revert materials are also used in overseas sinter mixes but as a smaller percentage of the sinter mix. The key items of interest are:

- The high Mn, P, Cu and S levels of the BOF slag because BOF slag has valuable Fe and flux units and is used up to the P and Mn limits in hot metal.

Table 8.16 North American Ores and In-Plant Revert or Recycle Materials

Chemistry	QCM Conc.	IOC Conc.	Wabush Low Mn Conc.	Minnesota Auburn Ore	Revert Materials				
					BOF Slag	Mill Scale	Scrap Fines	Pelle Fines	Flue Dust
Fe	66.2	66.0	66.6	62.3	20.0	68.0	36.0	62.0	29.0
66. ₂	66.0	66.6	62.30	20.0	68.0	36.0	62.0	29.0	
SiO_2	4.90	4.50	2.55	6.49	11.0	1.21	8.60	4.70	7.50
Al_2O_3	0.33	0.14	0.35	3.04	3.90	0.46	1.40	0.30	1.50
TiO_2	0.18	0.02	0.03	—	0.05	0.03	0.06	0.03	—
CaO	0.07	0.30	0.10	0.14	42.0	0.72	27.9	0.55	19.0
MgO	0.05	0.24	0.07	0.06	11.0	0.37	6.50	0.47	2.90
Na_2O	0.008	0.003	0.020	0.003	0.050	0.150	0.030	0.035	0.100
K_2O	0.008	0.002	0.032	0.026	0.070	0.010	0.035	0.010	0.220
Mn	0.025	0.170	1.150	1.462	3.07	0.590	2.500	0.120	1.000
P	0.015	0.008	0.006	0.055	0.500	0.040	0.300	0.020	0.100
S	0.003	0.004	0.017	0.010	0.190	0.030	0.060	0.010	0.400
V	0.002	0.010	—	—	—	—	—	—	—
Cu	0.002	0.001	—	—	0.660	0.020	0.010	0.010	—
Zn					0.020	0.005	0.020	0.008	0.240
C					1.0	0.78	0.500	—	18.0
LOI	0.05	0.08	—	—	—	—	—	—	—
Sizing, % +									
31.5 mm									
22.4 mm				1	1		1	4	
16 mm				3	1	1	3	16	
8 mm				10	2	2	9	20	
4 mm				35	3	14	26	20	
2 mm				18	9	18	26	14	1
1 mm	4		1						
500 μm	21	2	13	25	63	50	32	23	16
250 μm	32	25	40						28
180 μm	23	16	25						22
90 μm	10	30	10						10
63 μm	10	18	9	8	21	15	4	7	23
—63 μm		9	2						

- The mill scale material is high in Fe, low in gangue, and Na₂O and Mn are the only noteworthy impurities. It also mainly contains Fe in the form of FeO which provides energy to the sintering process.
- Scrap fines are mainly metallics reclaimed from steelmaking slag but this material still contains significant amounts of slag with the same P and Mn concerns as with BOF slag.
- Pellet fines, as expected, have the same chemistry as the pellets they were obtained from; the coarseness of size range and good chemistry are attractive to North American sinter plant operators.
- Flue dust provides Fe and carbon units but has significant gangue levels and impurities such as alkalis, Mn, P, S and Zn.

8.7.1.10 Chinese Ores

8.7.1.10.1 Northern China With the exception of the Fushan ore, all of the ores shown are fine sized concentrates and are well complemented by Australian ores which are coarse and very sinterable. The Chinese concentrates are also reasonably low in Al₂O₃, see Table 8.17 and Table 8.18, except for the Anshan Gong. concentrate. These northern Chinese concentrates have higher basic oxide levels but this is not necessarily a problem, as flux components have to be added to the sinter mix. Some deficiencies are the high S level of the Jinan, Tianjin, Anshan and Taiyuan steel plant materials while the local Taiyuan concentrate is very high in SiO₂, Al₂O₃ and basic oxide levels.

Table 8.17 Northern Chinese Ores

<i>Steel Plant</i>	<i>Tangshan</i>	<i>Baotou</i>	<i>Shougang</i>	<i>Jinan</i>	<i>Benxi</i>	<i>Tianjin</i>	<i>Tianjin</i>	<i>Anshan</i>	<i>Anshan</i>
	<i>Jidong</i>	<i>Flor</i>	<i>Qianan</i>	<i>local</i>	<i>Nanfen</i>	<i>Hanx</i>	<i>Fushan Ore</i>	<i>Qidashan</i>	<i>Gong.</i>
Chemistry	Conc.	Conc.	Conc.	Conc.	Conc.	Conc.	Conc.	Conc.	Conc.
Fe	65.4	60.6	63.4	64.1	67.3	63.1	46.2	62.1	61.8
SiO ₂	6.94	4.53	6.91	8.40	6.35	5.18	13.3	11.6	11.1
Al ₂ O ₃	0.50	—	0.83	0.80	0.51	0.50	1.80	0.71	1.29
TiO ₂	—	—	—	—	—	—	—	—	—
CaO	0.50	2.26	0.63	0.43	0.75	2.70	8.15	0.43	0.63
MgO	0.47	—	0.61	3.24	0.27	3.38	4.42	0.08	0.36
Na ₂ O	—	—	—	—	—	—	—	—	—
K ₂ O	—	—	—	—	—	—	—	—	—
Mn	—	—	—	—	—	—	—	—	—
P	0.022	—	0.022	—	0.016	—	—	0.03	0.02
S	0.048	—	0.060	0.112	0.018	0.205	0.175	0.59	0.52
V	—	—	—	—	—	—	—	—	—
Cu	—	—	—	—	—	—	—	—	—
F	—	1.03	—	—	—	—	—	—	—
LOI 0.05	—	—	2.1	—	—	—	—	—	—
Sizing, % +									
8 mm	—	—	—	—	—	—	27	—	—
4 mm	—	—	—	—	—	—	17	—	—
2 mm	—	—	—	—	—	—	8	—	—
1 mm	—	—	—	—	—	—	13	—	—
250 μm	—	—	—	—	4	—	—	—	—
180 μm	9	—	4	—	10	16	35	—	—
90 μm	26	8	23	44	12	25	—	13	11
63 μm	20	14	22	23	23	20	—	19	21
—63 μm	45	78	52	33	50	39	—	68	68

