CHAPTER 6.4

Magnetic Separation

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The science of magnetic separation has experienced exceptional technological advancements in the last three decades. As a consequence, new applications and design concepts in magnetic separation have evolved. This has resulted in a wide variety of highly effective and highly efficient magnetic separator designs, ranging a wide spectrum of industrial applications.

Magnetic separation may be used as an integral part of the primary process or as a secondary or scavenger operation to produce a mineral concentrate. It may also be used in applications involving the removal of tramp metal prior to crushing and grinding systems.

The applications of magnetic separation are diverse and employed in many different industries. It can be used to remove tramp metal, such as shovel teeth or chain in a crusher line, or micrometer-sized iron of abrasion from a high-purity industrial minerals process stream. It may be used to selectively concentrate magnetic components such as magnetite or hematite minerals in an iron ore concentrator. It is also used in removing deleterious magnetic elements to purify nonmagnetic elements such as in the manufacture of ceramics or refractories. In addition, recycling and secondary recovery applications are being developed with increasing interest using magnetic separation as an explicit method for recovering residual values from various process streams and hazardous constituents from waste streams.

MINERAL CHARACTERISTICS

The concept of magnetic separation is based on the ability to magnetize a particular mineral and then physically collect it. The magnetic susceptibility of the mineral is an inherent characteristic directly proportional to the response of a magnetic field and is the single most important variable when addressing the characteristics of magnetic separation.

When subjected to a magnetic field, all particles respond in a particular manner and can be classified as one of three groups: ferromagnetic, paramagnetic, or diamagnetic. Minerals that have a very high magnetic susceptibility and are strongly induced by a magnetic field are ferromagnetic. Following are the few common ferromagnetic minerals that respond to magnetic separation:

- Magnetite
- Titaniferous magnetite
- Monoclinic pyrrhotite
- Martite

Minerals that have a low magnetic susceptibility and a weak response to a magnetic field are termed *paramagnetic*. Following are several common paramagnetic minerals that respond to magnetic separation:

- Biotite
- Chalcopyrite
- Chromite
- Columbite
- Garnet
- Geothite
- Hematite
- Hexagonal pyrrhotite
- Ilmenite
- Monazite
- Siderite
- Specularite
- Staurolite
- Tantalite

Minerals with a negative magnetic susceptibility are termed *diamagnetic* and for all practical purposes are nonmagnetic. Ferromagnetic and, to a lesser extent, paramagnetic materials become magnetized when placed in a magnetic field. The amount of magnetization induced on the particle depends on the mass and magnetic susceptibility of the particle and the intensity of the applied magnetic field. This can be expressed as

$$M = m\chi H$$

where M is the induced magnetization of the particle, m is the mass of the particle, χ is the specific magnetic susceptibility, and H is the magnetic field intensity.

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MAGNETIC UNITS

The subject of magnetics is complicated by the lack of standardization throughout the scientific community on the units of magnetic quantities. The centimeter–gram–second (cgs) system was once prevalent and is still commonly encountered today. There has been, however, a movement to a single comprehensive system known as the International System of Units, abbreviated SI (from the French *Système International d'Unités*), which was officially adopted in 1960. Nearly all modem physics and electrical engineering textbooks as well as technical journals have adopted SI units.

Unfortunately, the conversion between SI units and cgs units is not straightforward. When a choice is to be made between SI units and cgs units, the choice is usually made on the basis of convenience. Because this chapter is for process engineers with a wide range of backgrounds, where appropriate, both systems of units are provided. Magnetic quantities and the associated system of units are a topic in itself. The intent is to provide the most basic understanding of the common units used in magnetic separation.

By convention, magnetic separators are rated on the magnetic induction or flux density. The magnetic induction or flux density is defined by the flux passing through a unit area normal to the direction of the flux. The unit of flux density in the SI system is Weber per square meter, but the term *tesla* (T) has now been adapted. The unit in cgs is measured in gauss (G), or the lines of flux passing through a square centimeter. The following equation can be used to convert the magnetic induction or flux density from SI units to centimeter–gram–second units:

$$H_{cgs} = H_{SI}(10^{-4})$$

or 1 G = 0.0001 T, and conversely, 1 T = 10,000 G.

MAGNETIC SEPARATOR CHARACTERISTICS

In the design of a magnetic separator, the magnetic field intensity and the magnetic field gradient are the two first-order variables that affect separation response. High-intensity magnetic separators typically operate in regions more than 5,000 G (0.5 T). Low-intensity separators are commonly referenced as those separators generating a magnetic field strength of less than 2,000 G (0.2 T), which is the practical limitation of conventional permanent ferrite magnets. The *magnetic field gradient* refers to the rate of change or the convergence of the magnetic field strength (Figure 1).

