CHAPTER 12.16

Iron Ore Beneficiation

S. Jayson Ripke, Joe Poveromo, Thomas P. Battle,
Henry Walqui, Howard Haselhuhn, and Mike Larson

Iron ore is a mineral substance, which when heated in the presence of a reductant, will yield metallic iron (Fe). Iron ore is the source of primary iron for the world's iron and steel industries. It is, therefore, essential for the production of steel, which in turn is essential for maintaining a strong industrial base. Almost all (98%) of the iron ore mined is used in steelmaking. Iron ore is mined in approximately 50 countries. The seven largest of these producing countries account for about three-quarters of total world production. Aside from production, when it comes to exportation, Australia and Brazil together dominate, each having about one-third of total exports (USGS, n.d.).

Iron ore is used in the form of pelletized concentrates, sintered fines, or lump ore as feed to the primary method of steelmaking, using blast furnaces (BFs) to basic oxygen furnaces in an integrated steel mill. Additional BF feeds include reductants (usually coke) and often fluxes (such as dolomite and/or limestone) to make the liquid hot metal (pig iron), which is the main ingredient in steel production. Pelletized concentrates and lump ore are also used in direct reduction (DR; usually with reformed natural gas) by the shaft furnace to make direct reduced iron and hot briquetted iron for use in electric arc furnaces (EAFs) where steel scrap is recycled in mini-mills, which is the secondary method of steelmaking. To reduce EAF slag production, iron ore pellets or lump reduced by DR for use in an EAF (called *EAF-* or *DR-grade*) usually contain fewer impurities (gangue) than BF-grade pellets or lump.

Iron was first produced circa 2000 BCE, but steel did not become a major commodity until the 1850s (Bell 2017). Iron ore reserves consist mostly of mixtures of gangue and iron oxides in the form of Fe_2O_3 (hematite) and Fe_3O_4 (magnetite, which only differs from hematite by FeO and can be written as $Fe_2O_3 \cdot FeO$), FeO(OH) (goethite), and to a lesser extent ironsands (such as $FeTiO_3$ [ilmenite] and titanomagnetites), $FeO(OH)n(H_2O)$ (limonite), or $FeCO_3$ (siderite). In addition to the iron ore minerals, terms such as *taconite*, *banded iron formation* (BIF), *itabirite*, and *laterite* are also used to describe the geologic occurrence of iron ores. Aside from iron oxides, iron sulfides such as FeS_2 (pyrite) are abundant, but because sulfur is a deleterious element to steelmaking, iron sulfides are not considered an iron ore reserve. In the United States (and other industrialized nations), the equivalent of 150 kg (330 lb) of iron ore must be provided annually per person to maintain the current modern way of life including infrastructure (beams, rebar) and transportation (cars, trucks, trains, planes) (MEC 2016).

According to stoichiometry, pure magnetite contains 72.4% Fe, pure hematite 69.9% Fe, pure goethite 62.9% Fe, and pure siderite 48.2% Fe. Typical gangue constituents are SiO_2 (silica) and Al_2O_3 (alumina). In addition to sulfur, other deleterious elements that are usually avoided or removed from iron ores include phosphorus, copper, manganese, chromium, and alkalis (such as sodium and potassium). In some cases, calcium and magnesium (usually in the form of limestone or dolomite) are added to the iron ore concentrate before balling and induration to create a *basic* or *fluxed* pellet (vs. an *acid* or *unfluxed* pellet). This is because Ca and Mg act as a basic flux for acidic gangue (silica and alumina) and therefore produce a sufficiently low-viscosity slag in the subsequent pyrometallurgical processing steps used for producing iron and steel.

Some ores, called direct shipping ores (DSOs), require little or no beneficiation and simply need to be crushed and screened to produce saleable products; other ores require significant beneficiation flow sheets that can vary widely depending on the type(s) and texture(s) of iron ore minerals associated with the ore. Goldring (2003) presented a relatively simple system that divides iron ores into eight categories, including (1–4) four types of BIF, (5) detrital, (6) fluviatile (channel iron), and (7–8) two types of hypogene magmatic (Kiruna or Andean/Magnitnaya). More than 90% of all iron

S. Jayson Ripke, Manager–R&D, Midrex Technologies Inc., Pineville, North Carolina, USA
Joe Poveromo, Raw Materials & Ironmaking Global Consulting, Self-Employed, Bethlehem, Pennsylvania, USA
Thomas P. Battle, Extractive Metallurgy Consultant, Self-Employed, Charlotte, North Carolina, USA
Henry Walqui, Director, Field Pilot Plant Programs, CiDRA Minerals Processing, Windsor, Connecticut, USA
Howard Haselhuhn, Applications Engineer–Industrial Minerals, Solvay Technology Solutions, Stamford, Connecticut, USA
Mike Larson, Applications Engineering Manager, Moly-Cop USA, Ewen, Michigan, USA

produced comes from BIFs, which from a mining perspective can often be divided into three zones:

1. DSO-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
2. The underlying iron formations, or taconite, from which most of these deposits have been derived
3. A hard, dense, low-grade material that requires extensive crushing, grinding, and concentration to produce an acceptable concentrate

COSMIC ABUNDANCE

Iron is one of the more intriguing elements in the periodic table. Because of its nuclear structure, it has a pivotal role in the generation of the heavier elements in the centers of stars. Because of its multiple valence states, and relative ease in reduction and oxidation, it has played a key role in the formation and geological history of the earth, from the creation of a molten Fe-Ni core, resulting in a magnetic field important to life, to its ready oxidation and precipitation from early oceans when oxygen first appeared in the atmosphere, leading to the formation of BIFs. Not only is iron relatively abundant in the earth's crust, but through these BIFs, it has been concentrated in huge ore deposits throughout the world. Of course, none of this would matter economically if the products of iron manufacture—iron itself, and steel—were not of fundamental importance to modern civilization.

The accepted theory of elemental formation in our universe indicates that after the big bang, only hydrogen and helium were present, along with minute amounts of slightly heavier elements. Clouds of gas began to collapse under their own gravity and eventually reached temperatures and pressures, such that four hydrogen atoms could fuse to form a helium atom. Because the mass of the products is slightly less than the mass of the reactants, energy is released, enough to stabilize the structure for millions of years, as a star. Eventually, the helium-rich core will contract further and heat up until the triple alpha process (three helium nuclei interacting) creates further energy by fusing to carbon. As core temperatures continue to increase, fusion of the heavier nuclei with alpha particles leads to yet heavier elements. If the star is large enough, this process will eventually lead to the formation of iron and nickel, but here it stops. Iron and nickel have the most tightly bound atomic nuclei of all the elements, so further fusion absorbs, not releases, energy. The star will undergo a catastrophic collapse, and then explode as a supernova. Just before and during the supernova explosion, all the elements heavier than iron are manufactured, and most of the contents of the star are blown into the interstellar medium, where they are available to the next generation of star formation (Chown 2001; Gribbin 2000).

Given its high *metal* content (to an astronomer, anything heavier than helium is a metal), the sun is felt to be at least a third-generation star. It contains roughly 35 atoms of iron for every million atoms of hydrogen and is exceeded in abundance only by H, He, O, C, Ne, N, and Mg, and equaled by Si (Choi 2017). Therefore, it played an important role in the development of the planets, especially with much of the hydrogen, helium, neon, and nitrogen remaining gaseous at temperatures where iron had already solidified, either as metallic iron (or Fe-Ni alloys) or as oxides. As the earth began to form, it also heated up, enough that the metallic iron melted and sank to the center of the planet, forming a liquid core and generating a magnetic field around the earth. There was still enough iron left after this to be a major component of the earth's crust, exceeded only by oxygen, silicon, and aluminum. But it is different from the other metals on the list because it is highly soluble in seawater in its reduced state. That did not have a significant effect on global mineralogy until a family of early organisms started releasing oxygen as a waste product; this turned the atmosphere into a more oxidizing medium, worth memorializing as the *great oxidation event*. But that meant that oceanic iron would oxidize from ferrous to ferric, and ferric is much less soluble in water than ferrous. Iron compounds crashed out of solution and settled on sea floors in bands of differing levels of iron compounds, typically colored black and red. These bands formed all over the world over hundreds of millions of years. Uplifted, twisted around, and weathered, they form the BIFs recognized from Western Australia to Minnesota (United States), from Quebec (Canada) to Brazil to India. More than 90% of the world supply of iron is mined from BIFs (Hazen 2012).

STATISTICS AND PRICING

The U.S. Geological Survey maintains up-to-date iron ore statistics in their annual *Mineral Commodity Summaries*, *Minerals Yearbook*, and monthly *Mineral Industry Surveys* that focus on the United States, but also cover the entire world (USGS, n.d.). Historical data can be found in their *Iron Ore Statistical Compendium* (Kuck 2013). Historical pricing for iron ore fines and pellets can be found at Infomine .com (Investment Mine 2016); for current index and spot pricing, see the Metal Bulletin. Iron ore is priced according to U.S. dollars (US$) or cents (US¢) per dry metric ton units. The Metal Bulletin publishes 13 individual iron ore indices based on detailed specifications that are explained in the Metal Bulletin iron ore indices (Metal Bulletin 2016).

In the United States, iron ore (i.e., pellets) is sold by the long ton (998 kg [2,200 lb]) and its end-product steel is sold by the short ton (907 kg [2,000 lb]).

TRANSPORTATION

Most iron ore (as fines, lump, pellets, or concentrate) is transported by bulk carrier (merchant ships of various sizes) or railroad. Iron ore concentrate can be transported by pipeline as a slurry, such as done by Minas-Rio (Anglo American 2015).

QUALITY

The quality requirements depend on how the iron ore is consumed. Concentrates and sinter feed must meet particle size distribution and chemistry requirements to make sufficient quality pellets or sinter. The chemistry must meet a minimum total iron content measured by titration and maximum *acid* gangue content, in particular SiO_2 and Al_2O_3 (and TiO_2). The basicity is important for downstream processing to produce a sufficiently low-viscosity slag. Basicity is a ratio of basic-to-acid components and can be increased by the addition of fluxes, such as dolomite and/or limestone, to increase the CaO and MgO. In addition to acid components, other deleterious elements must be below their maximum allowance.

- **Iron.** Total iron content should be as high as possible.
- **Acid gangue.** Acid gangue, namely $SiO_2 + Al_2O_3$, should be as low as possible, preferably below 5% for BF and below 2% for DR (to minimize slag volume in the EAF during steelmaking).
- **Alkali metals, Na, K, and Li.** Alkalis should be as low as possible because they promote pellet swelling and degradation, fume off during reduction, and can precipitate and form scaffolds within the BF.
- **Basic oxides.** Basic oxides, namely CaO + MgO, reduce the Fe content, but a limited amount of basic oxides (<3%) may displace purchased flux in ironmaking or steelmaking.
- **Phosphorus.** P should be as low as possible, preferably below 0.030%, as P must be removed in steelmaking.
- **Sulfur.** S should be below 0.020% for BF and below 0.008% for DR.
- **Manganese and titania.** Mn and TiO_2 should be as low as possible. For DR, TiO_2 should be below 0.15% to minimize slag volume in the EAF during steelmaking.
- **Zinc.** Zn is not normally present in ores.
- **Other minor elements.** Cr, Pb, Cu, Sn, Ni, Mo, As, Sb, V, and Li should all be as low as possible. For DR, the total of Cu, Ni, Cr, Mo, and Sn should be low as possible, as these are the key residuals being monitored in the scrap supply.
- **Free moisture and loss on ignition (LOI).** Free moisture and 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.

Pellets, sinter, and lump ore must meet certain physical and metallurgical properties, such as particle size distribution, strength (cold compression strength, drop, tumble), chemistry, and reducibility, to remain competent during handling and processing during reduction in a BF (or shaft furnace for DR of pellets or lump). Poveromo (1999) lists the chemistry and sizing for most iron ores with various grades (sinter, pellets, fines, lump) in several separate tables and describes pellet properties.

BENEFICIATION

The term *beneficiation* regarding iron ores encompasses all 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 (Poveromo 1999). Such methods include crushing, screening, blending, concentrating, and agglomerating.

The iron ores that fall within the preceding three categories (pellets, sinter, and lump ore) 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.

Direct Shipping Ores

DSOs typically require the least amount of processing, such as simply crushing, screening, and blending.

Crushing and Screening

Iron ore of merchantable grade must be properly sized prior to charging to the BF. BF technology commonly requires crushing and screening of direct charge lump ore to the size range from 6 to 30 mm (¼ to 1¼ in.). The specific size selected is based on the characteristics of the ore and is specified 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 are 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 desliming.

The –6 mm (–¼ in.) fines produced by crushing and screening are most commonly agglomerated by sintering or are sometimes reground and pelletized. The sinter produced is also crushed and screened to meet size specifications compatible with the other charge components.

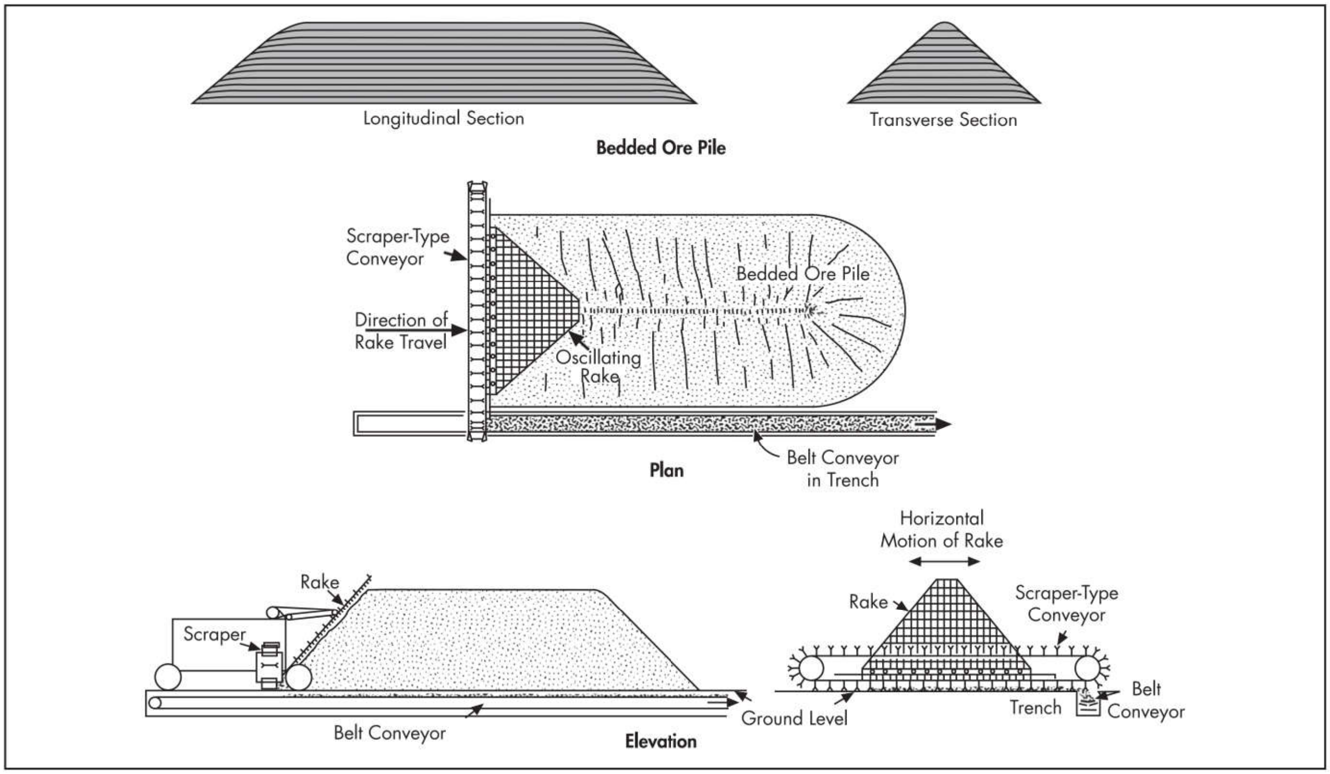
Blending

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 often do not provide enough mixing to meet quality assurance standards now required by industry, especially if both size distribution and chemistry standards are specified. Sophisticated combined blending and load-out facilities are now almost universal in the industry.