Table 8.18 Chinese Ores — Southern China and Northern China

Steel Plant	Southern China						Northern China	
	Wuhan		Meishan		Manshan		Taiyuan	
Chemistry	Local Conc.	Hainan Ore	Local Conc.	Aoshan Conc.	Dongshan Conc.	Tao. Conc.	Erkou Conc.	Local Conc.
Fe	67.1	51.9	52.5	63.5	60.2	53.5	65.3	54.2
SiO ₂	2.65	18.3	6.36	4.98	7.26	9.40	6.44	9.56
Al ₂ O ₃	1.39	2.55	—	1.51	3.07	0.89	0.77	2.53
TiO ₂	—	—	—	1.44	1.87	0.02	—	—
CaO	0.30	0.69	4.23	1.15	1.04	5.94	0.52	7.47
MgO	1.49	1.32	2.11	0.68	1.03	0.61	0.51	1.37
Na ₂ O	—	—	—	0.180	0.080	0.087	—	—
K ₂ O	—	—	—	*	*	*	—	—
Mn	0.110	0.930	—	0.156	0.157	0.115	0.050	0.06
P	0.019	—	0.360	0.540	0.840	0.014	0.023	0.04
S	0.259	0.380	0.580	0.160	0.550	0.330	0.146	0.128
V	—	—	—	0.140	0.110	—	—	—
Cu	0.055	0.058	—	—	—	—	—	—
LOI	1.4	—	10.3	—	—	—	—	—
Sizing, % +								
500 μm	2			1	5	22	7	8
250 μm				5	13	20		
180 μm	17		1	10	23	23		
90 μm	12		25	35	31	18		
63 μm	18		20	44	23	15	13	42
—63 μm	51		42	5	5	1	80	50

* Na₂O total includes Na₂O and K₂O

8.7.1.10.2 Southern China The southern China concentrates shown here are also fine sized but have more chemistry deficiencies than those of northern China. These include: high Al₂O₃ levels for all except the Tao concentrate, some high basic oxide levels, high alkali and V levels for the Manshan steel plant concentrates, high Mn levels for the Wuhan and Manshan steel plant ores, very high P and S levels for all ores.

8.7.2 Blast Furnace Lump Ores

The same iron ore mines which produce natural sintering ores from high grade ore deposits also can produce lump ore, typically +6 mm, by simply screening the high grade ore during the limited beneficiation processes. On the other hand, the upgrading of low grade ores to produce concentrates does not allow for lump ore production as the beneficiation processes usually require fine grinding of the crude ore so that beneficiation processes can proceed efficiently. Accordingly, lump ore availability is limited to that available from high grade ore deposits, primarily in Australia, Brazil, Venezuela, India, South Africa, Mauritania, etc.

North American use of lump ore is limited to several steel plants with ocean access using lump ore from Venezuela and Brazil and Chicago area steel plants using a limited amount of Minnesota lump ore.

The chemistry of leading lump ores on the world market is shown in Table 8.19. Others not shown can be assumed to be similar in chemistry to the coarse sintering ore fine of the same brand.

Table 8.19 Blast Furnace Lump Ore Chemistry

	Fe	SiO ₂	Al ₂ O ₃	CaO	MgO	TiO ₂	MnO	P	S	Na ₂ O	K ₂ O	H ₂ O
Australia												
Hammersley	65.07	2.80	1.53	0.040	0.030	0.07	0.060	0.055	0.010	0.008	0.008	1.80
BHP Mt. Newman	65.50	3.50	1.30	0.040	0.100	0.05	0.081	0.047	0.005	0.010	0.006	2.20
South Africa												
Sishen	66.50	2.80	1.20	0.040	0.030	0.07	0.060	0.040	0.013	0.020	0.140	0.95
Brazil												
Carajás	67.20	0.60	1.20	0.020	0.020	0.05	0.320	0.058	0.008	0.002	0.003	4.00
MER Aguas Claras	68.60	0.56	0.51	0.062	0.057	0.02	—	0.036	0.005	0.005	0.006	3.00
MER Pico Lump	68.70	0.50	0.73	0.018	0.010	0.04	—	0.038	0.007	0.006	0.006	1.30
Venezuela												
Cerro Bolívar	65.00	1.00	1.00	0.060	0.020	0.07	0.040	0.110	0.020	0.003	0.003	3.20
San Isidro	66.50	0.90	0.80	0.050	0.030	—	0.060	0.070	0.020	0.003	0.003	3.30