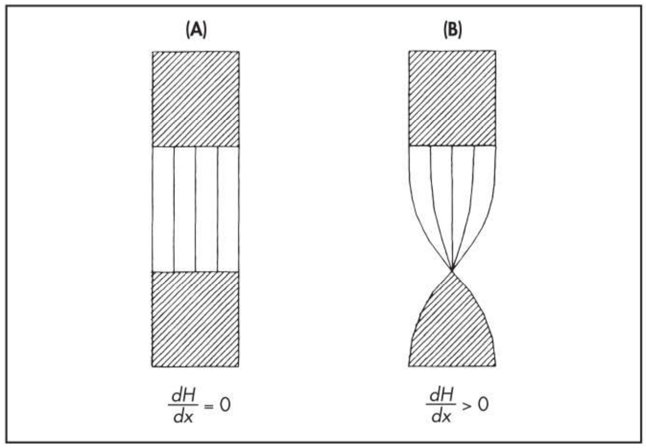


Figure 1 Magnetic field configurations

Case A has a very uniform pattern of flux lines without gradation. A magnetic particle entering this field is attracted to the lines of flux and remain stationary without migrating to either pole piece. Case B illustrates a converging pattern of flux lines displaying a high gradient. As these lines pass through a smaller area, there is a significant increase in the magnetic field intensity. A magnetic particle entering this field configuration is not only attracted to the lines of flux but also migrates to the region of highest flux density, which occurs at the tip of the bottom pole piece. This illustrates the methodology for magnetic separation. In simplified terms, the magnetic field intensity holds the particle while the magnetic field gradient moves the particle.

From the earlier equation for magnetization, the magnetic attractive force acting on a particle is the product of the particle magnetization and the magnetic field gradient and can be expressed as

$$Fm = m\chi H\frac{dH}{dx} \text{ or } M\frac{dH}{dx}$$

where Fm is the magnetic attractive force, and dH/dx is the magnetic field gradient. Maximum magnetic dx force results only when both the magnetic field intensity and field gradient are maximized.

Two common methods for producing a magnetic gradient in a magnetic separator exist. The first method, which is typical of magnetic circuits utilizing permanent magnets, is to concentrate the lines of flux on a steel pole piece within the circuit. This can be simply accomplished by placing a steel pole piece between two magnets. The magnetic flux is concentrated in the steel pole piece, resulting in an area of extreme magnetic field intensity.

The second method involves positioning a steel matrix, such as a metal mesh, directly in a uniform magnetic field generated by an electromagnetic solenoid coil. This matrix consequently amplifies the magnetic field and converges the lines of flux to produce localized regions of extremely high magnetic field intensity.

MAGNETIC FIELD GENERATION

Either permanent magnets or an electromagnet generates the magnetic field on any given magnetic separator. When addressing the historical aspects of magnetic separation, a strong differentiation exists between the developments of those separators utilizing permanent magnets and those separators using electromagnets. The two separators were developed independently and oftentimes in competition.

Ferrite Permanent Magnets

Two distinct types of permanent magnets are utilized in magnetic separators. The first type of permanent magnet is a *ferrite* magnet and is used in low-intensity magnetic separators. The formulation is $SrFe_{12}O_{19}$. Ferrite is an inexpensive material with a moderate energy product ranging up to 32 kJ/m^3, or 4 MGOe (mega-gauss-oersted; Supermagnete, n.d.). The energy product of a permanent magnet is a relative measure of the intrinsic strength. Ferrite magnets are primarily used in drum-type separators that are used for collecting ferrous material as well as magnetite and pyrrhotite. These separators generate a magnetic field strength ranging up to 2,000 G (0.2 T).

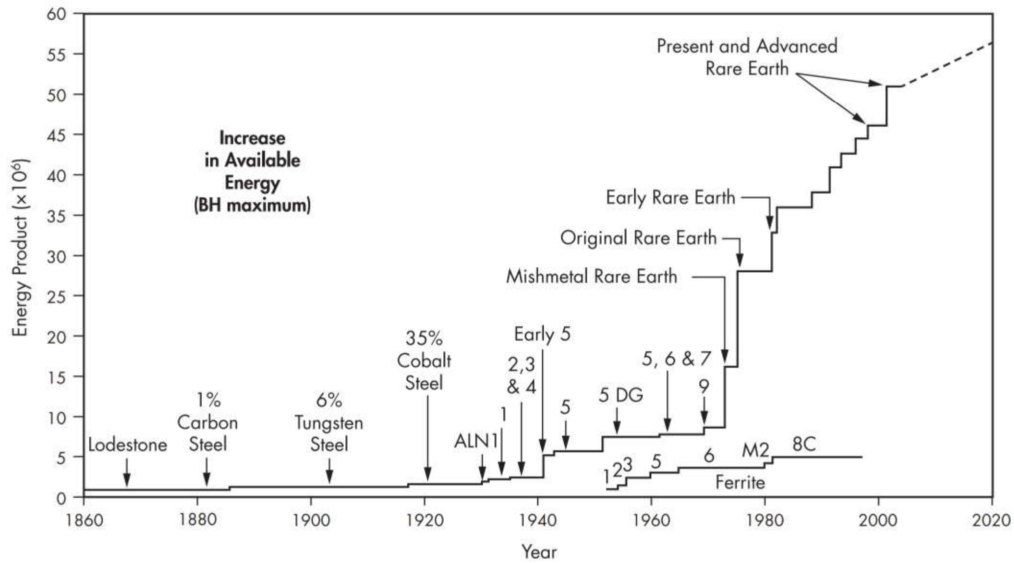


Figure 2 Chronology of permanent magnets

Rare Earth Permanent Magnets

The development of rare earth permanent magnets has revolutionized the field of magnetic separation. The advent of rare earth magnets has allowed for the design of high-intensity magnetic circuits operating energy free and surpassing the strength and effectiveness of electromagnets. Samarium and neodymium are the two most common elements used in the commercial manufacture of rare earth permanent magnets. The intermetallic compound $Nd_2Fe_{14}B$ is the third generation of rare earth magnets and is most prevalent today.