Stacking and reclaim systems are most commonly used. Stacking results in layering of the ores (Figure 1). Each successive layer represents an ore that may differ in size distribution 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 bucket-wheel 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.

Low-Grade Merchant Ores

The earliest iron ore beneficiation techniques were developed to upgrade the lower-grade ores associated with DSOs. 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 have been completely decomposed can be easily upgraded by simple washing techniques where the fine-grained friable silica particles can be separated from the heavier, denser, and coarser iron ore particles by hydraulic classification. Ores in which the silica-rich layers have not been weathered as intensely and are still relatively cohesive have to be broken by crushing and are 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 worldwide to similar deposits.



Source: Poveromo 1999

Figure 1 Principle of operation or a stacking-and-reclaiming system

Washing

Washing is the simplest iron ore concentration process and 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 finer than 50 mm (2 in.) in one or two stages. The crushed ore is fed to log washers that were specifically developed 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) combines with the counterflowing water to efficiently break up the ore and remove the fine silica to leave a coarse residual iron-rich product. The log washer overflow was often re-treated 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.

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 that carry a bed of ore 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 higher-density iron-rich particles segregate along the base. The two products are separated at the end of the jig, the silica-rich particles over the top of the discharge weir and the iron ore concentrate under the bottom. Iron ore jigs work best on particles ranging in size from 25 mm to 1 mm (1 in. to 1⁄16 in.).

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 medium with a specific gravity of approximately 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 higher than 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 to 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. Furthermore, the cost of magnetite is much less than ground ferrosilicon.

The fluid 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.

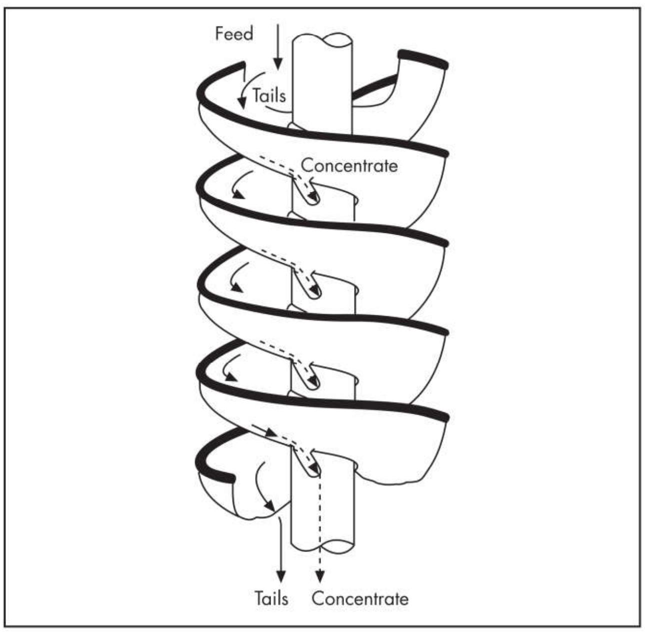
Spirals

The Humphrey spiral, first developed for the treatment of beach sands, is used in iron ore concentration to treat –6 to +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.

The spiral concentrator is a curved-bottom trough, wound around a vertical axis in the form of a helix (Figure 2). 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.

Reichert Cone

The principal advantages of the Reichert cone are capacity and the ability to recover fine heavy minerals efficiently down to approximately 325 mesh, which is finer than is attainable in spirals. A single Reichert cone has a capacity of up to 100 t/h (metric tons per hour; 98.4 ltph [long tons per hour]) and can be effectively used to recover specular hematite fines as well as merchant ore fines. Desliming of the feed is desirable—and essential for merchant-type ore fines.



Source: Poveromo 1999

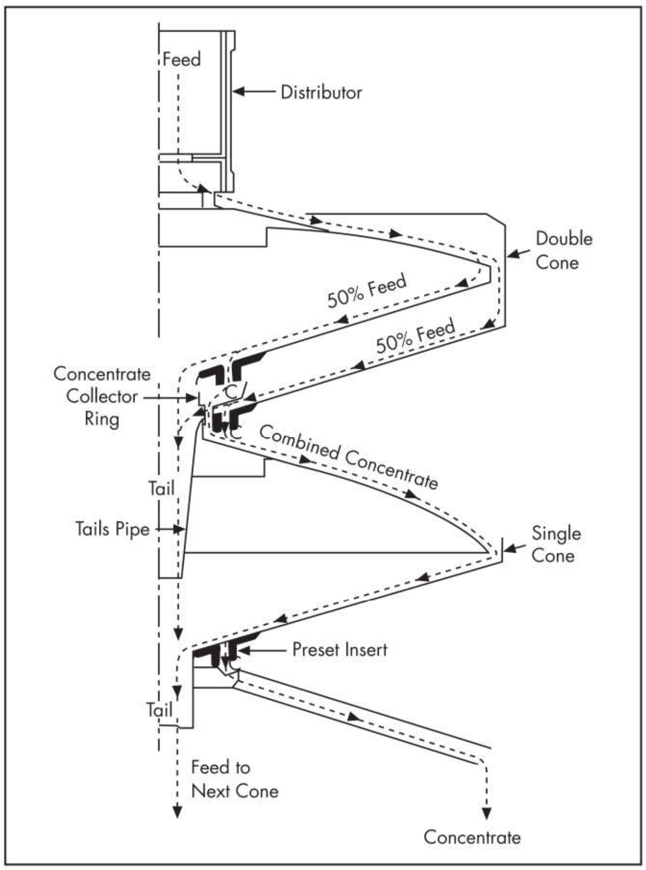
Figure 2 Spiral classifier

The Reichert cone (Figure 3) 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 removed through an annular slot near the apex of the cone. The tailings flow over the slot and are 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.

Wet High-Intensity Magnetic Separation

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

In WHIMS, electromagnets produce a very high-strength magnetic field that is applied to a matrix consisting of steel



Source: Poveromo 1999

Figure 3 Reichert cone concentrator section

balls, spaced grooved plates, steel wool, or pieces of expanded metal. The matrix is contained in an annular ring that is rotated 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 iron oxide minerals while the siliceous gangue is washed through. The iron oxide concentrate is released and discharged as the matrix moves out of the magnetic field.

Primary Ores

Primary iron ores contain only 25%–35% recoverable iron that is present as either magnetite or hematite. Typically, the ore is very hard and has a high work index; in addition, it is finely disseminated so very fine grinding is required 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. The high quality of the pellets and sinter produced from the concentrates, however, has revolutionized BF ironmaking. Concentrates containing 4.0% silica are now the norm, and the unfluxed (a.k.a. acid) or fluxed (basic) indurated pellets 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 using sophisticated computerized mine plans.

Currently, the greatest production in North America is from the magnetite taconites of Minnesota and Michigan. This iron ore beneficiation and palletization technology was developed by E.W. Davis (1964). 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.

Comminution

Comminution means to break into smaller parts. The following subsections discuss the different ways this is done.

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.

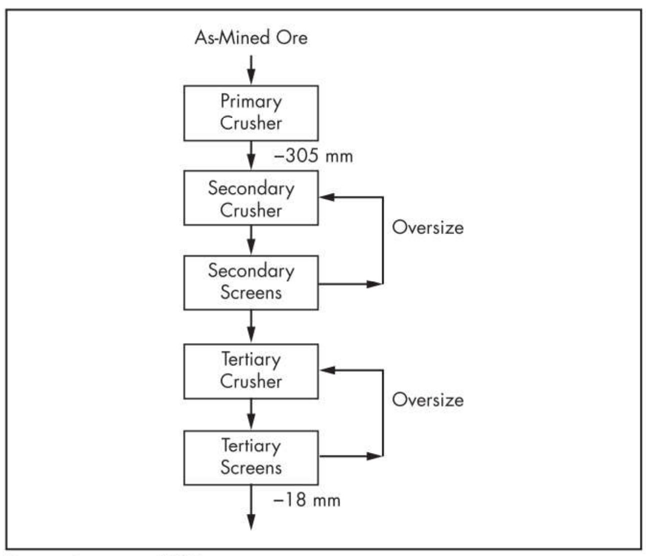
Primary, secondary, and tertiary crushing. Because of the hardness of the ore, three and sometimes four stages of crushing are used in magnetite-taconite plants to reduce the ore to rod mill feed size (Figure 4). Primary and secondary crushing is almost universally done by gyratory or cone crushers. (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 completed by shorthead crushers operating in closed circuit with screens. Relatively recently, and after having been successfully used for fine comminution in the cement industry, high-pressure grinding rolls (HPGRs) have become a common alternative to tertiary crushing and rod milling. HPGRs 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; therefore, the HPGR has replaced both tertiary crushing and rod mills in some taconite plants.

Autogenous milling. Autogenous grinding is an alternative to multistage crushing. Autogenous mills use the ore as the 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 the 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 oversize pebbles are recirculated. This recirculating pebble load tends to build up in some circuits and will eventually curtail mill production. The most recent process improvement applied to autogenous milling circuits has been the addition of magnetic cobbing and pebble crushing to reduce 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 HPGRs.

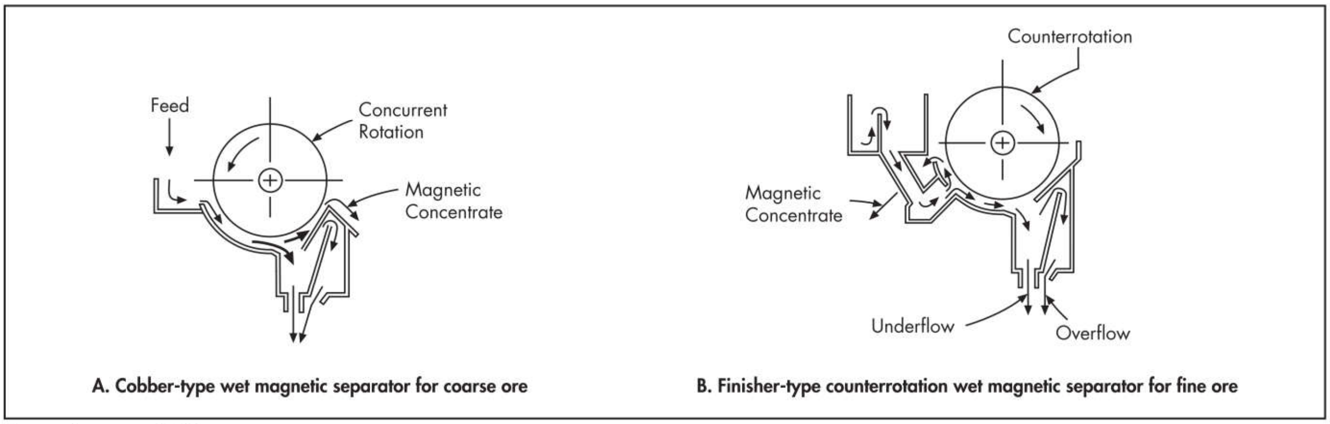
The final product size from autogenous milling is controlled by cyclone classification of the trommel undersize. In some plants, the autogenous mill grinds to final liberation size, –200 mesh. Other plants close the autogenous mills at a coarser size, –6 mm (–¼ in.), and achieve the final grind in conventional ball mills or pebble mills.

Semiautogenous 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 *semiautogenous grinding*, or *SAG*. The other components of the circuit are essentially as described for autogenous milling.



Source: Poveromo 1999

Figure 4 Flow sheet of an iron ore crushing circuit



Source: Poveromo 1999
Figure 5 Concurrent separators

Rod milling. Rod mills were designed to grind nominal –35 mm (–1¼ in.) feed, usually prepared by tertiary cone crushers, to –3 mesh. They are tumbling mills with a length-to-diameter ratio of 1.5:2.0. The grinding media are steel rods up to 100 mm (4 in.) in diameter. The ore is ground wet at approximately 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.

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.

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.

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.

Coarse dry magnetic cobbing. Coarse magnetic cobbing of tertiary crusher discharge at –19 to –25 mm (–¾ to –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 in radial or axial configurations 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 more than 98% of the magnetite is possible depending on the grade of the feed. Magnetic separation at –75 mm (–3 in.) was also used at one mine to upgrade lean ore stockpiles.

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 tailings, which reduces downstream grinding and concentration costs. The magnetic cobbers (Figure 5) 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 0.2 T (2,000 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 1.2-m (4-ft) diameter have a capacity of more than 32.7 t/h per meter of length (10 ltph per foot of length).

Finisher and cleaner magnetic separation. Finisher and cleaner 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 magnet separators and the feed and tailings discharge systems are different than those of 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. 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 0.08 T (800 gauss) have been specified for some plants. Capacity of 1.2-m (4-ft)-diameter separators treating fine material is also somewhat lower, generally less than 16.4 t/h per meter of width (5 ltph per foot of width).

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 is then fed to the final magnetic separators.

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 at approximately 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 are 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.

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 (United States).

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 negatively 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 approximately 10 mm (⅜ in.).

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. See additional information from Silva et al. (2011).

Magnetite-taconite concentrates. Supplementary upgrading of magnetite concentrates is practiced at several taconite plants to lower the silica content for BF pellets. It will also be an essential part of the flow sheet for the production of low-silica concentrates for DR 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 as 2%–4% depending on the efficiency of the magnetic separation plant and the characteristics of the crude ore.