8.7.3 Blast Furnace Pellets

8.7.3.1 North America

Pellets are the dominant burden material in North American blast furnace operations accounting for over 85% of the iron units. The rationalization of excess and obsolete pellet plant capacity has left the North American steel industry with 12 pellet plants in the U.S. and Canada (seven in Minnesota, two in Michigan and three in Canada), all of which are large scale, relatively modern and capable of producing high quality pellets. The chemistry of these pellets was given in Table 8.5. These pellets include acid pellets and fluxed pellets; the fluxed pellets have improved furnace performance considerably but other steel plants have used acid pellets with improved properties along with fluxed sinter to achieve comparable performance. Several steel plants are still constrained to use of 100% acid pellets but are still achieving good productivity, but at slightly higher fuel rates. The physical properties are not shown in Table 8.5 but all are world class: fines levels below 4%, tumbler strength >95 % +6 mm, compression strength > 250 kg, LTB strength >90 % +6 mm and ISO reducibility > 1.20 for fluxed pellets.

8.7.3.2 Worldwide

The chemistry data on pellets in the international market are presented in Table 8.20. These tables also repeat the data for Canadian pellets as these pellets are shipped to Europe and Asia, as well. This table is presented in three parts. Table 8.20a compares acid pellets however we can identify only three outside of North America: Hierro Peru, Kudremukh and Kostamuksha. Kudremukh could also be considered a partially fluxed pellet. Table 8.20b compares fully fluxed pellets. Table 8.20c compares various olivine fluxed and partially fluxed pellets

This table does not include captive pellets which are used almost exclusively in blast furnaces of the same company adjacent to the pellet plants and are rarely sold on the open market; these would include Kobe Steel, BHP Whyalla, Hoogovens and AHMSA (Mexico) pellets. It also does not include other pellets in Russia and China.

The SiO₂ content of the acid pellets in Table 8.20a is typically between 4–6% as production of lower silica acid pellets for blast furnace use presents challenges with respect to swelling properties. As with all pellets, the levels of other impurities are low except for higher alkali levels with the Hierro Peru and Kostamus pellets and the V level in the Kudremukh pellets.

Table 8.20a Comparison of Pellet Chemistry — World Acid Pellets

Chemistry	QCM	Hierro Peru	Kudremukh	Kostamuksha	IOC limestone	Wabush 1% Mn, .5% limestone
Fe	65.00	65.50	65.5	65.00	65.20	66.00
SiO ₂	5.30	4.00	4.00	6.00	4.73	3.25
Al ₂ O ₃	0.53	0.60	0.50	0.35	0.30	0.40
CaO	0.60	0.60	1.70	0.37	0.92	0.30
MgO	0.25	1.00	—	0.19	0.34	0.10
Mn	0.026	0.020	—	0.030	0.10	1.20
P	0.017	0.018	0.028	0.019	0.007	0.010
S	0.003	0.014	0.010	0.010	0.014	0.010
TiO ₂	0.22	—	—	0.010	0.031	0.027
Na ₂ O	0.030	0.08	0.011	0.053	0.027	0.022
K ₂ O	0.020	0.90	0.023	0.127	0.014	0.030
V	<0.0002	—	0.118	0.020	<0.010	—
CaO/SiO ₂	0.11	0.15	0.425	0.06	0.19	0.09
B/A	0.14	0.26	0.378	0.09	0.25	0.10

Table 8.20b Comparison of Pellet Chemistry — World Basic Pellets

Chemistry	QCM BAF	QCM BSA	CVRD Nibrasco	CVRD BFPII	Samarco	Algarrobo	CVG Sidor	IOC	Wabush
Fe	63.00	65.10	65.90	64.25	66.20	65.70	66.30	61.90	63.25
SiO ₂	4.00	2.50	2.36	4.21	2.40	1.96	1.94	4.75	3.25
Al ₂ O ₃	0.50	0.40	0.48	0.46	0.60	0.50	0.81	0.31	0.40
CaO	3.92	2.25	2.60	4.32	2.10	2.27	1.61	4.21	2.90
MgO	1.30	0.90	0.10	0.32	0.15	0.60	0.37	1.81	2.00
Mn	0.025	0.020	0.080	—	0.030	0.040	—	0.31	1.10
P	0.014	0.010	0.014	0.015	0.045	0.047	0.060	0.010	0.010
S	0.011	0.008	0.004	0.003	0.005	0.004	—	0.014	0.010
TiO ₂	0.17	0.12	0.07	—	0.05	0.13	—	0.035	0.027
Na ₂ O	0.030	0.030	0.01+	0.020	0.010	0.076+	—	0.027	0.022
K ₂ O	0.025	0.025	==	0.010	0.010	=	—	0.014	0.030
V	0.0022	0.0022	—	—	—	0.007	0.19	0.010	—
CaO/SiO ₂	0.98	0.90	1.10	1.03	0.88	1.16	0.83	0.90	0.90
B/A	1.16	1.09	0.95	0.99	0.75	1.16	0.72	1.19	1.34

These basic pellets in Table 8.20b typically have lower SiO₂ contents as this is beneficial to minimize total flux input. The CaO/SiO₂ ratios typically are 0.90 or higher as these levels are required to achieve the desired metallurgical properties while still maintaining good physical properties. The variability in overall basicity reflects different philosophies with regards to the desired MgO level.