Neodymium magnets are experiencing tremendous growth. Much of the growth is strictly caused by the economics of using a much more abundant rare earth (neodymium is 10 times more abundant than samarium), coupled with inexpensive iron and boron. The energy product of the neodymium-based magnets now ranges up to 422 kJ/m^3, or 53 MGOe (Supermagnete, n.d.). Rare earth magnets are used in high-intensity drum- and roll-type separators that are effective for collecting paramagnetic minerals. Dependent on the magnetic circuit, these separators generate a magnetic field strength ranging up to 24,000 G (2.4 T). Presented in Figure 2 is a chronology of permanent magnets illustrating the increase in energy product.

Electromagnets

Industrial electromagnetic separators are typically designed utilizing a solenoid electromagnetic coil. Some separators use the bore of the solenoid coil as the separating zone. Other separators use the solenoid coil to convey the magnetic flux through a steel circuit or a C-frame circuit. The magnetic field in the gap, either the bore of the solenoid or the gap of the C frame, serves as the separation zone in a magnetic separator. Several operational factors have to be taken into consideration with a production magnetic separator designed for continuous use. There has to be a balance between the magnetic field strength, the associated steel circuit, the power requirements, and cooling factors.

Production-scale electromagnetic separators always employ a steel circuit to convey the magnetic flux and to pattern the magnetic field in the separating zone. The steel circuit tremendously enhances the magnetic field strength in the separating zone. The power input to the separator must also be designed to avoid saturating the steel circuit and overheating the electromagnet. Typically, electromagnetic separators operate up to approximately 20,000 G (2 T). At this magnetic field strength, the iron circuit begins to saturate.

MAGNETIC SEPARATION SYSTEMS

Both electromagnets and permanent magnets are used in separation systems. The following sections provide more detailed information.

Magnetic Field Generation

Two distinct methods can be used to generate a magnetic field. The first method, which has a long history, is the use of an electromagnet. Electromagnets employed in magnetic separators are almost exclusively solenoid coils. The second method is the use of a permanent magnet. Both methods of magnetic field generation have application in the advanced magnetic separation techniques of today. Each type of magnet, with its associated circuit design, has many parameters of distinction. In most instances, a specific type of magnetic circuit is selected to accommodate the application.

Mode of Separation

Two basic modes of magnetic separation systems exist. The first mode is the use of magnetic separation for the removal of tramp iron from a process stream. The second mode is the use of magnetic separation as an integral unit operation in the recovery process.

Tramp Metal Removal

The removal of tramp metal from a process stream is the most common application of magnetic separation. This application is straightforward and well documented. Following is an overview of this methodology. The basic premise is that tramp metal or ferrous contamination is present to some extent in all bulk materials. This contamination must be removed to (1) protect downstream equipment from potential damage, (2) ensure product quality, and (3) protect against fire or explosions in the process line.

Tramp metal may commonly originate in the following forms:

- Metal parts from earthmoving equipment
- Wire, cable, chain, reinforcing bar, or support structures from mining or quarrying operations
- Nails, clips, strapping, or other hardware from shipping containers
- Welding rod, nuts, bolts, and washers, or other hardware inadvertently introduced from maintenance and repair procedures
- Rust, chips, and fine iron of abrasion continually eroding from pipe lines, chutes, bins, and process equipment

When there is only an occasional piece of tramp metal or a very low level of ferrous contamination, a manual clean magnetic separator suffices. These separators are stationary systems utilizing either permanent or electromagnets to generate the magnetic field. The magnet effectively captures the tramp metal and holds it until it is manually removed.

A relatively large amount of ferrous contamination present in the process stream necessitates more frequent removal of the collected ferrous tramp. At this point, a self-cleaning separator such as a magnetic drum or a magnetic pulley is recommended.

Integral Separation

Magnetic separation as an integral unit process is used in many industries. The most notable applications are minerals, abrasives, ceramics, and secondary recovery processing. In these types of applications, the magnetic fraction and the nonmagnetic fraction may occur as a homogeneous blend. The magnetic separator is therefore subjected to continuous operation performing a continuous separation. In one case, the magnetic fraction can represent the product, and upgrading can take the form of the magnetic collection and recovery of the magnetic minerals. In another case, the nonmagnetic fraction can represent the product and upgrading can take the form of the magnetic removal of deleterious iron-bearing constituents from nonmagnetic minerals.

In some applications, the magnetic fraction represents the value. This is most prevalent in the concentration and recovery of iron-bearing magnetic minerals such as magnetite (Fe_3O_4) and hematite (Fe_2O_3). Iron ore concentrators typically treat thousands of tons per hour of milled ore, recovering the magnetic iron-bearing minerals from the nonmagnetic host rock.

Magnetite and ferrosilicon (FeSi) are commonly recovered from heavy media operations using magnetic separators. Other common magnetic minerals of value that are treated on large economies of scale are ilmenite ($FeTiO_3$) and chromite ($FeCr_2O_4$).