Conventional mechanical flotation cells, 14–43-m^3 (500–1,500-ft^3) 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 re-treatment because column flotation units recover –500 mesh magnetite more efficiently than the conventional mechanical cells.

Hematite ores. The basic selective flocculation, cationic silica flotation flow sheet was developed specifically to concentrate the ores of the Tilden mine, described later.

Concentration Plant Flow Sheets

The type of beneficiation process depends on the ore mineralogy (composition and distribution) and the ultimate destination (or end-use application) of the iron concentrate. Mineralogy of both the iron and gangue phases (in particular silica, phosphorus, and alumina) play a fundamental role in determining proper unit operations and flow sheet design (or selection) and was well-explained by Silva; this applies broadly to most hematite BIFs around the world (Brazil, South Africa, India, and Australia) although he focused specifically on Brazilian ores (Silva et al. 2011; Araujo et al. 2003). Examples include gravity separation (jigs and spirals) magnetic separation (rare earth wet drums, ferrous wheel, and Jones-type magnetic separators), and flotation. When it comes to end use, for example, DR feed requires a much lower silica content, necessitating a more elaborate beneficiation flow sheet than does BF feed.

MODERN FLOW SHEETS, DESIGN, AND OPTIMIZATION

The following iron ore beneficiation flow sheets represent the most modern designs in use around the world today.

United States

The 2015 status of the U.S. iron operations are shown in Table 1 when some of the plants listed with "iron ore pellets" as their primary product were idled and/or operating at reduced capacity because of a slow economy, but by 2018 they were all actively targeting full production capacity.

Magnetation

The Magnetation assets were acquired by, and are now called, ERP Iron Ore. Essar Minnesota assets were acquired by Chippewa Partners and are now called Mesabi Metallics. The

Table 1 Iron operations in the United States, 2015*

Operation and Location	Operator	Primary Product	Status	Capacity, Mt (million lt)†	Production, Mt (million lt)†	Reserves, Mt (million lt)‡
Voestalpine Texas LLC, Corpus Christi, TX	Voestalpine	Hot briquetted iron	Active	2.0 (1.9)	2.0 (1.9)	§, **
Iron Dynamics Inc., DeKalb County, IN	Steel Dynamics Inc.	Hot metal	Active	0.3 (0.29)	0.3 (0.29)	§
Reynolds Pellet Plant, White County, IN	Magnetation LLC	Iron ore pellets	Active	3.3 (3.2)	Not available	§
Nucor Steel Louisiana LLC, St. James County, LA	Nucor Corp.	Direct reduced iron	Active	2.5 (2.4)	1.1 (1.0)	§
Empire, Marquette County, MI	CCI (formerly CNR)††	Iron ore pellets	Permanent closure 2016	5.6 (5.5)	3.1 (3.0)	8.7 (8.5)
Tilden, Marquette County, MI	CCI	Iron ore pellets	Active	8.1 (7.9)	7.7 (7.6)	395 (388)
Hibbing Taconite, St. Louis County, MN	CCI	Iron ore pellets	Active	8.1 (7.9)	8.2	267 (262)
Keewatin Taconite, Itasca County, MN	United States Steel Corp.	Iron ore pellets	Active	5.4 (5.3)	1.7 (1.6)	349 (343)
Mesabi Chief Plant 1, Itasca County, MN	Magnetation LLC	Iron ore concentrates	Idled indefinitely (February 2015)	0.4 (0.39)	0.3 (0.29)	3.6 (3.5)
Mesabi Chief Plant 2, Itasca County, MN	Magnetation LLC	Iron ore concentrates	Idled indefinitely (January 2016)	1.0 (0.9)	0.9 (0.88)	18 (17.7)
Mesabi Chief Plant 4, Itasca County, MN	Magnetation LLC	Iron ore concentrates	Idled indefinitely October 2016; planned restart in 2018	2.0 (1.9)	1.4 (1.3)	‡‡
Mesabi Nugget Delaware LLC, St. Louis County, MN	Steel Dynamics Inc.	Iron nuggets	Idled temporarily (May 2015 onward)	0.4 (0.39)	Not available	§
Mining Resources LLC, St. Louis County, MN	Steel Dynamics Inc.	Iron ore concentrates	Idled temporarily (May 2015 onward)	1.0 (0.9)	0	Not available
Minntac, St. Louis County, MN	United States Steel Corp.	Iron ore pellets	Active	15 (14.7)	12 (11.8)	464 (456)
Minorca, St. Louis County, MN	ArcelorMittal S.A.	Iron ore pellets	Active	2.7 (2.6)	2.7 (2.6)	126 (124)
Northshore, St. Louis/Lake counties, MN	CCI	Iron ore pellets	Active	6.1 (6.0)	4.4 (4.3)	830 (816)
United Taconite, St. Louis County, MN	CCI	Iron ore pellets	Active	5.4 (5.3)	3.2 (3.1)	474 (466)

Adapted from Tuck 2018

* Listed operations do not include blast furnaces.

† As reported or calculated from data in company annual reports, oral communications, published online data, or U.S. Securities and Exchange Commission filings.

‡ Proven and probable reserves or equivalent, including those on owned and leased property, as reported by the company on the last publicly available date.

§ Facility does not operate an independent mine and has no reserves.

** Facility buys seaborne DR-grade pellets.

†† In 2017, Cliffs Natural Resources (CNR) returned to its previous name of Cleveland-Cliffs Inc. (CCI).

‡‡ Magnetation LLC owned mineral rights for 1,400 Mt (million metric tons; 1,378 million long tons) of unspecified iron ore equivalent resources or reserves as of April 2014.

Magnetation pellet plant was built in record time, with construction starting in June 2013 and the first pellets produced at the end of September 2014. The plant has a design capacity of 3,000,000 t (2,952,619 lt) of fluxed pellets, with the feed being mostly hematite concentrate. The plant incorporated the latest technology in environmental pollution control with the addition of low nitrogen oxide (NOx) burners and a gas suspension absorber (GSA).

Iron ore concentrate is received from the processing plants in Minnesota via rail and unloaded in Reynolds, Indiana, using a rotary car dumper, one car at a time. Unit trains with 120 cars are unloaded over a 12–18-hour time frame. The concentrate goes through a double-roll crusher (1.5 m wide and 7.3 m in diameter [6 ft wide and 24 ft in diameter]) during the winter to break frozen chunks that are present on the concentrate cars.

The unloaded concentrate is transported via a conveyor to the ore barn where a 116-m (380-ft) long shuttle conveyor spreads the concentrate the length of the ore barn (245 m [804 ft] long by 61 m [200 ft] wide) with a design capacity of 160,000 t (157,473 lt). Wheel loaders are then used to reclaim the concentrate and feed it to the grinding circuit through two reclaim hoppers into a conveyor. The feed rate is determined by the grinding demand. The reclaimed concentrate discharges into a repulper sump where it is mixed with water to target 55%–60% solids by weight. Water addition is controlled to maintain the level of the repulper sump and hit the target percent solids. The slurry then feeds two large storage tanks.

Slurry from the concentrate grinding storage tanks feed a cyclone sump, which is then pumped to a cyclone cluster with a combination of 51-cm (20-in.) and 66-cm (26-in.) cyclones.

The cyclone underflow is gravity fed to a 3,729-kW (5,000 hp) ball mill (9 m [31 ft] long and 5 m [16 ft] in diameter) running at 14.6 rpm. The mill is controlled between 3,579 and 3,654 kW (4,800 and 4,900 hp), while the target grind is controlled to 80% passing 325 mesh. The discharge from the mill goes to the cyclone sump to close the circuit. The product of the grinding circuit (cyclone overflow) discharges by gravity to a 23-m (75-ft) thickener. The filter feed thickener overflow goes to a process water sump where the water is reclaimed to be used throughout the process.

The thickened concentrate is sent to two filter feed storage tanks at 50% solids. From the storage tanks, it gets pumped to a pressurized distributor that feeds five rotary disk filters (with 4-m [12-ft] diameters). The moisture of the concentrate is controlled to 11.5%–12.0% to meet balling needs. Filter concentrate is conveyed to a 2,000-t (1,968-lt) concentrate storage bin.

Additives are also received and ground on-site. Limestone and dolomite come by truck from nearby quarries and are stored in a covered barn. They are then individually fed into raw storage bins, which feed a vertical ring roller dry grinding mill with a 75-t/h (73.8-ltph) capacity. The ratio of dolomite to limestone is controlled to meet the pellet chemistry needs. The ground and dried mix of limestone and dolomite is pneumatically transported to a storage bin. Coke breeze is used as an internal fuel to compensate for the composition of the iron ore concentrate that is mainly hematite. The raw coke arrives in trucks that are unloaded and conveyed to a raw storage bin that feeds a separate vertical ring roller dry grinding mill with a 10-t/h (9.8-ltph) capacity. The coke breeze is ground and dried, then collected in a storage bin.

The ground concentrate, limestone–dolomite blend, coke breeze, bentonite, and recycle process dust taken from stream dust collectors are then metered in with weight belt feeders in parallel lines at the required ratios. Automation in place, together with the equipment installed, ensures a very precise control of the additives, which leads to tightly controlled pellet chemistry. The mix then feeds two parallel high-intensity paddle mixers (298 kW [400 hp], 5 m^3 [176 ft^3] working capacity); here water is added to improve the performance of the balling circuit. The discharge from both mixers is combined and fed via conveyors to the balling feed bins (100 t [98.4 lt] each).

At the balling building, six balling disks (7.4 m [24 ft] in diameter, 186 kW [250 hp]) are used to produce green balls. Each balling disk has a roll screen (584 cm [230 in.] length, 231 cm [91 in.] width, 145 cm [57 in.] rolls) to remove undersize (<9.5 mm [⅜ in.]) and oversize material (>12.7 mm [½ in.]). Screen undersize and oversize are collected and recirculated to mix with the fresh feed. The on-size green balls from each of the disks are collected on a single conveyor that is then spread on a 4-m- (13-ft)-wide belt via an oscillating conveyor. Prior to entering the indurating furnace, the green balls go to a final screening stage on a roll screen feeder (4.2 m [14 ft] wide).

The green balls feed a straight-grate furnace, which measures 96 m (315 ft) long by 4 m (13 ft) wide. Hearth and side layer pellets are added prior to the green balls landing on the grate to protect the pallet cars and support strong pellet quality. The furnace is divided into six different zones: updraft drying, downdraft drying, preheat zone, firing zone, first cooling, and second cooling. The Magnetation pellet plant was the first facility to install low-NOx burners. A total of 14 are installed plus 2 smaller preheat burners. In addition, a GSA scrubber is used to treat the off gases and minimize sulfur oxides (SOx) emission.

The grate discharges to a single collecting conveyor that takes the fired pellets to a hearth layer separation bin, where a portion of the pellets are returned to the furnace to be used as the hearth layer. The final product is conveyed to two pellet load-out bins to be directly loaded into pellet trains.

Essar Steel Minnesota

Currently, the Essar Steel Minnesota project is on hold; however, it is an example of the latest concentrator design. The concentrator flow sheet and its development was presented at the 2009 Society for Mining, Metallurgy & Exploration conference in Minnesota (Murr et al. 2009). Both the concentrator and the pellet plant represent the latest design. The furnace is a recently designed straight-grate system. The low-NOx burner design for this project was pioneered by Essar (incidentally, Magnetation's furnace is the first commercial application of this low-NOx burner). The off-gas treatment system, which combines a GSA with activated carbon injection, is the first of its kind in the world on an iron ore induration furnace. It is the only plant designed to remove and capture chlorides, fluorides, SOx, and mercury and subsequently remove them from the property. Together, these advancements will make the plant the cleanest pellet plant in the world. Also noteworthy, it is a zero-discharge facility (J. Swanson, personal communication).

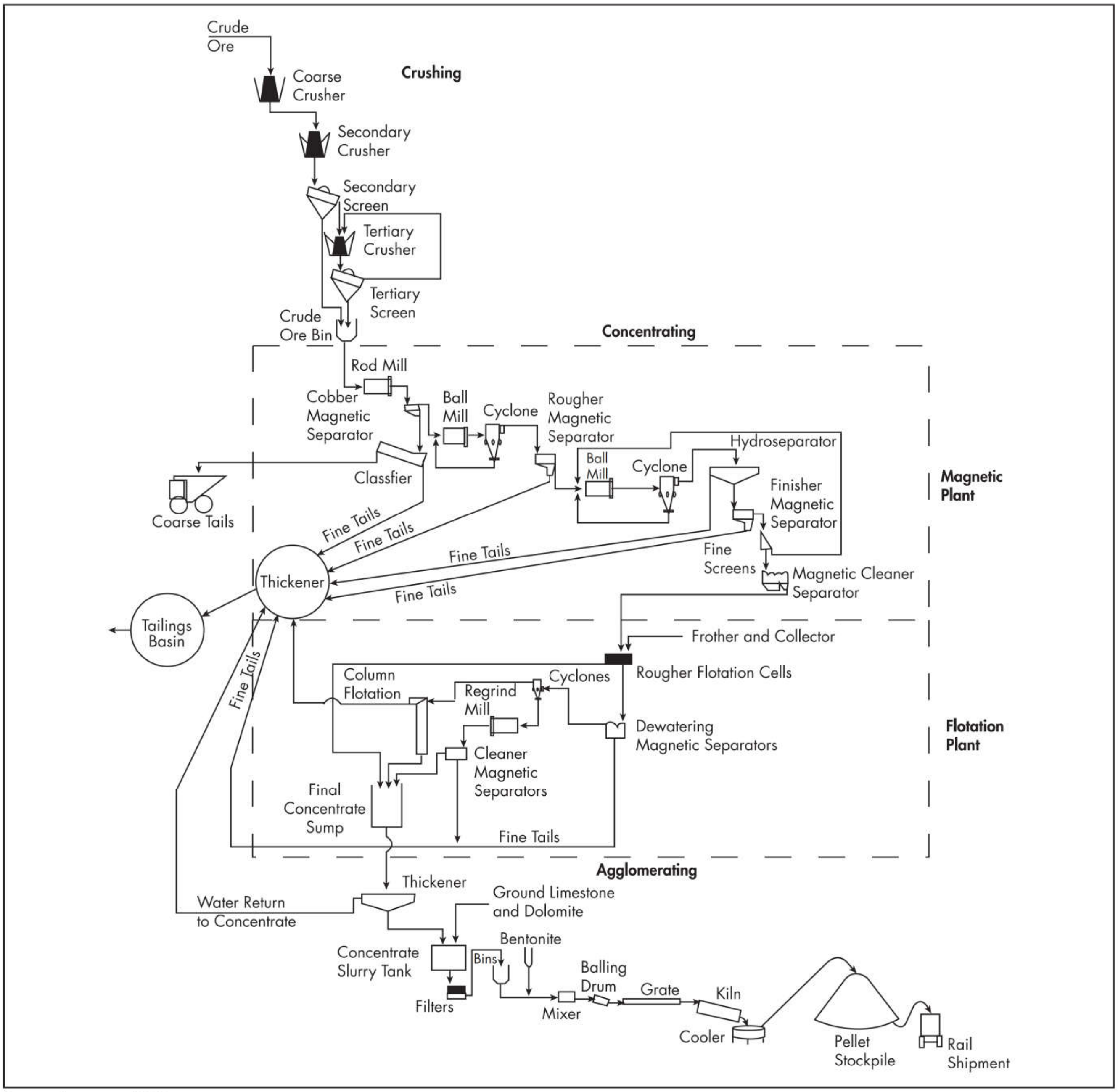
United States Steel Corporation

U.S. Steel operates the Minntac and Keetac mines on the Mesabi iron range in northern Minnesota.