Unlike the flux pellets in Table 8.20b, the LKAB and Savage River olivine and partial basic pellets in Table 8.20c have MgO levels comparable to North American fluxed pellets but CaO levels are very low. LKAB is currently developing a limestone based pellet.

The physical and metallurgical properties are not shown in the Table 8.20 as test procedures and emphasis on desired pellet properties differ around the world. The properties listed in Table 8.7 are generally met, with the exception of dynamic LTB, by all of the pellets shown in Table 8.20.

Table 8.20c Comparison of Pellet Chemistry — World Olivine, Partial Basic Pellets

Chemistry	LKAB KBPO	LKAB MBPO	Savage River	Ferteco Fabrica	Krivoi Rog
Fe	66.70	66.80	65.99	65.00	60.15
SiO ₂	2.10	2.00	2.16	3.30	8.08
Al ₂ O ₃	0.23	0.40	0.39	0.80	0.21
CaO	0.25	0.35	0.15	2.50	4.95
MgO	1.55	1.40	1.72	0.10	0.41
Mn	0.06	0.05	0.05	0.20	0.09
P	0.026	0.009	0.016	0.035	0.009
S	<0.001	<0.001	0.002	0.008	0.022
TiO ₂	0.23	0.25	0.95	0.06	0.01
Na ₂ O	0.040	0.040	0.028	0.020	0.050
K ₂ O	0.040	0.020	0.011	0.020	0.040
V	0.21	0.20			
CaO/SiO ₂	0.12	0.18	0.07		0.61
B/A	0.77	0.73	0.73	0.63	0.65

8.7.4 Direct Reduction Pellets, Lump Ore and Fine Ores

The special requirements for direct reduction ferrous raw materials may be summarized as follows, with additional details found reference cited in the Bibliography at the end of this chapter.

8.7.4.1 Chemistry Considerations for Direct Reduction

The key considerations for iron bearing raw materials for direct reduction and for smelting reduction differ in a number of ways starting with chemistry. In the direct reduction process the primary chemical change is the removal of oxygen from the ore; the remaining constituents stay with the direct reduced iron product but are increased in concentration due to the removal of oxygen. The nature and level of these constituents directly affect the process performance and economics of the subsequent electric furnace melting vessel, or any other process in which DRI is used. In any smelting reduction process, including the blast furnace, the formation of a refining slag allows modification of the resultant hot metal product, within some limits, to meet the requirements of the subsequent steelmaking process.

However, with respect to direct reduction we also are aware that, at the time this chapter was being drafted, another process scheme was being implemented, the Iron Dynamics Process, involving the production of a moderate gangue DRI followed by an intermediate melting and refining step, followed by introduction of hot metal into an EAF.

The important chemical properties are described here.

Iron—Total iron content should be as high as possible, preferably > 67%.

Acid Gangue—Acid gangue, namely SiO₂ + Al₂O₃, should be as low as possible, preferably below 2%. Acceptable limits are up to 3%.

Basic Oxides—Basic oxides, namely CaO + MgO, reduce the Fe content but a limited amount of basic oxides, <3.0 %, may displace purchased flux in steelmaking;

Phosphorus—Phosphorus should be as low as possible, preferably below 0.030%, as P must be removed in steelmaking.

Sulfur—Sulfur should be below 0.008% as it is released during shaft furnace reduction and goes to the process gas which is fed to the reformer; excessive sulfur can foul the reformer tubes in the Midrex process.

Manganese and Titania—Manganese, Mn, and titania, TiO_2 , should be as low as possible to reduce EAF slag formation; TiO_2 should preferably be below 0.15%.

Alkalis—Alkalis, Na and K, should be as low as possible as these promote swelling and degradation during reduction.

Zinc—Zinc, Zn, is not normally present in ores but Zn from recycled material would be unsuitable for shaft furnaces processes due to internal recycling. Zn could be processed in the off gases from RHF or rotary kiln processes.

Other Minor Elements—Chromium, Cr, lead, Pb, copper, Cu, tin, Sn, nickel, Ni, molybdenum, Mo, arsenic, Ar, antimony, Sb, vanadium, V, and lithium, Li, should all be as low as possible. The total of Cu, Ni, Cr, Mo and Sn should be low as these are the key residuals being monitored in the scrap supply.

Free Moisture and LOI—Free moisture and loss on ignition (LOI) as CO_2 and H_2O are undesirable in the feed material because of the extra heat load and increased volume of gas to be handled.

As noted above, the chemistry effects are mainly significant in the subsequent electric furnace processing of DRI. Flux materials may have some impact on pellet reduction and sticking properties while alkalis and Zn could also affect shaft furnace performance.

Subsequent processing of off gases provide an opportunity for Zn recovery in rotary kiln and rotary hearth processes. At present several companies are developing processes incorporating RHF technology and off gas processing. Commercial facilities are in operation at Nucor Hickman, the All-Met process, and at American Steel in Knoxville, Tenn., the MRT Process.

The pellets shown in Table 8.21 constitute over 90% of the merchant pellets traded internationally; other pellets such as Sidor, Oskol, Pena Colorado, Alzado, etc., are mainly consumed in their home countries. Inspection of the above properties indicate broad conformance to the requirements specified earlier. Accordingly, all of the above pellets, when converted to DRI, will fulfill the role of diluting residuals in EAF charge mixtures. Any contemplated additional direct reduction pellet capacity would have to be able to match the chemistry of the pellets shown above to be competitive.