In other applications, the nonmagnetic fraction represents the value. The most notable application is the magnetic cleaning of industrial minerals such as silica, quartzite, feldspar, nepheline syenite, and fluorspar used as glass batch feedstock material. In these types of applications, the product has to essentially be free of iron-bearing particles. Increasingly, there is also a demand for higher-purity feedstock materials used in the manufacture of items such as specialty ceramic components, insulators, substrates, refractories, electrical components, specialty glasses, optical fibers, and grinding and polishing compounds. The brightness of kaolin clay used for paper coating is increased by removing paramagnetic contaminants.

The integral unit process necessitates a self-cleaning separator. Magnetic drums, pulleys, and roll-type separators are widely used as well as high-intensity and high-gradient matrix-type separators. For all practical purposes, magnetic separator selection can be reduced to the decision tree illustrated in Figure 3. The first node indicates that the separation is either tramp metal removal or an integral separation. The integral separation has subsequent nodes to indicate if the mineral is to be treated as either a slurry or as dry and free-flowing and the magnetic field strength necessary for effective separation.

MAGNETIC SEPARATORS FOR TRAMP METAL COLLECTION

Stationary, suspended, and trunnion permanent magnet separators are all used for tramp metal collection. Details of each of these magnets are provided in the following sections.

Stationary Permanent Magnetic Separators

The most enduring design incorporates simplicity. This is certainly the case when addressing stationary permanent magnetic separators. These separators, specifically plates, grates, and traps, represent the first industrial application of magnetic separation and perhaps the most prevalent type of separator in use today. These separators perform very well in removing tramp metal from a process and protecting downstream equipment as well as ensuring product quality.

Stationary permanent magnetic separators are configured with the common names of *plate*, *grate*, or *trap* and are illustrated in Figures 4, 5, and 6. These are simply enclosed barium ferrite or rare earth permanent magnets. The process stream flows over, around, or through the permanent magnets, and ferrous tramp metal is collected and held. For example, plate magnets are permanent magnets in a stainless-steel fixture and installed in a chute. Grate magnets are permanent magnets in stainless-steel tubes. Material flows around the tubes when placed in a dry process stream. Although trap magnets are also permanent magnets in stainless-steel tubes, this type of separator is placed in line with a slurry stream and the slurry flows around the tubes.

The prevalence of stationary permanent magnets can be attributed to several characteristics. They provide inexpensive insurance in the removal of tramp metal, which protects downstream equipment, such as mills, crushers, shredders, granulators, mixers, and fine screens, from potential damage. They are relatively low cost compared to most other types of magnetic separators. Permanent magnets are used to generate the magnetic field and require no utility for operation: There is no operating cost. Maintenance costs are virtually eliminated because there are no moving parts.

Suspended Magnetic Separators

When addressing the magnetic collection of tramp metal, the suspended electromagnet (SE) is undoubtedly the industry workhorse. Figure 7 shows a standard manual-cleaning SE; this separator has a deep magnetic field to effectively remove tramp ferrous iron. The SE is a widely used magnetic separator.