Minntac. Minntac is located in Mountain Iron, Minnesota. In addition to the original plant (step 1), it has had two expansions (steps 2 and 3). Minntac processes magnetite ore concentrate pellets in grate-kiln-cooler induration (Figures 6 and 7). Step 1 had three lines, but lines 1 and 2 were decommissioned. Line 3 remains operational. Step 2 has lines 4 and 5, and step 3 has lines 6 and 7. They use Ovation process control software, which was upgraded from Westinghouse software (T. Colerich, personal communication).

Keetac. In addition to Essar Steel Minnesota, another example of a modern flow sheet that is also successfully proven to operate is Keetac (formerly National Steel Pellet Company [NSPC]) (Kawatra 1997). The NSPC facility, located in Keewatin, Minnesota, has produced iron ore pellets since 1966. The flow sheet has been optimized through pilot-scale testing and computer simulation studies. Energy consumption was reduced and grinding capacity increased by replacing the original hydrocyclone classification with fine screens. 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 are used alone (Poveromo 1999).

The density effect in classification is important to understand, in particular during concentrator design. There are examples where a fine screen manufacturer is not involved in projects until after start-up when it is realized that the Fe/SiO_2 grade in the plant with cyclones does not match the Fe/SiO_2 grade achieved in a laboratory with screen classification at the same P_{80}. Cyclone classification generally requires a finer P_{80} to achieve the same Fe/SiO_2 grade as screen classification (J. Wheeler, personal communication). Wennen, Murr, and others describe this as a shift in the "grind–grade" relationship



Source: Poveromo 1999

Figure 6 Minntac flow sheet

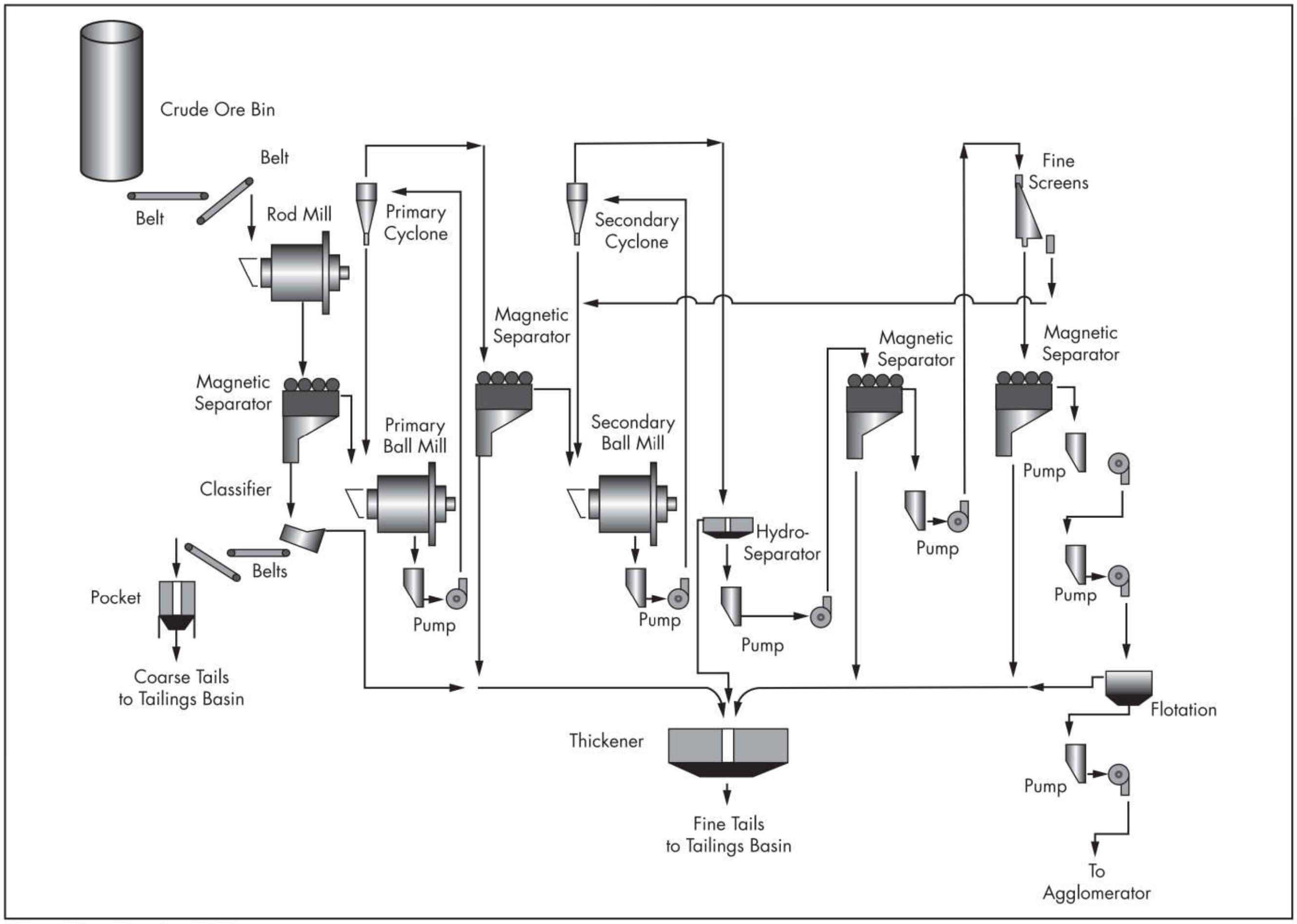
(J.E. Wennen, personal communication; Murr et al. 2009). Bleifuss (1968) has described the cause in greater detail.

Cleveland-Cliffs

In 2017, Cliffs Natural Resources reverted to its former name of Cleveland-Cliffs Inc. (CCI). CCI is the largest iron ore producer in North America with its U.S. production capacity of 19.6 t/yr (19.3 ltpy) of BF-grade iron ore pellets produced by five mines: Northshore Mining (NSM), United taconite (UTAC), and Hibbing taconite (Hibbtac) in Minnesota and Empire and Tilden in Michigan's Upper Peninsula. In addition to their BF-grade pellets, CCI has developed a DR-grade (also known as EAF-grade) pellet at its NSM operation. Aside from North America, CCI operates the *Koolyanobbing complex*, a collective term for the operating deposits at Koolyanobbing, Windarling, and Mount Jackson, located in Western Australia.

Northshore Mining. NSM produces 5.5 Mt (million metric tons; 5.4 million lt) of iron ore pellets per year. The magnetite ore is mined in Babbitt, Minnesota. Coarse crushed ore is shipped 76 km (47 mi) by rail to the fine crusher, concentrator, and pellet plant located along the shore of Lake Superior in Silver Bay, Minnesota, and was named the E.W. Davis Works in honor of this pioneer of taconite.

The concentrator plant operates 11 sections (lines) to produce the magnetite concentrate for iron ore pellet production (Figure 8). Each section had four Stearns 1 × 3-m (3 × 10-ft)



Adapted from Frosaker 2005

Figure 7 Latest Minntac flow sheet

concurrent flow rougher magnetic separators that were installed in 1979. Their typical magnetic iron recovery averaged 99.4%. Because of outdated rougher magnetic separators, 75% of unrecovered magnetite was lost in the tails. Past evaluations of upgrading the rougher magnetic separators were uneconomical, but in 2003, an economic opportunity arose when used machines from Cliffs Erie became available, which maintained concentrate grade and improved throughput and recovery (Ripke and Hoff 2005).

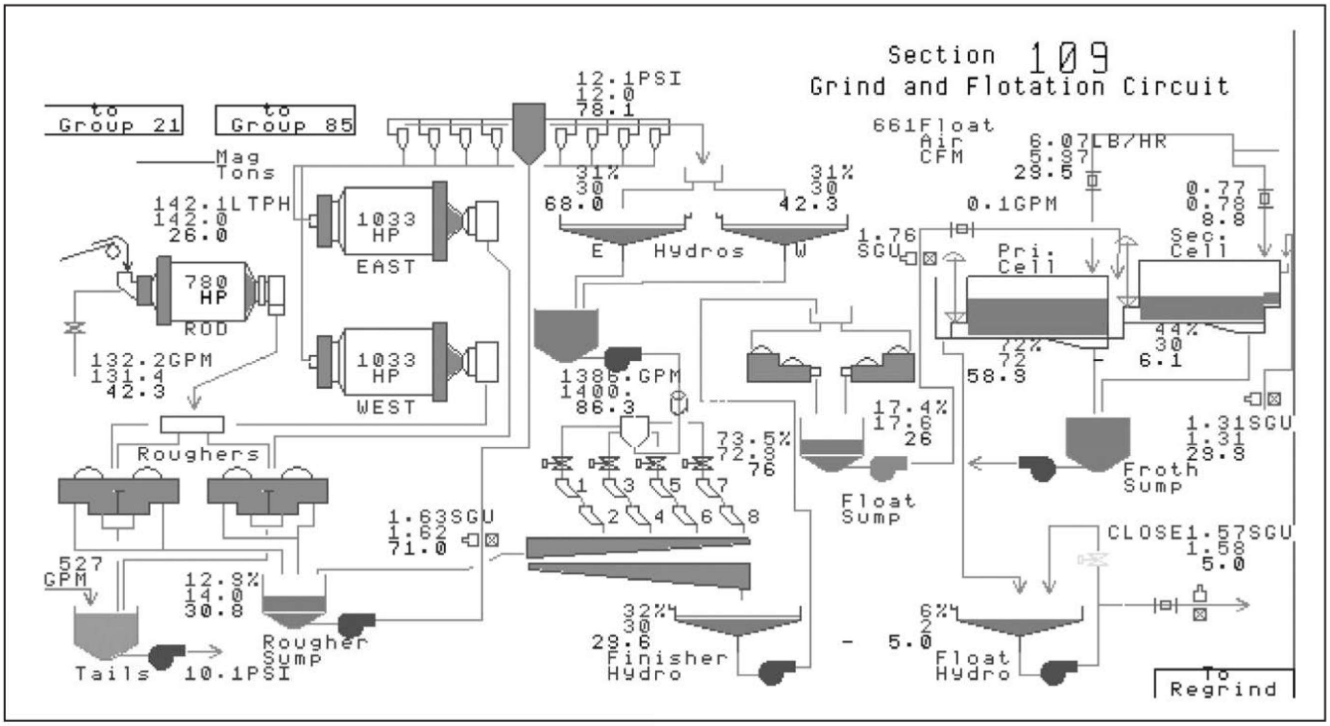
Tilden. The Tilden mine is owned by CCI. The mine, concentrator, and pellet plant are located in Ishpeming, Michigan, adjacent to the Empire mine, pellet plant, and concentrator. In 2014, Tilden produced 7.7 Mt (7.6 million lt) of iron ore pellets per year with its installed capacity of 8.0 t/yr (7.9 ltpy). Although hematite is the primary ore processed at Tilden, it also has the installed capability to process magnetite, although it has not done so since 2011 or 2012.

Magnetite was typically processed between December and March or April. This has an advantage because the lower temperature of the water system during winter negatively impacts hematite recovery; this is not much of an issue with magnetite. In addition, indurating furnace repairs can also be done during magnetite production because the plant becomes heavily concentrator constrained.

It takes about two days to convert the flow sheet from magnetite to hematite and less when going to magnetite because fewer grinding lines are used and the process is simpler. The screen decks on the primary mills are also swapped out: 2 mm (5⁄64 in.) for hematite; smaller, 1.6 or 1.4 mm (1⁄16 in.) for magnetite (anything bigger can plug the tailings line). When magnetite was being processed, Eriez wet magnetic separators were used for both cobbers and finishers.

So that the Cliff Drives III pit close to Tilden could be employed, series desliming was performed prior to the finishers and flotation. Using diamine and frother after cold water interferes with dispersants in desliming. And although the water system could be closed up and recycled again, it would affect water chemistry. However, significant amounts of magnetite would be stockpiled as concentrate to blend with hematite later.

Tilden hematite. The Tilden mine is a unique mine in that it processes a low-grade ore (30%–34% Fe) containing fine, disseminated hematite. Run-of-mine (ROM) ore is crushed to 225 mm (9 in.) and then ground in primary fully autogenous mills along with caustic soda to increase pH throughout the beneficiation plant (McIvor and Weldum 2004). The primary mill discharge is screened to remove –2 mm (–5⁄64 in.) (–8 mesh) particles, which are reground to 80% –74 µm (–200 mesh) in fully autogenous pebble mills. Part of the



Source: Ripke and Hoff 2005

Figure 8 Display of Northshore mining concentrator flow sheet

primary mill screen oversize is used as grinding media in the pebble mills, and the remainder returns to the primary mill. The 75-mm (3 in.) by 32-mm (1¼ in.) fraction of the screen oversize is crushed using secondary cone crushers before it is returned to the grinding mill to avoid accumulation of this critical size material in the primary mill circuit (Poveromo 1999). The pebble mills are closed with cyclones with an overflow size fraction at 80%–90% passing at 25 µm. This fine-size fraction is required to achieve the product silica set point and poses many challenges in the beneficiation process. A dispersant is added to the pebble mill feed to aid in mill efficiency and in the downstream mineral separation process (Keranen 1986).