Table 8.21 Chemistry of Merchant Grade Direct Reduction Pellets

Chemistry	QCM	Samarco	LKAB	CVRD	GIIC	Hierro	CAP	Kudremukh
	BBS	PMX	MPRD	DRPM	Midrex	Peru		
Fe	67.80	67.63	67.50	68.00	67.60	68.40	67.33	67.10
SiO_2	1.70	1.63	0.95	1.15	1.40	1.32	1.40	2.75
Al_2O_3	0.40	0.45	0.24	0.50	0.30	0.24	0.23	0.33
CaO	0.50	0.64	1.05	0.68	1.10	0.32	1.00	1.00
MgO	0.30	0.44	0.75	0.26	0.30	0.49	0.10	0.10
Mn	0.02	0.03	0.06	0.05	—	0.016	0.01	0.01
P	0.010	0.040	0.025	0.023	0.022	0.013	0.028	0.028
S	0.002	0.004	0.001	0.001	0.004	0.007	0.010	0.010
TiO_2	0.10	0.05	0.16	0.05	—	—	0.10	0.10
Na_2O	0.020	0.020	0.050	0.004	—	0.109	0.011	0.011
K_2O	0.010	0.020	0.030	0.005	—	0.040	0.023	0.023
Cu	0.001	0.002	0.001	—	—	0.008	0.002	0.002
Pb	< 0.001	0.001	—	—	—	—	0.022	0.022
Zn	< 0.001	0.001	—	—	—	—	0.006	0.006
V	< 0.001	0.004	0.118	—	—	—	—	—
CaO/ SiO_2	0.29	0.40	1.10	0.63	0.78	0.26	0.36	0.36
B/A	0.38	0.53	1.50	0.58	0.82	0.47	0.36	0.36
Moisture	2.00	1.50	1.50	2.00	1.00	0.50	2.00	4.00

Table 8.22 Chemistry of Merchant Grade Lump Ores

Chemistry	MBR	Ferteco	Bailadilla	Sishen	San Isidro	Corumba
Fe	68.62	68.00	67.50	66.00	66.50	67.00
SiO ₂	0.78	0.99	1.20	3.20	0.90	2.50
Al ₂ O ₃	0.47	0.72	1.50	0.90	0.80	1.00
CaO	0.13	0.05	0.40	0.11	0.05	0.06
MgO	0.07	0.05	0.60	0.03	0.03	0.04
Mn	—	0.10	—	0.01	0.06	0.02
P	0.035	0.046	0.040	0.043	0.070	0.055
S	0.003	0.005	0.008	0.015	0.020	0.060
TiO ₂	—	0.03	—	0.052	0.070	—
Na ₂ O	—	0.02	—	0.021	0.003	0.008
K ₂ O	—	0.01	—	0.120	0.003	0.005
Cu	—	—	—	0.0005	—	—
Pb	—	—	—	0.0010	—	—
Zn	—	—	—	0.001	—	—
V	—	—	—	0.0028	—	—
LOI	—	0.78	—	—	4.00	0.6
Moisture	—	2.69	—	0.7	3.30	4.50

Table 8.23 Chemistry of Lump Ores Used In Rotary Kiln Direct Reduction Processes

Chemistry	Lump Ores		New Zealand Beach Sand	Australia Ilmenite
	India	S. Africa		
Fe	65.5	66.8	58.0	30.0
FeO	0.3	0.3	12.0	4.0
TiO ₂	0.0	0.0	8.0	61.0
S	0.016	0.015	0.020	0.000
LOI	1.8	0.9	0.2	1.9

Lump ores such as those shown in Table 8.22 are used typically at 25–50% of the iron bearing burden in shaft furnaces along with pellets. The motivation for lump ore use is both economic and technical. Lump ore is less costly than pellets and in shaft furnaces a certain amount of lump ore helps to minimize the sticking of pellets. However, fines from lump ore reduce yield and may impair gas flow.

In the commercial rotary kiln processes, lump ore plays a more important role than pellets. The economics of these processes dictate that the higher capital cost of these processes be offset by the use of local low cost lump ores or other iron bearing materials. The rotary kiln processes are prominent in areas such as India, South Africa and China. Some typical iron ore chemistries are shown in Table 8.23.

8.7.4.2 Chemical Properties for Fine Ore Processes

The above discussion of direct reduction pellet and lump ore chemistry would apply exactly for fine ores as the chemistry mainly affects the utilization of the resultant DRI (or HBI) product. However, the nature of several of these fluidized bed and rotary hearth processes have chemistry implications.

Unlike the gas based Midrex and HYL processes, several of these processes are coal based. Therefore the disposition of the ash and sulfur in the coal may influence DRI product quality. The Circufer process provides for magnetic separation of the gangue content in the product; this applies to gangue from the ore as well. In the rotary hearth furnace processes, Fastmet and Inmetco, most of the coal ash and sulfur stay with the product; however, if these processes are followed by a melting process (before the EAF), it may be possible to refine ash and S components from coal as well as higher gangue levels from an iron ore. The EAF would also benefit from the energy contribution of liquid hot metal.