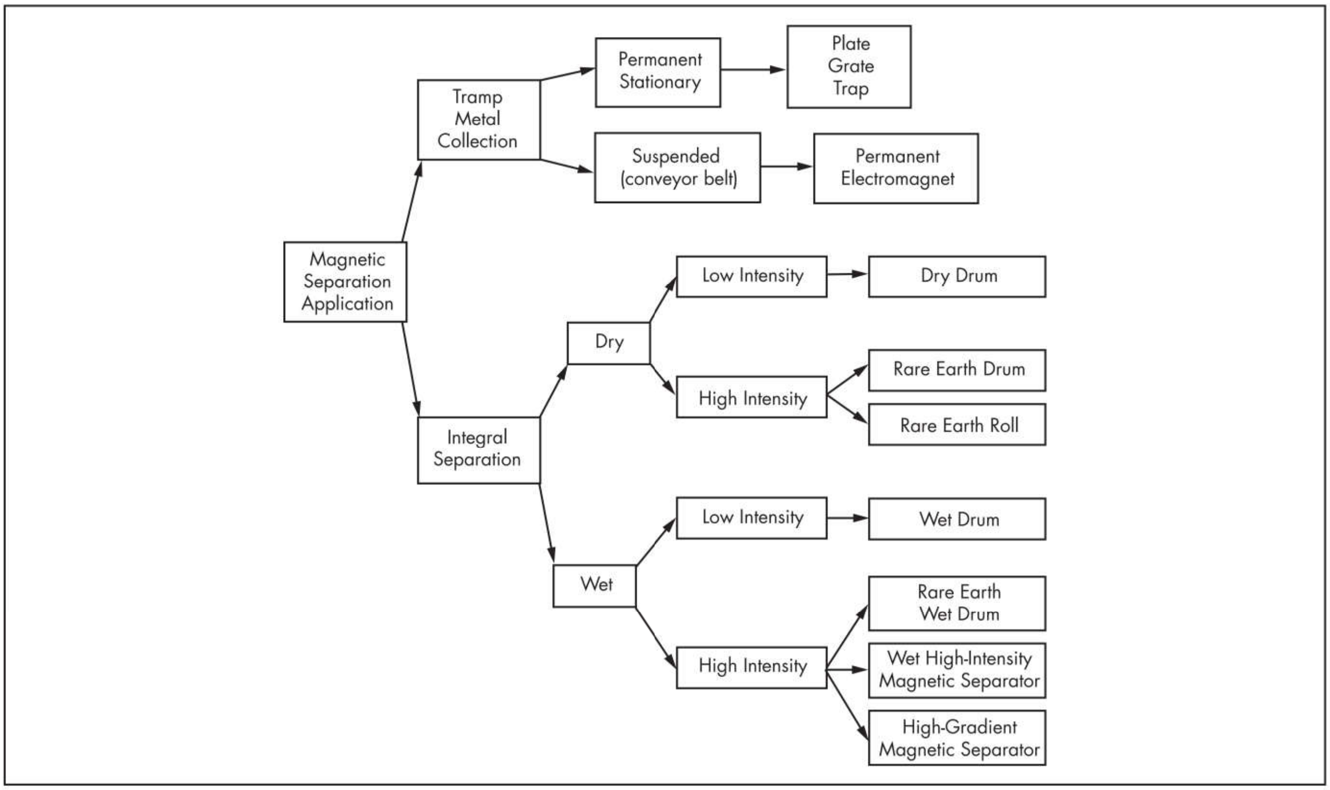


Figure 3 Magnetic separation decision tree

Figure 4 Plate magnet

Figure 5 Grate magnet

The electromagnet is mounted or suspended over a conveyor belt to remove relatively large pieces of tramp metal that represent a potential hazard to downstream crushers, mills, and grinders. The SE consists of an aluminum conductor coil with a cylindrical steel core. The coil magnetically induces the steel core, which in turn configures the magnetic field for the collection of tramp metal from a moving conveyor belt. The coil is housed in a steel box that has the dual purpose of protecting the coil and completing the steel circuit. The coil is submerged in an oil bath within the housing to provide convection cooling. A rectifier is used to supply direct current to the magnet. Specifications of selected SEs are shown in Table 1.

Suspended Magnetic Separator Applications

The largest market for SEs is in coal mining, hard-rock mining, and aggregate products for removing shovel teeth, cable, tools, and bolting prior to crushing and grinding. The foremost factor in SE selection is the burden depth of the material on the conveyor belt. The burden depth accounts for the belt speed, belt width, capacity, and bulk density and determines the suspension height of the magnet and consequently the effective magnetic field strength at the belt surface. SEs are mounted in one of two positions over a conveyor belt, as shown in Figure 8. In position 1, the magnet is mounted directly over the conveyor belt prior to the head pulley and treats the entire

Figure 6 Trap magnet

Figure 7 Suspended electromagnet

material burden on the belt. This position requires higher magnetic field strengths to attract the ferrous component, shift the direction of momentum, and pull it through the bed of material.

In position 2, the magnet is mounted just over the stream of material leaving the head pulley and treats the material as it discharges from the belt. This position utilizes the full potential of the magnet as it reacts with the material in suspended trajectory. Tramp metal is easily pulled through the suspended burden. Further, the flow of material is directed toward the magnet face. Collection of the tramp metal from the material flow does not necessitate a change in direction. At conveyor belt speeds of less than 100 m/min, the suspended trajectory of the material is minimal and becomes near vertical. In this case, the magnet must be shifted to a position approaching directly over the head pulley.

SEs are available in either a manual cleaning style or a self-cleaning style. Manual-cleaning magnets are best suited where only small amounts or occasional pieces of tramp metal are encountered. The manual-cleaning magnets must be periodically turned off to remove tramp iron accumulation from the magnet face.

Self-cleaning magnets employ a cross-belt running around the magnet face to provide continuous removal of

Table 1 Suspended electromagnet specifications

Belt Width, m	Weight, kg	Power, W
0.9	823	3,800
1.2	1,916	6,300
1.5	3,731	9,940

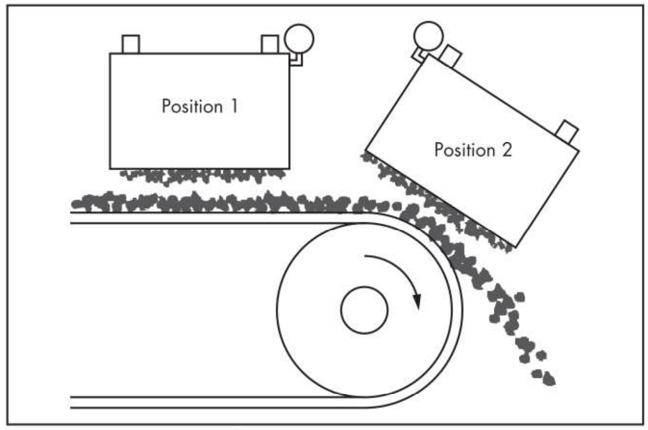


Figure 8 Positioning of suspended magnet

collected tramp iron. When tramp metal is attracted to the magnet face, the cross-belt intercepts it and discharges it to the side away from the conveyor belt. The self-cleaning magnet is best suited where a high level of tramp iron or large pieces of tramp iron are anticipated. The cross-belt is continuously driven around the magnet on a system of four pulleys driven with a small gearmotor.

In most applications, the magnet is suspended 5–8 cm over the top of the burden. Experience dictates that the operating magnetic field strength or the magnetic field strength at the belt surface should be 400–600 G (0.04–0.06 T) for adequate ferrous collection. As the magnet width increases to accommodate the belt width, the magnetic field strength increases at any given distance. A wider magnet simply has a larger core and coil.