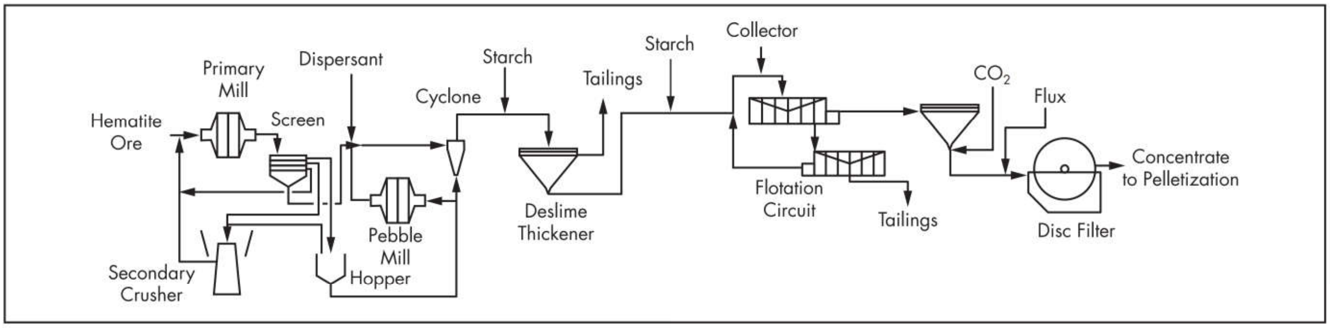
A cooked modified cornstarch is added to the cyclone overflow immediately prior to entering the deslime thickeners (Keranen 1986). The cornstarch is added to selectively flocculate the liberated hematite. After almost five decades of successful use, the mechanism of selective adsorption of starch is still debated among researchers in the field (Pradip 1994). The deslime thickeners allow selectively flocculated iron-bearing minerals as well as coarse particulates to settle into the underflow while dispersed siliceous gangue minerals are rejected through the overflow. This process defines the uniqueness of this operation and is required to economically produce high-grade iron oxide pellets from this ore. The deslime thickeners upgrade the ore from ROM to 45%–50% Fe prior to flotation.

The deslime underflow is further concentrated by flotation to at least 65% Fe using a rougher-scavenger circuit (Siirak and Hancock 1988). Starch is again added to this process to depress iron oxide surfaces while ether amine is added as a flotation collector for the reverse flotation of siliceous material not removed by the deslime thickeners (Keranen 1986). The final concentrate is then thickened, mixed with limestone flux, and filtered using disk filters. Filter cake is pelletized using a bentonite binder, balling drums, and a grate-kiln sintering furnace. A process flow diagram is included in Figure 9.

Because of the surface-chemistry-intensive nature of this process, the water chemistry is as important as the reagents used to facilitate beneficiation. The pH must be held between 10.5 and 11 throughout the process, partly because of the dispersive nature of alkaline environments with oxidized ores and partly because of the increased starch selectivity in this pH range. Of particular importance is the water hardness within the process, as free water hardness–contributing ions, particularly calcium and magnesium, within the process water act to nonselectively flocculate iron oxides and the associated gangue minerals during desliming. Water hardness contributing ions also reduce the selectivity of starch to hematite surfaces. Levels of water hardness in excess of 20 ppm can cause a substantial loss in deslime thickener underflow grade associated with an increase in deslime iron recovery (Haselhuhn and Kawatra 2015). This loss in deslime grade must be accounted for during the flotation process, which can handle excursions but results in a significant loss in flotation iron recovery. This is a significant balancing act understood by the Tilden process engineers as an optimal pH, and water hardness must be maintained to maximize overall plant iron recovery.

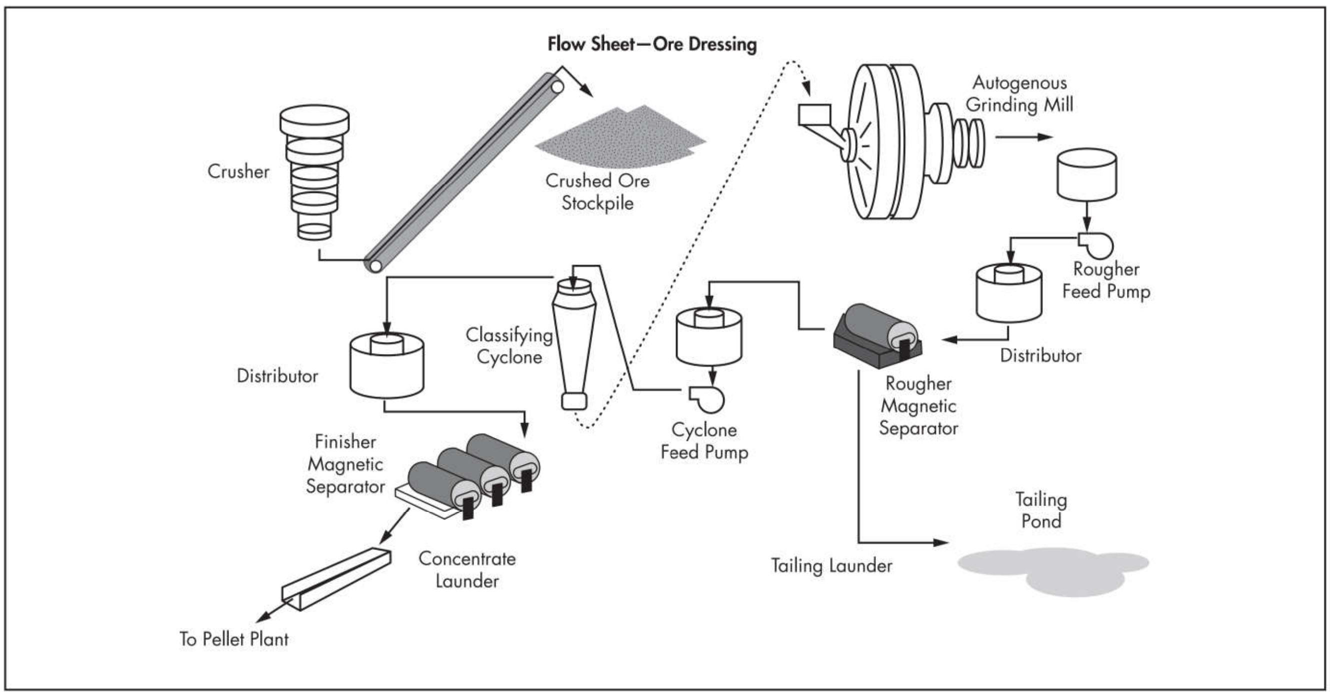
Hibbing taconite. CCI operates Hibbtac, which is located in Hibbing, Minnesota (Pforr 1974). The plant has a capacity of 8.2 Mt/yr (8.1 million ltpy). The concentrator flow sheet uses autogenous grinding and is shown in Figure 10 (Bymark 1985).

Essar Steel Minnesota. This project went idle in 2015 and then bankrupt. As of 2018, a new owner is vowing to be mining and processing ore by early 2020. The beneficiation flow sheet is shown in Figure 11.



Adapted from Keranen 1986

Figure 9 Tilden flow sheet



Source: Bymark 1985

Figure 10 Hibbing taconite flow sheet

Canada

In 2018, there were two commercially operating iron ore pellet operations located in Canada (ArcelorMittal Mining Canada and Iron Ore Company of Canada) with one idle (Wabush) and some additional projects under consideration.

ArcelorMittal Mining Canada

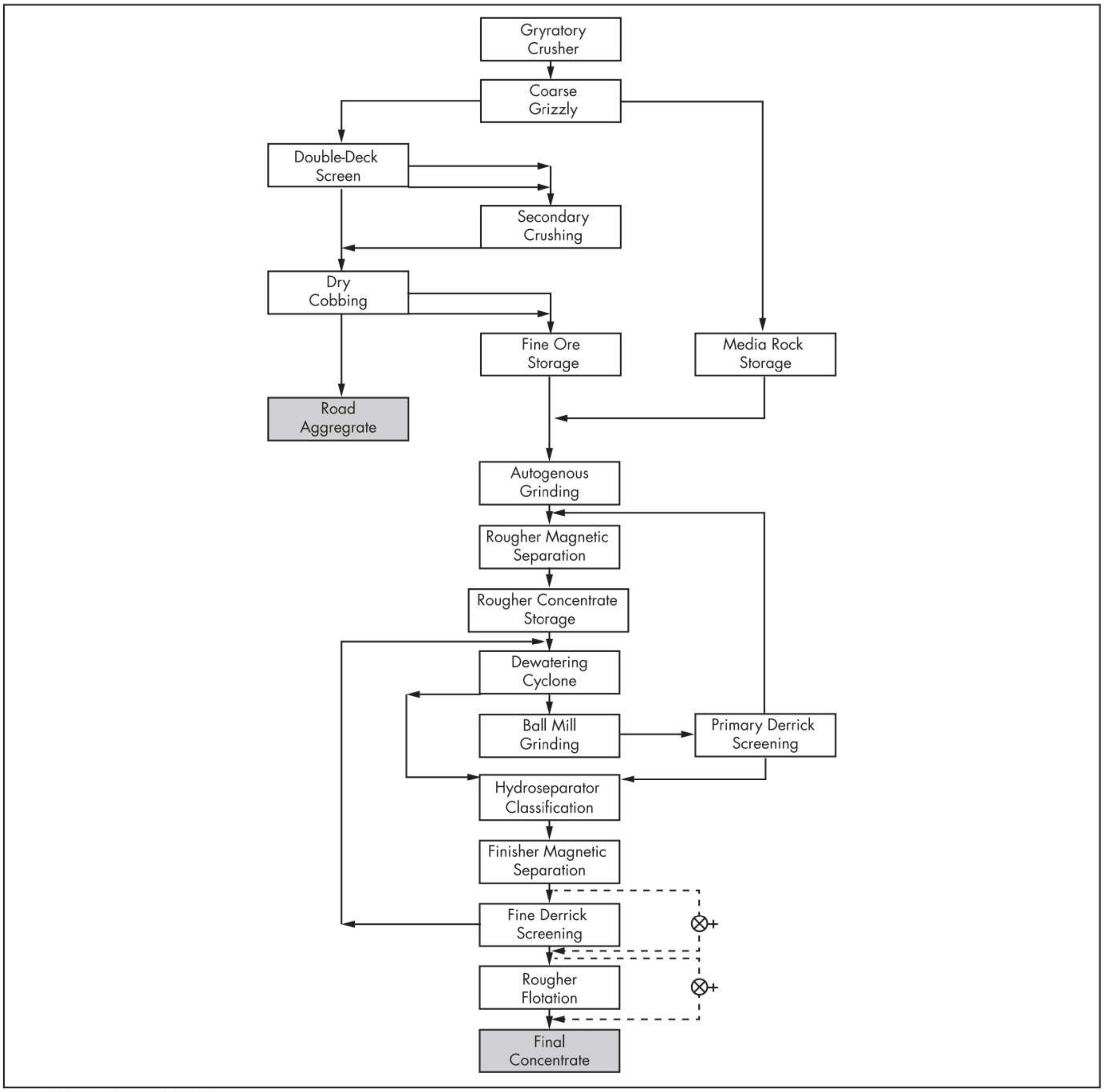
ArcelorMittal Mining Canada (AMMC), formerly Quebec Cartier Mining, is located in Mt. Wright, Quebec, Canada. AMMC is an open pit iron ore mine that produces concentrate and pellets. The former and most recent flow sheets are shown in Figures 12 and 13, respectively.

Iron Ore Company of Canada

Iron Ore Company of Canada, located in Labrador City, Newfoundland, conducted a concentrator audit in 1998, which exclusively used thousands of wash water spirals for recovery of their hematite ores. They determined that controlling this quantity of spirals was almost impossible. They sought a more simplified flow sheet and investigated nine variations before selecting and installing their choice (Hearn 2002), which was to use hindered settling separators as the primary separator before the spirals to significantly reduce the number of spirals.

Wabush Mines

Although the Wabush mines closed operation in 2014, the Wabush mines concentrator produced a relatively coarse (–1 mm) specular hematite concentrate using a unique revised flow sheet (Figure 14). The *Mining Engineering* (1970) article, "Wabush: A \$300-Million Iron Operation," shows the original flow sheet with autogenous grinding, primary and secondary Humphreys spirals, drum filters, fluo-solids dryers, and high-tension electrostatic separation. In 2000, the concentrator flow sheet was modified. The primary rougher spirals were replaced with Reichert spirals, and the secondary cleaner spirals were replaced with Hydrosizers (Ripke 2007).



Adapted from Murr et al. 2009

Figure 11 Essar Steel Minnesota concentrator flow sheet

Mexico

Lump ore, fines, and concentrate are produced from a variety of operations in Mexico by ArcelorMittal including at Lazaro Cardenas Volcan Mines, Pena Colorada, and Las Truchas.

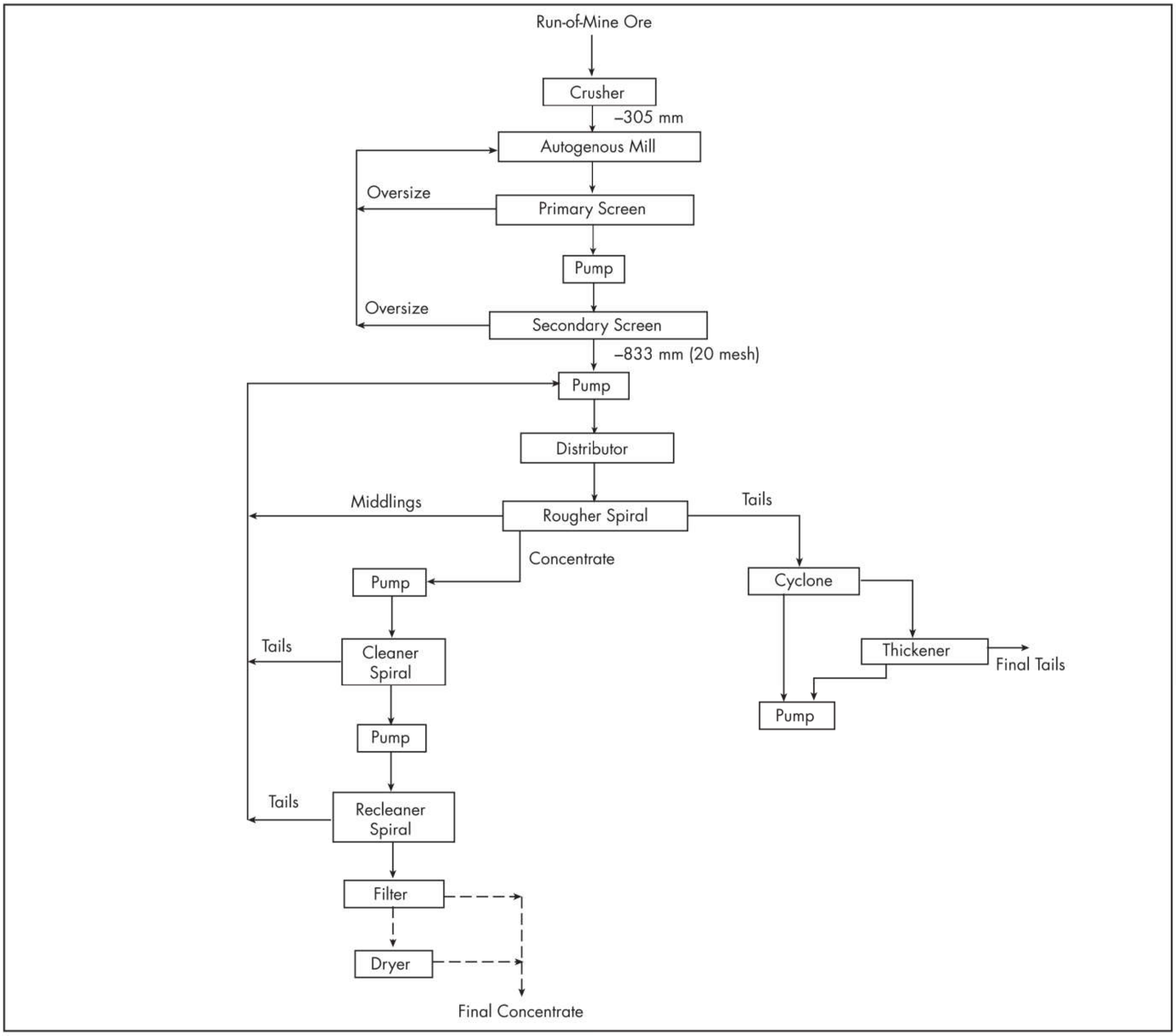
Brazil

Brazil is a major producer of iron ore and pellets by Vale and Samarco (a joint venture owned by Vale and BHP Billiton). Samarco is currently idled after having a tailings disaster in 2015.