Although gas based, the iron carbide process provides for finished product treatment, magnetic separation, which can separate more than two-thirds of the gangue, thus one could use an ore with higher gangue levels than shown already for pellets.

At the time this chapter was written the only commercial fine ore direct reduction facilities in operation (with ores used shown in parentheses) were the Fior plant (CVG) in Venezuela and the Nucor Iron Carbide Plant (Samitri) in Trinidad (shut down in 1999), FINMET (BHP), Iron Dynamics (Mt. Wright), Circored-Cliffs/LTV/Lurgi (CVRD Carajás) and Qualitech Iron Carbide (CVRD Carajás).

8.7.43 Chemical Properties for Smelting Reduction Processes

The chemistry requirements for smelting reduction processes are more relaxed for certain elements because these processes, like the blast furnace, include a slag phase which captures much of the gangue and sulfur of the input iron bearing materials. Accordingly, the chemistry considerations are similar to those of a blast furnace.

One notable exception is the Corex process which provides for a bleed of alkalis in the off gas processing from the smelting vessel. This feature provides a niche for the Corex process as a consumer of higher alkali ores not well suited to the blast furnace. The first commercial Corex plant was built in South Africa and operates primarily on high alkali ores such as Sishen and Thabazimbi. The chemistry of these lump ores is shown in Table 8.25.

Table 8.24 Chemistry of Merchant Fine Ores for Direct Reduction

Chemistry	CVRD	MBR	Mt. Wright	CVG	BHP	
	FDR	PF			Port Hedland	Samitri
Fe	67.00	68.20	66.00	65.50	67.60	66.60
SiO ₂	0.70	0.74	4.90*	0.90	1.60	2.10
Al ₂ O ₃	0.95	0.60	0.33	0.80	0.60	0.82
CaO	0.02	0.03	0.07	0.05	0.05	0.07
MgO	0.03	0.04	0.05	0.02	0.11	0.04
Mn	0.21	0.23	0.025	0.05	0.05	0.37
P	0.040	0.030	0.015	0.070	0.045	0.047
S	0.008	0.005	0.005	0.050	0.007	—
TiO ₂	0.06	0.04	0.18	—	0.11	0.03
Na ₂ O	0.003	0.006	0.008	0.003	0.040	—
K ₂ O	0.002	0.004	0.008	0.003	0.030	—
Cu	—	—	0.001	—	0.005	—
Pb	—	—	< 0.001	—	—	—
Zn	—	—	0.0006	—	—	—
V	—	0.006	< 0.0002	—	—	—
LOI	1.30	0.67	0.05	4.0	2.0	0.72
Moisture	7.3	8.9	3.2	3.0	3.0	—

* SiO₂ reduced to 2.0 % or less in the Iron Dynamics Process beneficiation process

Table 8.25 Chemistry of Lump Ores used in the Iscor Corex Plant

Chemistry	Sishen	Thabazimbi
FeO	66.00	62.90
SiO ₂	2.82	5.20
Al ₂ O ₃	0.96	0.80
CaO	0.22	0.90
MgO	0.11	0.50
Mn	—	0.11
P	0.04	0.05
S	0.03	0.01
K ₂ O	0.13	0.09

Other smelting reduction processes may also provide an opportunity to treat volatile elements such as the alkalis and Zn in the off gas processing systems.

8.7.44 Physical Properties for Direct Reduction

The required physical properties are dictated, as discussed below, by the reaction vessel type: shaft furnace, rotary kiln, fluidized bed or rotary hearth.

8.7.4.4.1 Shaft Furnace Processes The important physical properties for pellets are size consist and mechanical strength, expressed in terms of the following properties in Table 8.26.

The physical properties are economically important in terms of: (a) yield of initial pellet or lump ore quantities ultimately converted to DRI and (b) the performance of the shaft reduction furnace.

Unlike in the blast furnace, the pellets and lump ore are the only solid materials present so the size range and strength of these materials completely determine the distribution, overall permeability and reduction characteristics of the direct reduction shaft furnace.

Table 8.26 Physical Properties for Shaft Furnace Pellets

Size Range

Midrex	9 × 16 mm, 85% min., but preferably over 95%
HYL	10 × 16 mm, 85% min. +16 mm, 5% max. -10 mm, 9% max

Fines

Midrex	-5 mm, 5% max., but preferably less than 3%
HYL	-6.3 mm, 1% max.

Tumbler Strength

Midrex	+6.3 mm, 92% min., preferably 95% -0.5 mm, 6% max., preferably below 4%
HYL	+6.3 mm, 95% min. -0.65 mm, 5% max.

Compression Strength

Midrex	150 kg min., but preferably over 250 kg
HYL	200 kg min.

The performance of the shaft furnace is adversely affected by increased amounts of fines in two important ways: increased pressure resistance and impaired gas–solid contacting effectiveness. The latter will decrease the effective utilization of the reducing gas fed to the furnace. The increased pressure resistance will limit the maximum flow of gas in the furnace. The combined effect of these will limit productivity and increase natural gas consumption.

Pellet size range is also important as excessively large pellets will be more difficult to heat up and to reduce. Once pellets are reduced to DRI the tumbler and compression strengths drop to lower values but these DRI physical properties are typically proportional to the initial oxide pellet properties. Strong, well-sized oxide pellets will result in reasonably strong, well-sized DRI being fed to the EAF.