Exceptions to the sizing of the SE exist. The response of the magnet is influenced by the following factors:

- **Belt speed.** As the belt speed increases, it becomes increasingly difficult to attract and collect ferrous components. This is especially difficult when the magnet is situated in position 1 where the momentum of the ferrous component has to change direction.
- **Burden depth.** As the burden depth increases, an increase in the magnetic field strength is required. A ferrous component situated on the surface of the belt, buried under a heavy burden, requires an increased magnetic attractive force for collection.
- **Size of ferrous component.** The suspension height of the magnet must be increased if relatively large ferrous components are anticipated. The suspension height of the magnet, with the ferrous component attracted to the face, must clear the burden on the conveyor belt and not impede the flow of material. The higher suspension height requires a stronger magnet to maintain the magnetic field strength at the working distance.

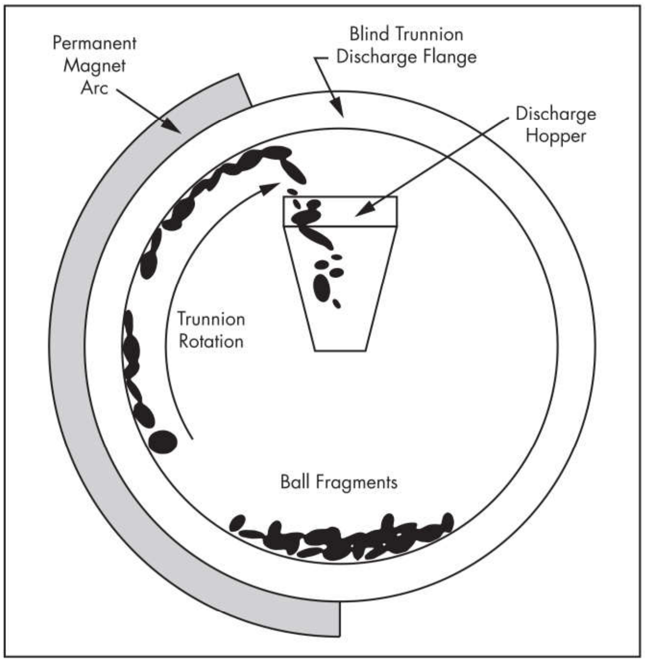


Figure 9 Trunnion magnet

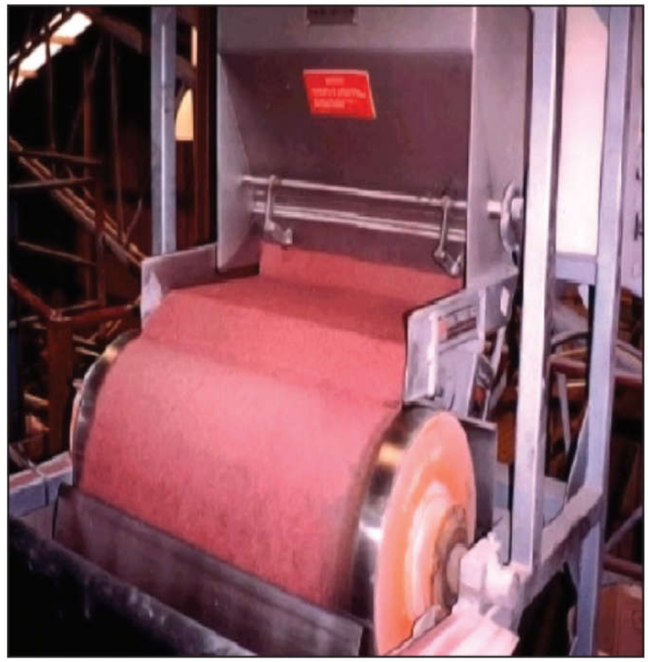


Figure 10 Drum-type magnetic separator treating garnet concentrate

- **Shape of ferrous component.** The shape of the ferrous component is also a factor. Steel plate, for example, has a high surface area relative to its weight. This configuration reacts with a high magnetic attractive force when exposed to a magnetic field. In contrast, a sphere has the lowest surface area relative to its weight. This configuration reacts with a minimal magnetic attractive force.

As conveyor belts are increasing in width and speed to provide greater capacity, the magnets have had to increase in size and strength. Conventional suspended magnets weighing as much as 88 t (metric tons) are in service. For extremely demanding duty at a Chinese coal port, suspended magnets using superconducting coils have been installed. These generate a magnetic field of 4,000 G (0.4 T) at 500 mm from the magnet face. Protection of the pebble crusher commonly used in semiautogenous grinding mill comminution circuits is a typical application for self-cleaning SEs. The large grinding balls and chips can quickly damage the cone crusher.

Permanent suspended magnets are also available where operational conditions suffice. The advantage of a permanent suspended magnet is that it operates energy free without peripheral equipment. The drawback of a permanent magnet is that it cannot generate the depth of magnetic field required for treating high burden depths on the conveyor belt. The range of the burden depth is from 13 to 23 cm corresponding to a maximum suspension height of 20–30 cm. At these operating distances, the permanent magnet rivals the electromagnet.