Vale

Vale uses USIM PAC mineral-processing modeling software. the company's research and design strategy is to conduct in-house pilot plant tests. Vale uses ASEA Brown Boveri (ABB), Siemens, and others for concentrator process control. Vale's various pellet feeds and sinter fines are described in Table 2; each have a 10% filter cake moisture.

Current flotation practices in Brazil are explained by Silva et al. (2011) as follows: In the past, iron ore producers would only use either (1) mechanical (i.e., tank) or (2) column



Source: Poveromo 1999

Figure 12 Past AMMC flow sheet

cells, but not combine them. The latest trend has been to combine tank and column cells. Some producers place mechanical cells first in the configuration (which is preferred), and others place their cells column cells first (and have not reconfigured them, but probably should) (Araujo et al. 2003; Silva et al. 2011). A potential alternative to tank cells or columns may be the staged flotation reactor (Swedburg et al. 2016).

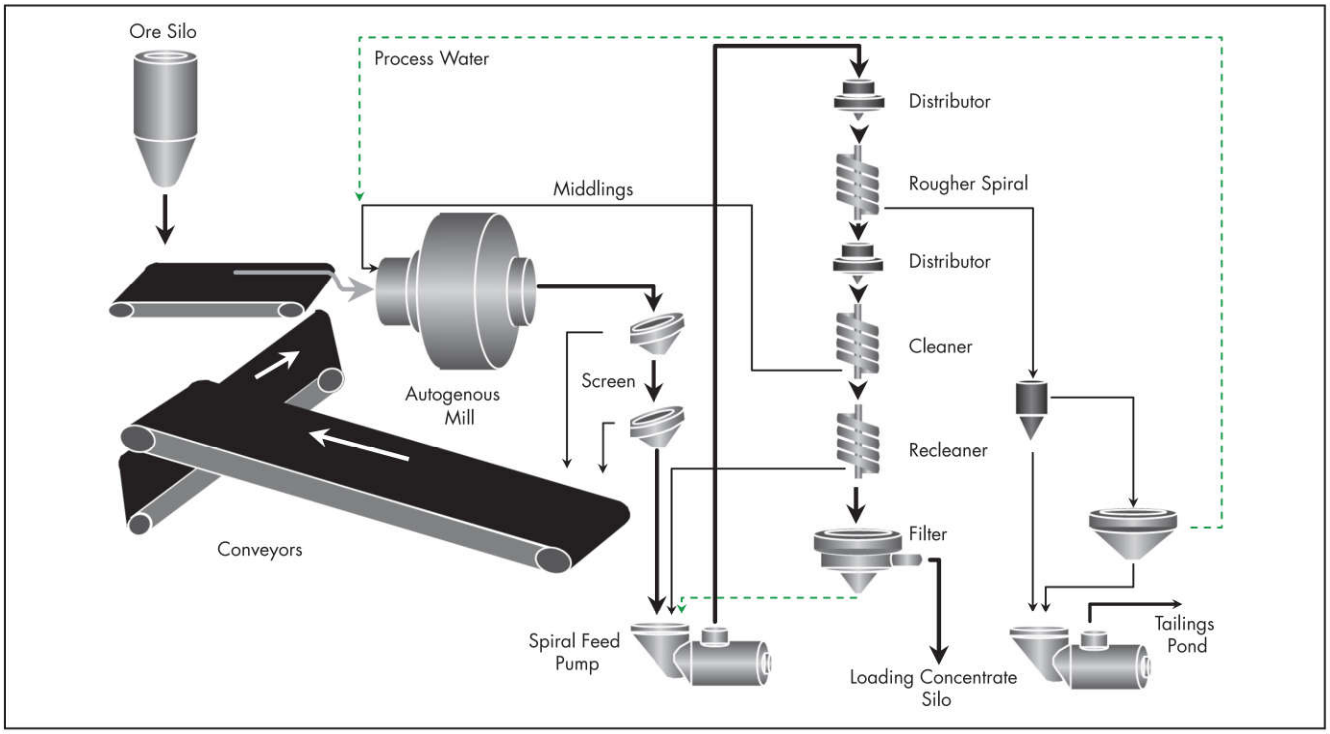
Minas-Rio

Minas-Rio produces 26.5 Mt/yr (26.1 million ltpy) of pellet feed, by the flow sheet shown in Figure 15, for the BF or DR shaft furnace. It beneficiates two ore types: an itabirite and a friable ore that generates a high percentage Fe product with low contaminants (Anglo American 2015). The concentrate takes about four days to travel by pipeline as a 68% solids slurry over 529 km (329 mi). Additional information is provided by Mazzinghy et al. (2015).

Samarco Mineração

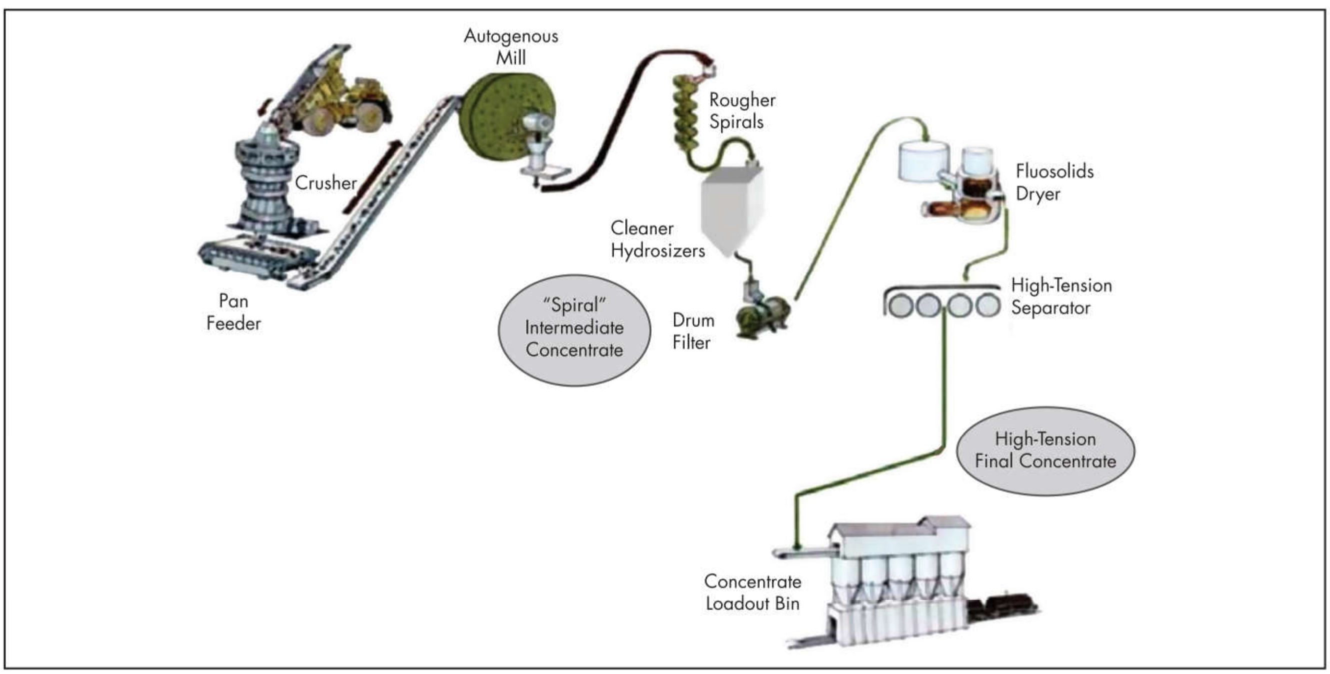
Samarco Mineração designed a specific SAG mill for the 15 different itabirites found in its projects (Rosa and Rocha 2015):

> Ore characterization is a major factor for a proper concept of grinding circuits and for equipment sizing, but there is still not a consensus if the traditional laboratory tests applied to characterize grinding behavior of ores, such as [drop weight test] DWT, SMC [Test], and Bond [work index], are the best applicable methodology for understanding the grinding performance of all ores. In this sense, the characterization of friable itabirites, a metamorphic banded iron formation with iron oxides layered with quartz, is still a challenge once their comminution behavior is incorrectly predicted by these traditional



Courtesy of RBC Dominion Securities Inc.

Figure 13 Recent AMMC flow sheet



Source: Ripke 2007

Figure 14 Wabush Mines concentrator flow sheet

methodologies. Samarco Mineração S.A conducted detailed studies on the mineralogical characterization of the itabirites reserves to support the geometallurgical models of its deposits. These studies show that for friable itabirites the ore size distribution and ore hardness are not necessarily correlated. More hydrated itabirites showed lower grinding kinetics, regardless of particle size. …

Samarco [semiautogenous] milling studies raised doubts about the grinding classification of

Table 2 Vale iron ore process*

Process	Natural Moisture Beneficiation Process	Utilization of Flotation Process for Fines of Low-Grade Itabirite	Beneficiation Process of Hard and Low-Fe-Grade Itabirites	Application of High-Intensity Magnetic Separators as Scavengers on the Reverse Flotation of Quartz Aiming Reducing %Fe on the Tailings, <8% Fe	Application of High-Intensity Magnetic Separators for the Concentration of Coarse Particles, −1 +0, 15 mm (10/16 in.)
Years of operation	From 2008	From 1974	From 1974	From 2014	From 1974
Product type†	Natural fines, −16 mm (10/16 in.)	Pellet feed	Pellet feed	Pellet feed	Sinter feed
Ore type	Hematite	Low-grade itabirites	Low-grade itabirites	Low-grade itabirites	Low-grade itabirites
Tons, Mt/yr (million ltpy)	90 (88.6)	100 (98.4)	50 (49.2)	5 (4.9)	10 (9.8)
Name	Carajás mine	Iron Quadrangle	Iron Quadrangle	Iron Quadrangle	Iron Quadrangle
Crushing and screening steps	1° jaw crusher, 2° and 3° conic crushers; 1°, 2°, and 3° screening	NA‡	1° jaw or gyratory crusher, 2°, 3°, and 4° conic crushers; 1°, 2°, and 3° screening	NA	NA
Grinding	NA	NA	Ball mill in closed circuit with cyclones	NA	NA
Beneficiation steps	NA	Mechanical and column flotation cells on the reverse flotation of quartz with amine and cornstarch	Mechanical flotation rougher, cleaner, scavenger, recleaner, reverse flotation of silica with amine; vacuum disk filtration	Mechanical flotation rougher, cleaner, scavenger, recleaner, reverse flotation of silica with amine; vacuum disk filtration	One step of magnetic separation
Weight recovery, %	100	50–70	50–60	30–40	55–60
Fe recovery, %	100	70–80	75–85	70–80	60–65
Lines per plant	2	10	4	1	3
Total grade, %Fe	65	>65	>65	>65	>62
Contaminants, %	2.5 SiO_2, 1.0 Al_2O_3, 0.100 P	1.5 SiO_2, 0.5 Al_2O_3, 0.060 P	1.5 SiO_2, 0.5 Al_2O_3, 0.060 P	1.5 SiO_2, 0.5 Al_2O_3, 0.060 P	4.5 SiO_2, 0.5 Al_2O_3, 0.060 P

Courtesy of Vale
* Information obtained by the chapter authors' survey.
† The pellet feeds and sinter fines each have a 10% filter cake moisture.
‡ NA = not applicable.

ore hardness that is commonly used for itabirites. Based on our observations from pilot plant tests, it was clear that ore hardness is not always correlated to particle size distribution.

These observations led us to further investigations that correlated different ore typologies to grinding kinetics. For Samarco's ores with similar iron content, the more hydrated the ore, the higher the energy consumption in the grinding stage. Additionally, it was possible to include a grinding parameter in our geometallurgical model, which made it possible to map the ore hardness of our reserves.