In Section 8.7.4.5 we will discuss the metallurgical properties, mainly the reducibility, but it is important to note that the physical characteristics will dominate the behavior and performance of the pellets; a highly reducible but weak and/or poorly sized pellet will impair permeability and gas–solid contacting effectiveness such that it will not be possible to realize the benefit of inherent excellent reducibility in such a pellet.

8.7.4.4.2 Rotary Kiln Processes The size distribution of feed materials for use in a rotary kiln process is less critical than in the vertical shaft furnace because the heat and mass transfer in a rotary kiln are not greatly influenced by the permeability of the bed. For example, iron bearing materials such as beach sand and ilmenite, as fine as -0.5 mm (-32 mesh), which would not be suitable in a vertical shaft furnace, are processed satisfactorily in rotary kiln reduction systems. As in the vertical shaft processes, feed materials with good cold strength are also desirable. Materials that degrade during heating or reduction are undesirable because they generate fines that would leave the kiln as unreduced dust and would require special handling. Swelling of the feed material during reduction does not adversely affect the rotary kiln as it does a vertical shaft furnace. Materials that have the tendency to stick together or form clusters may adversely affect the kiln operation by the formation of ring-type buildups along the wall of the kiln. Formation of clusters during reduction could also result in non-uniformity in product quality. At present, most commercial rotary kiln operations process local lump ores; pellets are used on a limited basis.

8.7.4.4.3 Fluidized Bed Processes The fluidization processes favor ores which are: (a) fine-sized and (b) in a narrow size range. A finer size minimizes the fluidization velocity and energy requirements; however, too fine of a size will reduce the gas volumetric flow rate and therefore the productivity for a given sized unit. Excessive gas flow rate with fine ores will increase ore fines carryover into the process dust system. An ore with a very wide size range presents this dilemma; a low gas velocity will be insufficient to fluidize the coarse fractions while a high gas velocity will increase fines carryover. Each of the fluidized bed processes has different fluid bed characteristics, arrangements and sizes, all of which affect the desired size range in some manner.

Certain ore fines are not amenable to processing in a fluidized bed because of their strong tendency to stick together and form agglomerates during reduction. This sticking tendency during reduction is often associated with the topochemical reduction of the iron ore particle, because the formation of a coherent layer of reduced iron on the particle surface at a relatively low overall degree of reduction promotes welding together of the particles. Various developers of fluidized bed reduction processes have developed bench scale tests to ascertain fluidized bed characteristics of prospective ores.

8.7.4.4.4 Rotary Hearth Furnace Processes The rotary hearth furnace (RHF) processes involve the production of green balls which are then placed on the rotary hearth. The production of quality green balls and the resultant reducibility on the RHF are dependent upon fineness of grind, typically -200 mesh. Accordingly, pellet feed and fine-sized concentrates are well suited while coarse concentrates and natural sintering ores could also be used, but such would require progressively greater amounts of grinding. The production of quality green balls is also dependent upon the moisture level and the type of binder used, if any.

8.7.4.4.5 Smelting Reduction Processes The Corex process includes a pre-reduction shaft furnace in which the physical requirements for pellets and lump ore are similar to those requirements for a Midrex or HYL direct reduction shaft furnace.

The physical requirements for fine ores for the bath smelting processes, namely CCF/AISI, Romelt, Ausmelt, and Technored, are limited to those properties necessary to convey and inject fine ores from holding hoppers into the smelting reduction vessel. The exception is the Technored process which utilizes green balls; here the discussion of green balling for the rotary hearth furnace processes above would apply to Technored.

The conveying and injecting of fine ores into the smelting vessels would be dependent upon the texture, size range and moisture of such ores or dust particles. Materials which are high in moisture, sticky and with a wide size range would be less suitable for injection-type process feed systems; gravity feed systems would be used. However, the behavior of the gases in the free space above the molten bath would have to be such as to avoid having fine ores blown out into the off gas system.

8.7.4.5 Metallurgical Properties for Direct Reduction

The use of highly reducible, strong, non-sticking and non-swelling materials is necessary to attain maximum productivity in direct reduction processes. Generally, good reducibility is associated with materials having a highly porous structure which provides passage for the reducing gas to penetrate and react with the iron oxide surfaces and for gaseous products of the reduction reactions to escape. Over-fired iron ore pellets and hard, dense lump ores are not highly reducible because of their relatively low porosity.

In addition to good reducibility, the top size of the material should be limited to obtain a good reduction rate. Other factors that adversely affect process efficiency include degradation, swelling and sticking of the material during reduction. Some materials have the tendency to disintegrate during reduction at moderately low (500–600°C) temperatures under mildly reducing conditions. This breakdown is associated with the reduction of hematite to magnetite.

Sticking or clustering of pellets during reduction can be minimized by the use of additives, such as limestone or dolomite in the pelletizing process, or by oxide coatings after the pelletizing process, as discussed subsequently.

8.7.4.5.1 Shaft Furnace Processes The key pellet metallurgical properties are reducibility, sticking tendency, and metallization. The reducibility and sticking tendency directly determine the shaft furnace productivity and fuel consumption; as noted above the inherent reducibility of the pellet is not the only factor governing overall degree of reduction and ultimate metallization.