Trunnion Magnets

A more recent development is the trunnion magnet, illustrated in Figure 9. This specific design removes balls and ball chips contained in the discharge of a ball mill. Removal of this unwanted steel not only reduces the damage to the pumps and hydrocyclones but can also increase the capacity of the mill by reducing the volume of steel in the mill. The trunnion magnet consists of a barrel that is attached to the rotating ball mill discharge trunnion and a 180-degree arc of stationary permanent magnets. The magnets attract and hold the steel to the inside of the rotating barrel where they are conveyed out of the mineral flow to the top of the trunnion where they are released and fall onto a chute that discharges them into a waste container. Typically, several tons of ball chips are removed from the mill during the initial days after installation, but then the system stabilizes and the discharge of chips is reduced.

INTEGRAL SEPARATION

The following sections discuss magnetic separators for the concentration and recovery of minerals, also known as *integral separation*.

Magnetic Drum Separators

The magnetic drum separator consists of a stationary, shaft-mounted magnetic circuit completely enclosed by a rotating drum. The magnetic circuit is typically comprised of several magnetic poles that span an arc of 120 degrees or more. When material is introduced to the revolving drum shell (concurrent at the 12 o'clock position), the nonmagnetic material discharges in a natural trajectory. The magnetic material is attracted to the drum shell by the magnetic circuit and is rotated out of the nonmagnetic particle stream. The magnetic material discharges from the drum shell when it is rotated out of the magnetic field. A magnetic drum separator is shown in Figure 10.

Separation Variables

The magnetic attractive force generated by a drum-type separator is opposed by centrifugal force. The primary variables affecting separation efficiency are the magnetic field strength,

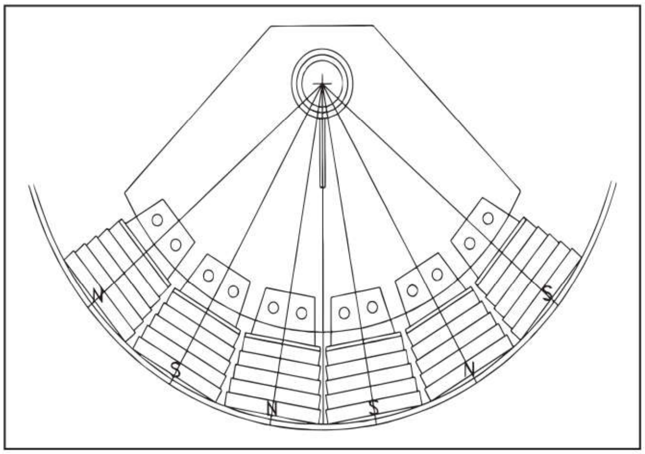


Figure 11 High-gradient magnetic element

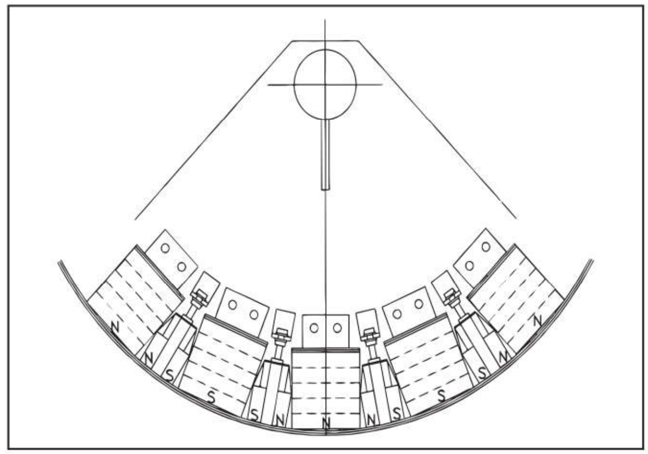


Figure 12 Interpole magnetic element

feed rate, linear speed of the separator surface, and particle size. An effective separation requires an equilibrium among the variables described as follows:

- A balance must be struck between an economic feed rate, product specifications, and recovery. As the feed rate increases, the layered particle bed on the separator surface increases in height, and the collection of magnetics decreases.
- The linear speed of the drum is also a primary variable related to the feed rate. As the linear speed is increased, the layered particle bed decreases in height, responding with an improved collection of the magnetic particles.
- The centrifugal force exerted by the drum or roll surface is the critical factor in providing separation. Beyond the critical speed, the centrifugal force overcomes the magnetic attractive force and the separation efficiency deteriorates.
- Particle size also affects separation efficiency independent of all other variables. Coarse particles provide a relatively high burden depth on the separator surface and respond with a relatively high magnetic attractive force.
- Coarse particles typically provide high unit capacities with high separation efficiencies. Fine particles with relatively low masses respond detrimentally to electrostatic forces. As a consequence, precise magnetic separations balancing magnetic forces against centrifugal forces deteriorate.

Dry Magnetic Separators

Dry magnetic separators include drum- and roll-type machines, both low and high intensity.

Low-Intensity Drum Type

Low-intensity drum magnetic separators are effective in collecting ferromagnetic materials and are used in various applications in the minerals processing industries. These separators combine the attributes of the permanent magnetic field with the self-cleaning feature. Magnetic drum-type separators are a staple in many mineral processing industries and are commonly used in two different modes of operation. The separator is equally effective in a treating a process stream for (1) concentrating and recovering a magnetic mineral and (2) rejecting magnetic minerals to produce a *clean* nonmagnetic mineral product.