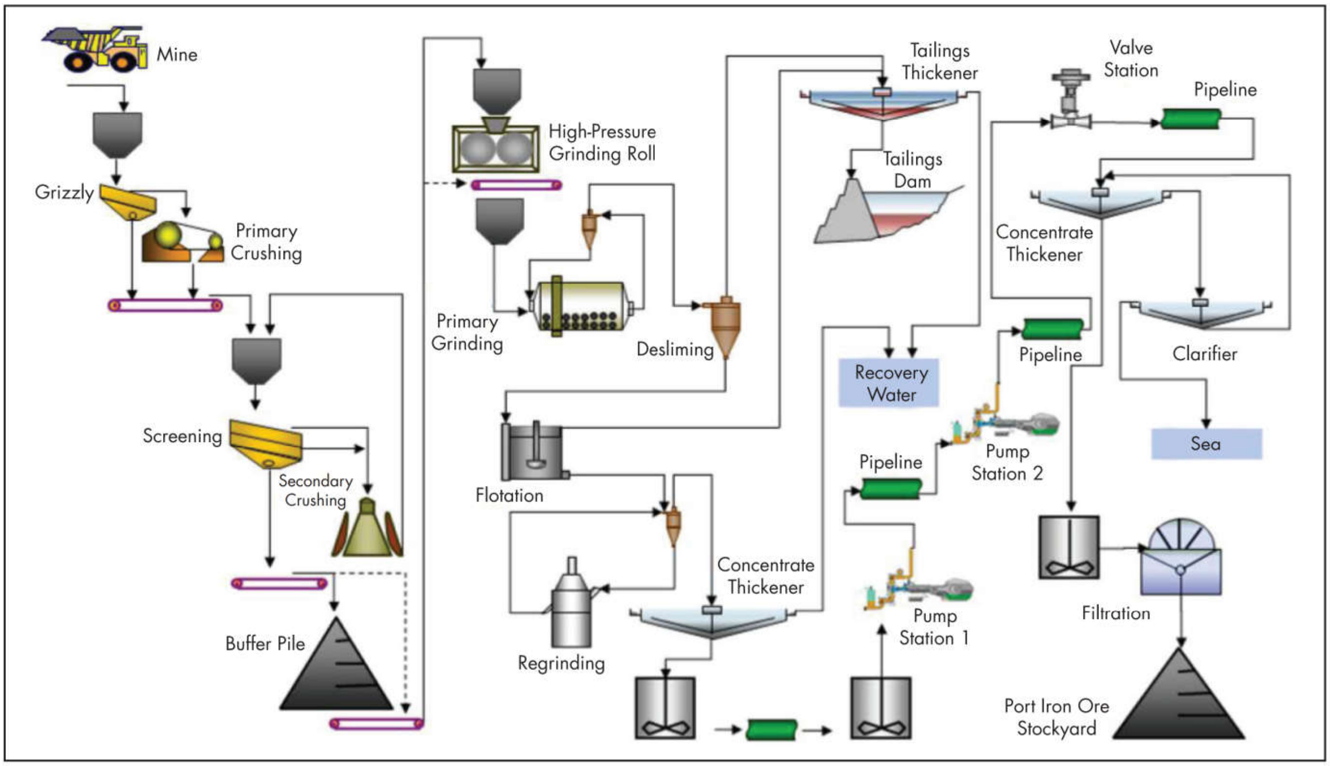
This grinding parameter is also used for process control in our current concentrator, for ball mill circuits. Based on our observations from pilot plants we are confident that our internal methodology can be adjusted for [semiautogenous] milling as well.

Australia

The three major iron ore producers in Australia are Rio Tinto, BHP Billiton, and Fortescue Metals Group. However, because they produce DSO, they use little or no beneficiation, so the following additional producers are highlighted.

Arrium Mining

In 2017, Arrium was acquired by GFG Alliance and renamed SIMEC Mining. The concentrator, outside Whyalla, South Australia, installed and commissioned a 3-MW (4,023-hp) M10000 IsaMill tertiary stirred mill in late 2013. Prior to the project proceeding, extensive test work was conducted at ALS Metallurgy (formerly AMMTEC) in Perth, Australia, to compare the IsaMill option with the existing ball mill and determine the correct IsaMill layout within the existing plant. Both continuous testing and signature plot semibatch testing were completed under the supervision of Arrium personnel. Multiple signature plots were planned on different ores from around the property to investigate grinding energy variability. On start-up of the IsaMill, two months of on-site optimization took place to bring the mill to full tonnage while reducing the internal component wear rates. During this time, process guarantee sampling took place validating the previous work done at ALS Metallurgy. Once the mill configuration was set, further sampling took place as a final confirmation of the 1:1 M4 laboratory scale-up and choice of grinding media size. After liberation data showed that a coarser grind from the IsaMill than the design still resulted in an acceptable concentrate grade, work was undertaken to increase the throughput of



Source: Mazzinghy et al. 2015

Figure 15 Minas-Rio flow sheet

the mill past the original maximum design. The initial Arrium hematite flow sheet is shown in Figure 16.

This project has seen the Arrium magnetite operation undergo an overhaul, allowing it to produce magnetite concentrate using a lower-grade feed material at an increase in production capacity of more than 400,000 t/yr (393,682 ltpy) (Arrium Mining and Materials 2016). This throughput has continued to be expanded as the maximum capacity of the IsaMill has been pushed well beyond the original design (Figure 17). After a challenging start, handover of the plant was completed on budget and ahead of schedule. Through methodical implementation procedures, step-by-step improvements in throughput and mill wear have been realized, allowing the plant to process tonnage well beyond anything for the original design (Larson et al. 2015).

Fortescue Metals Group

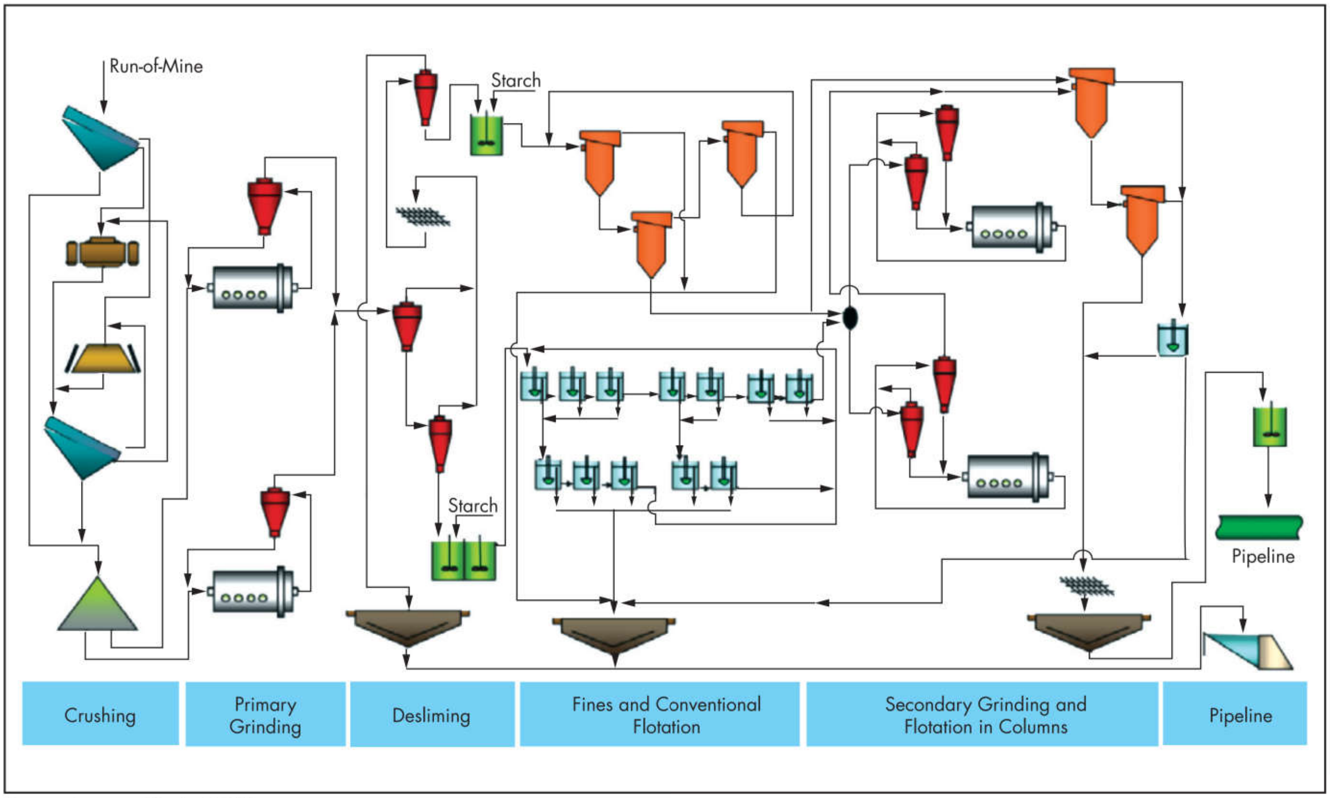
Fortescue Metals Group (FMG) has become the world's fourth largest seaborne iron ore producer since being founded in 2003 and shipping its first ore to China in 2008. It currently has a capacity to produce 165 Mt/yr (162 million ltpy) of iron ore Rocket fines (59% Fe, for sinter feed) and lump from the Pilbara region of Western Australia for BF feed. Their Cloudbreak and Christmas Creek mines feed their Chichester hub with 90 Mt/yr (88 million ltpy). Their Firetail and Kings mines feed their Solomon hub with 70 Mt/yr (69 million ltpy). The >58% Fe ore is mined (in some cases with autonomous production trucks, as noted in *Mining Engineering* [2013]), screened, crushed, and desanded. "Low-phosphorous Kings ore is a stand-alone product, while higher-grade Firetail ore is blended with low-impurity Chichester ore, allowing Fortescue to maximize the benefits of both ore bodies and reduce cutoff grades" (FMG 2015). Iron ore is shipped from the mines to the hubs to the Herb Elliott port in Port Hedland by railway that consists of 620 km (385 mi) of the fastest and heaviest haul line in the world.

FMG ore processing. Clout and Rowley (2010) provide an excellent description of FMG's ore processing facilities:

> The Cloudbreak ore processing facility consists of … screening, crushing, and a beneficiation facility referred to as the "desand" … producing either fines-only or lump and fines. The ore processing facility has a nominal nameplate capacity of 45 Mt/yr [44 million ltpy] of wet product.

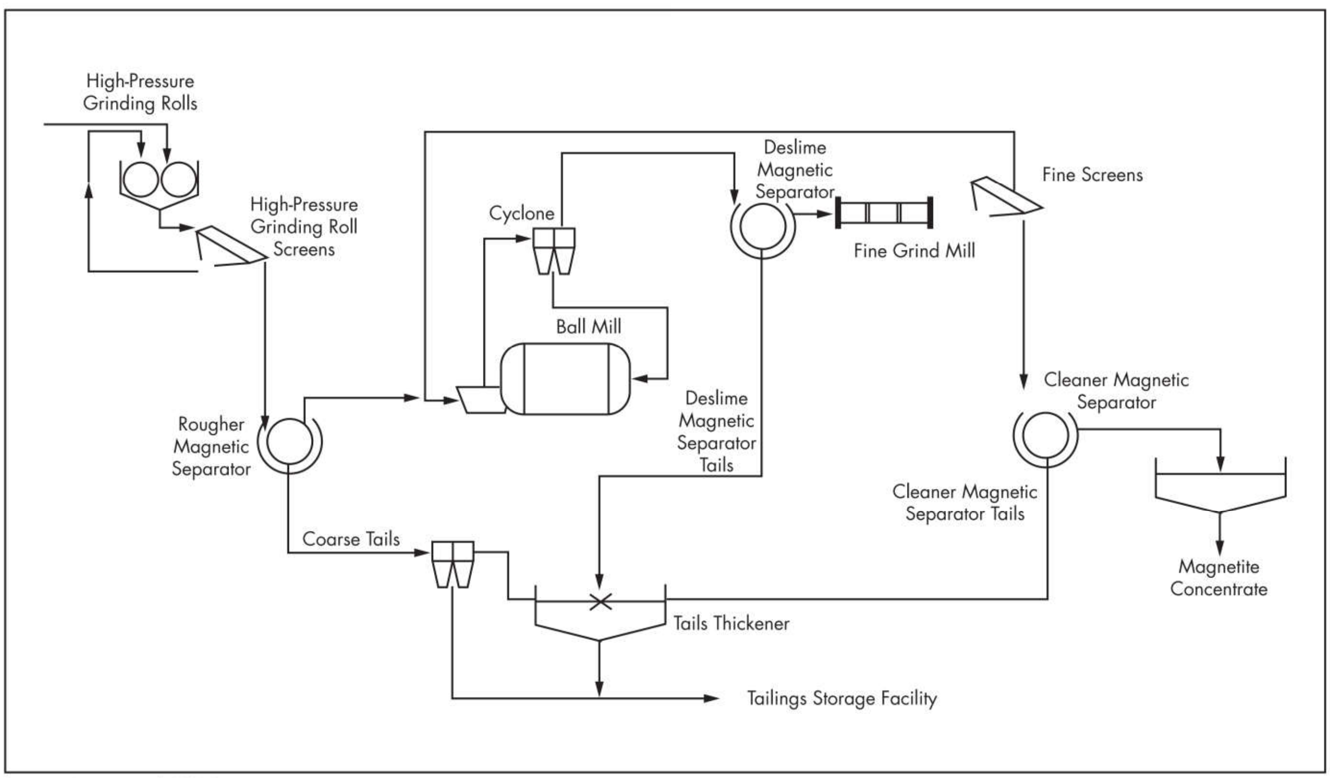
FMG product. Clout and Rowley (2010) provide the following description of FMG's product:

> The main Fortescue product exported to date is Rocket fines, which has 64.6 percent calcined Fe content and low contaminant levels, including low phosphorous and alumina and high loss on ignition. The Rocket fines calcined Fe is mid-way between the high-grade fines products and the premium Brockman fines products from the Pilbara, with less than about 1 percent calcined Fe separating them. Shipments of 24.6 WMt [24.2 million wlt] of Rocket fines for the first 12 months of operation were very close to the target product grade.