The issue of metallization value is more complex. The value of metallization is clearly only of interest in the electric furnace; its value will be shown subsequently. However the attainment of a given metallization value in the direct reduction shaft furnace is a complex function of both the initial direct reduction pellet properties and the manner in which the direct reduction furnace is operated. The manner in which the direct reduction furnace is operated is in turn related back to direct reduction pellet properties, one of which is reducibility which is inherently related to metallization, another of which is sticking which is not really inherently related to metallization.

Another complexity is the fact that direct reduction product metallization decreases as the direct reduction shaft furnace production rate is increased, with all other factors being equal. Hence overall plant economic goals will partially determine effective metallization levels.

The measurement of direct reduction pellet metallization is another difficult issue. One can use laboratory tests such as the hot load or Linder tests. Midrex has published guidelines, presented in Table 8.27, using these lab tests.

The sticking tendency of direct reduction pellets is measured by various clustering tests; one of which is the hot load test shown in Table 8.27. As with reducibility, there is no universally accepted clustering test. The sticking tendency is vitally important to direct reduction furnace performance as the maximum furnace bustle (process) temperature is limited by the level at which pellets begin to stick. The maximum bustle temperature determines the effective reducibility, the overall productivity and the metallization degree in the furnace.

Table 8.27 DRI Pellet Physical Properties, Post-reduction

	Acceptable	Preferred
Linder Test (760°C)		
Metallization, %	91	93
Degradation, % -3.36 mm	5	2
Hot Load Test (815°C)		
Tumbler strength, % +6.73 mm	—	90
Compression strength, kg	50	100
Clustering (% +25 mm after 10 rev.)	0	0

Fundamentally the tendency for pellets to stick is increased as the Fe content increases and the gangue content decreases; therefore the highest quality direct reduction pellets from a chemistry viewpoint would have a high sticking tendency. However the major breakthrough in recent years has been the advent of coating techniques. The use of coatings, which could include limestone, dolomite, cement, etc., all finely ground, has virtually eliminated sticking as a factor limiting the bustle temperature. Increases in bustle temperature have led to production increases in the range of 10–20%.

For lump ores we are also concerned about reducibility and metallization, but sticking is not an issue. In fact, many direct reduction operators prefer to use 15–30% lump ore for the technical reason that lump ore, when mixed with pellets, reduces pellet–pellet contact and reduces the overall degree of clustering.

Unlike pellets, most lump ores are subject to thermal fragmentation. Thermal fragmentation, believed to be a stress relief phenomenon, occurs when heating the ore to a temperature ranging from 375–425°C. The rate of heating to this temperature range does not seem to be important. However, when the ore reaches the temperature range, some of the lump ore disintegrates into fragments.

8.7.4.5.2 Rotary Kiln Processes In the rotary kiln processes the key metallurgical properties are reducibility and degradation during reduction. Sticking or swelling would not be concerns due to the presence of carbon and the excess freeboard space in these reactors.

8.7.4.5.3 Fluidized Bed Processes In the fluidized bed processes the key metallurgical properties are reducibility, but also extend to sticking tendency and thermal decipitation. Each process has characteristics designed to minimize the possibility of sticking: the iron carbide process specifies the selection of low process temperatures; Circofer specifies the use of fine coal as a lubricant; and Circored, Fior/FINMET specify the use of multiple fluid beds with selected temperature regimes.

Thermal decipitation is a concern because ore particles which may initially be well-sized for a fluidized bed process, upon fragmentation, break up into fine particles which will be subject to carryover.

8.7.4.5.4 Rotary Hearth Furnace Processes In the RHF processes we are concerned mainly with the reducibility of the green balls, which in turn is dependent upon the fineness of the grind and the inherent reducibility of the ore grains. The reducibility and metallization also depend upon the presence of carbon; if the carbon is depleted before the end of the process then reducibility and metallization will suffer.

8.7.5 Trends in Iron Ore Production by Type

In the preceding sections we have outlined quality aspects of sintering ores, pellets and lump ores. Before closing this chapter it would be worthwhile to examine long term trends by type of iron ore as shown in Table 8.28.

Table 8.28 Development of Iron Ore Production in the Western World, 1960–94

	1960	1975	1994
Pellet, %	4	21	24
Fine Ores, %	48	49	46
Lump Ores, %	48	30	20
Total Production, Mt/y	340	580	617

Table 8.29 Seaborne Iron Ore Demand by Type of Product

	1997	2000	2005
For Direct Reduction, Mt/y	33	48	67
Fines, Mt/y	9	13	20
Lump, Mt/y	4	6	8
Pellets, Mt/y	20	29	39
For Blast Furnace/Sinter Plant, Mt/y	379	397	423
Fines, Mt/y	249	262	280
Lump, Mt/y	78	80	81
Pellets, Mt/y	52	55	62
Total Demand, Mt/y	412	445	490

Table 8.26 shows how use of pellets has grown dramatically at the expense of lump ore. The fine ore percentage, mainly for sinter plant use, has decreased slightly, but given the dramatic overall increase in ore production the absolute tonnage of fine ores has sharply increased.

In order to further examine the breakdown by ore type, and also to look at the growing role of ore demand for direct reduction, we examine Table 8.29, which projects demand through 2005. Please note that the tonnages refer to seaborne demand only so the totals are less than those shown in Table 8.28 which refers to total ore production.

The data in Table 8.29 indicate that ore demand for the blast furnace route dominates the iron ore trade but that direct reduction ore demand will nearly double in the next decade.

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