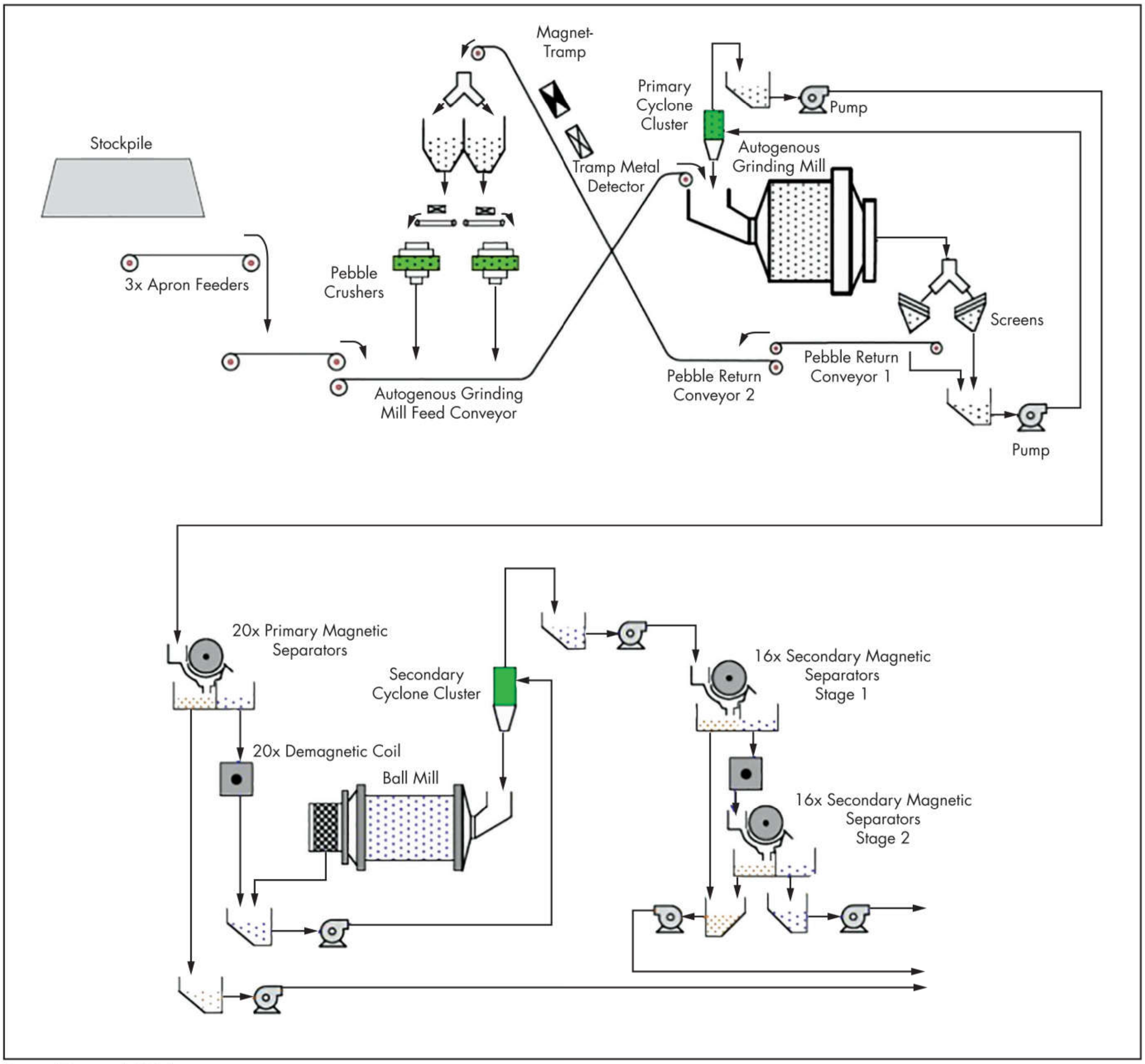
Source: Rosa and Rocha 2015

Figure 16 Arrium flow sheet



Source: Larson et al. 2015

Figure 17 Arrium modified flow sheet



Source: Tian et al. 2015

Figure 18 Sino Iron magnetite flow sheet

Sino Iron

According to Tian et al. (2015) and J. Tian (personal communication; see Figure 18):

> Since 2015, CITIC Pacific Mining has been operating six lines of milling circuits in its Sino Iron plant, each including a 40' × 33' @ 28 MW autogenous grinding mill, the largest in operation in the world. …
>
> [Autogenous] milling is proven a more suitable than [semiautogenous] milling for magnetite processing for the Sino Iron project due to its ability to produce fine product without using grind media. This allows the plant to optimize the grind power balance between the [autogenous] milling and the following regrinding circuit in order to achieve the maximum system milling capacity, by setting the optimal grind size for the [autogenous] milling circuit.

New Zealand

New Zealand has abundant sources of iron ore in its ironsands.

New Zealand Steel

New Zealand Steel operates ironsand mining and beneficiating at its Waikato North Head deposit in Glenbrook and its Taharoa deposit in New Zealand.

Taharoa. The native ironsand dunes are mined by a dredge located within a constructed pond. The dredge houses a concentrator plant with gravity separation by spirals and cones followed by magnetic separation (Buist et al. 1973). The 57% Fe titanomagnetite concentrate, which contains about 7.8% TiO_2, is stored in a surge pile until shipping, using a specially designed ship for loading and transporting iron ore concentrate slurry. Starting in 1972, the concentrate has been reslurried and pumped to the ship through an offshore pipeline to a single mooring buoy. The system was expanded in 1978 (Cooper and Gadd 1980). In 2001, the mine's 250-t (246-lt) dredge, 500-t (492-lt) surge bin, 1,000-t (984-lt) concentrator plant, and ancillary equipment was relocated by road on trailers from the Southern Mining Region across a specially designed haul road to the Central Mining Region (Van Deventer and Rowe 2001).

Waikato North Head. Ironsand with 34% magnetics is processed at 600–2,000 t/h (590–1,968 ltph) by double-drum magnetic separation, scrubbing (to liberate clay slimes), dewatering by cyclones, and vibratory screening to reject coarse unliberated material before gravity separation by cones and spirals (Stevens and Jokanovic 2002) into a 58.8% Fe concentrate.

This concentrate is then reduced with coal by multi-hearth furnaces followed by rotary kilns and then smelted in a submerged arc furnace to produce pig iron for steelmaking. Vanadium is also recovered during the pyrometallurgical process (New Zealand Steel 2016).

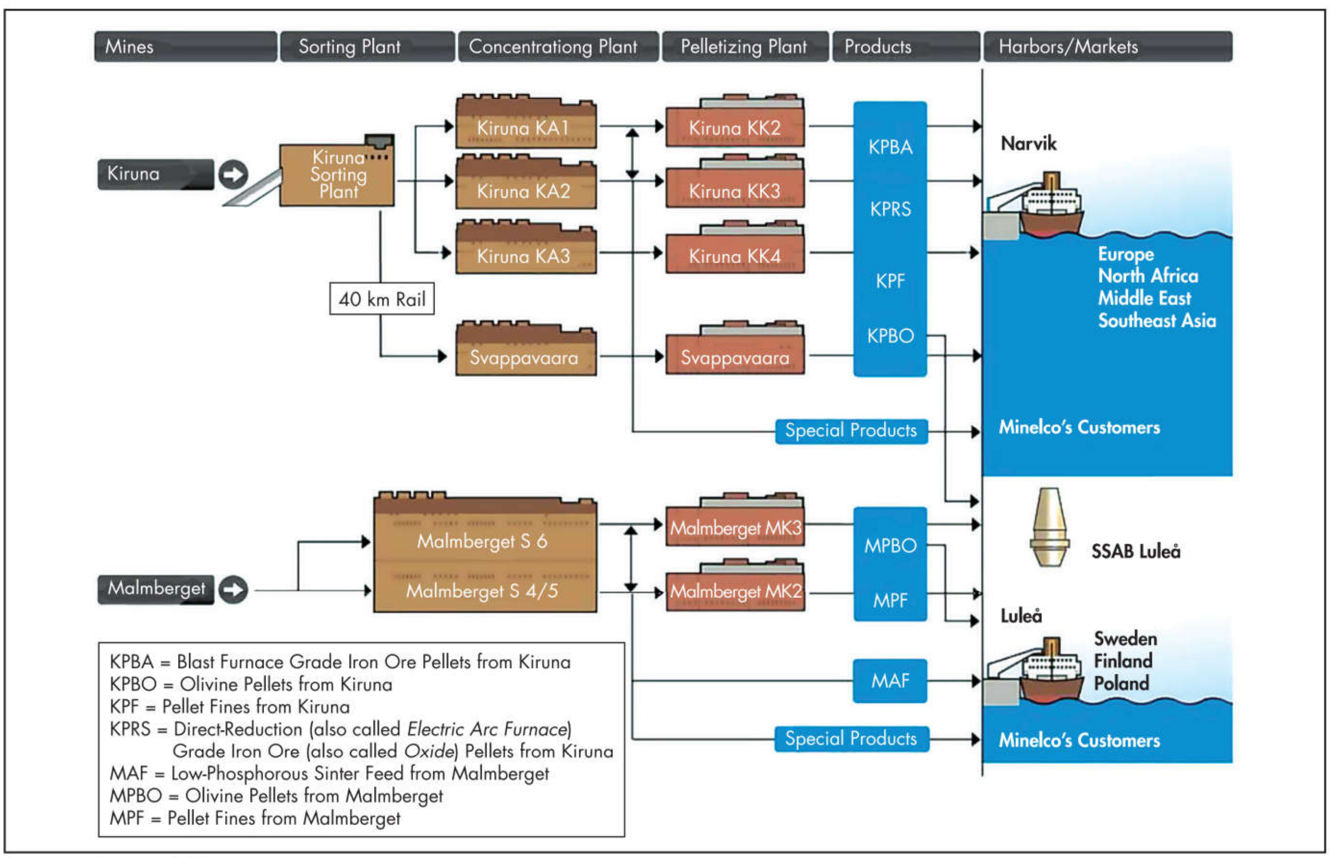
Sweden

Luossavaara-Kiirunavaara AB (LKAB) has been mining in Sweden for more than 120 years (Figure 19). Most of LKAB's ore deposits must be extracted from underground mines, which are several hundreds of meters below the surface, by sublevel caving.

Luossavaara-Kiirunavaara AB

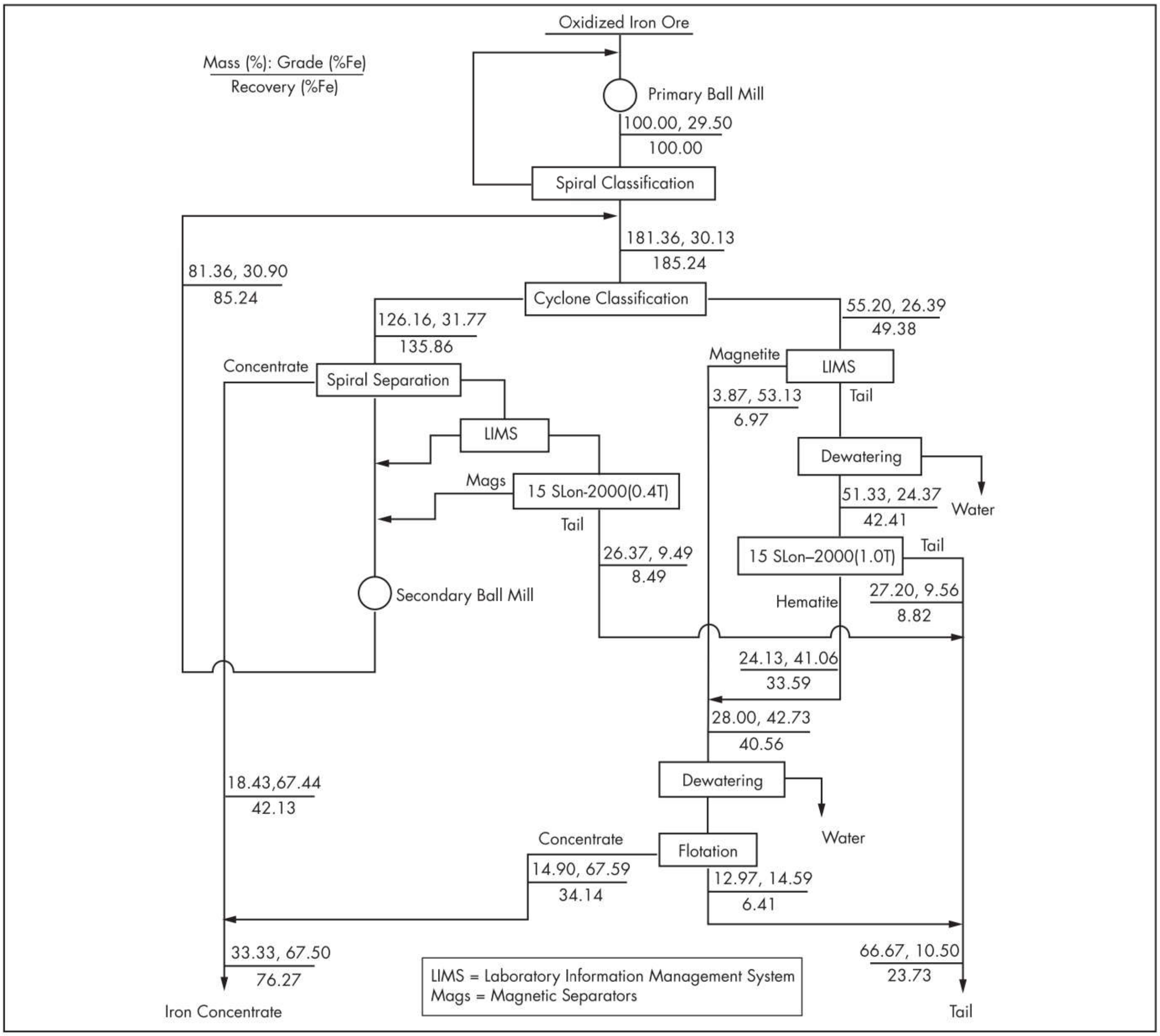
LKAB operates the world's largest and most modern underground iron ore (magnetite) mines at Kiruna, Malmberget, and Svappavaara (LKAB 2013):

> **Kiruna.** The ore body in Kiruna is about 4 km [2.5 mi] long and has a depth of 2 km [1.2 mi]. To date, more than 1 billion metric tons have been mined. A new main haulage level at 1,365 m [4,478 ft] came into operation in 2013 and will secure mining operations for another 20–30 years.
>
> **Malmberget.** The Malmberget mine consists of about 20 ore bodies. The deposits are pure magnetite ore. In the Malmberget mine, a new main haulage level at 1,250 m [4,101 ft] was inaugurated in 2012, which will considerably extend the lifetime of the mine.
>
> **Gruvberget.** The newly opened Gruvberget mine in the Svappavaara ore field is operated as an open pit mine. Production from this mine, together with the planned Leväniemi and Mertainen mines close to Svappavaara, will produce approximately 25% of the company's total output of iron and ore in 2015.



Source: Lindroos et al. 2011

Figure 19 LKAB production facilities



Source: Dahe 2009, reprinted with permission from the Australasian Institute of Mining and Metallurgy

Figure 20 Latest flow sheet for the Diao Jun Tai iron ore processing plant

Beneficiation includes either fully autogenous or semiautogenous grinding, wet magnetic separation, and froth flotation to reject phosphorus. The concentrates are then pelletized by balling and induration in a grate-kiln to produce BF- and EAF-grade products.

Iran

Chadormalu and Gol Gohar iron ore are the two largest iron ore mines (accounting for more than 80% of iron ore production in Iran) (Turquoise Partners 2016). Sangan iron ore mines produce 2.6 Mt/yr (2.5 million ltpy) iron ore concentrate as pellet feed from magnetite ore with 45%–55% Fe by crushing, grinding, low-intensity wet magnetic drum separation (1.3 T [1,300 gauss]), and sulfur froth reverse flotation. Grinding is done in three stages: primary autogenous (up to 700 t/h [689 ltph]), secondary ball milling to 80% –70 µm, and tertiary tower milling (5 mills) to the product size of 80% –38 µm press filtered to 8.5%–9.5% moisture (Middle East Steel 2016).

China

Hematite is the main source of iron ore in China and is difficult to beneficiate (Zou 2007). Low-grade hematite ores containing 18%–26% Fe are typically processed by gravity concentration, low-intensity magnetic separation, high-intensity magnetic separation, and reverse froth flotation (Wei et al. 2011; Liu et al. 2014). Zou (2007) and Dahe (2009) provide details for two Chinese iron ore mineral processing plants and credit two factors for their improved beneficiation: the SLon high-intensity magnetic separator (Outotec 2013) and anionic collectors for reverse silica froth flotation (Figure 20).

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