An array of magnetic elements are available. Agitating magnetic elements are used in most integral applications where a clean magnetic product is desirable. The magnetic poles have alternating polarity to provide agitation. The agitating-type element minimizes the loss of nonmagnetics to the magnetic product (termed *misplacement*) because of physical entrapment.

In drum-type magnetic separators, two basic types of magnetic circuits are used. Figure 11 is a schematic of a low-intensity, high-gradient magnetic element consisting of alternating polarity magnetic poles. This element produces a high magnetic gradient near the surface of the drum, which measures 0.9 m in diameter.

The *high-gradient* element, as the name implies, is designed to produce very high magnetic field gradient and subsequently high attractive force. Several identical magnetic poles comprise the element. The poles are placed together, minimizing the air gap between them to produce the high surface gradient. Because of the high gradient, the attractive force is strongest closer to the drum, making it most effective when utilized with a relatively low material burden depth on the drum surface and lower unit capacity.

The interpole-style element uses a true ceramic *bucking* magnetic pole or *interpole* between each main pole. The magnetic field of the bucking elements are charged to oppose both of the adjacent main poles, resulting in increased magnetic field at depth. Therefore, the interpole elements allow relatively high material burden depths on the drum surface and thus higher unit capacity or improved separation efficiency in difficult applications. Figure 12 is a schematic of an interpole magnetic element. The interpoles oppose the polarity of the main poles to produce a deep magnetic field. Depending on the application, there are several variations of these two basic magnetic circuits. Table 2 presents general specifications of magnetic drum separators.

Magnetic drum separators incorporating either a radial or agitating magnetic element are commonly used to collect tramp metal from a mineral stream. The element typically contains large strontium ferrite poles to provide depth of field as well as a high surface gradient. This is necessary

Table 2 General specifications of magnetic drum separators

Drum Type	Attributes	Applications	Unit Capacity
Radial or agitating magnetic circuit for tramp metal collection	Radial or high-gradient agitating magnetic element using strontium ferrite magnets. Magnetic element designed to produce a deep magnetic field; 1,200 G (0.12 T) magnetic field strength on surface; 0.8 m/s drum speed; 0.4–0.8 m diameter.	Widely used drum throughout industries. Functional for tramp metal and iron of abrasion removal. Effective in removing large tramp metal such as nuts and bolts at high capacity. Effective in removing fine iron of abrasion at relatively low capacities.	Tramp metal applications can operate at high capacity; 0.4-m-diameter drum operates at 20–26 t/h/m width; 0.6-m-diameter drum operates at 30–40 t/h/m width. Reduce capacity by 50% for fine iron of abrasion.
Agitating magnetic circuit for coarse material up to 25 mm top size	High-gradient agitating magnetic element using strontium ferrite magnets; 1,200 G (0.12 T) magnetic field on drum surface; 10–15 magnetic poles with wide (8–10 cm wide) spacing. Magnetic element designed to produce a deep magnetic field. Up to 2.5 m/s drum speed; 0.9 m diameter.	Provides preconcentration of coarse ores up to 25 mm top size. Applications include magnetite recovery from iron ore and metallics recovery from slag.	Coarse minerals of 6–25 mm can generally be treated at high capacities. Unit capacities ranging up to 80 t/h/m width.
Agitating magnetic circuit for coarse material to 6 mm top size	High-gradient agitating magnetic element using strontium ferrite magnets. 1,100 G (0.11 T) magnetic field on drum surface; 20 magnetic poles with wide (5–8 cm wide) spacing. Magnetic element designed to produce a deep magnetic field. Up to 5.0 m/s drum speed; 0.9 m diameter.	Provides cleaning or concentration of minerals in the 100 mesh to 6 mm top size. Applications include cleaning industrial minerals such as alumina and silicate minerals; also magnetite recovery from iron ore and metallic recovery from slag.	Coarse minerals (6 mm) can be treated at unit capacities up to 65 t/h/m width. Minerals in the 100 mesh range can be treated at unit capacities up to 33 t/h/m width.
Agitating magnetic circuit for fine material (–100 mesh)	High-gradient agitating magnetic element using strontium ferrite magnets; 1,000 G (0.1 T) magnetic field on drum surface; 30–40 small magnetic poles with narrow (2–4 cm wide) spacing. Up to 7.6 m/s drum speed; 0.9 m diameter.	Provides cleaning or concentration of minerals in the –100 mesh size range. Applications include upgrading magnetite from milled preconcentrates, magnetite recovery from fly ash, and upgrading iron carbine.	High drum speed maintains a low burden depth, allowing unit capacities up to 33 t/h/m width.
Salient pole rare earth	Salient pole agitating magnetic element using rare earth magnets; 7,000 G (0.7 T) magnetic field on drum surface; 0.4, 0.6, 0.9, and 1.2 m in diameter. Magnetic element employs 5–12 magnetic poles spanning a 110-degree arc.	Effective in magnetically collecting an entire range of paramagnetic minerals such as hematite, specularite, and ilmenite. Effective in cleaning industrial minerals such as silica, quartzite, feldspar, nepheline syenite, alumina, and zircon.	Minerals in the 100 mesh range can be treated at unit capacities of 10–16 t/h/m width on a 0.4-m-diameter drum, 16–23 t/h/m width on a 0.6-m-diameter drum, and 26–33 t/h/m width on a 0.9-m-diameter drum.

to attract and hold ferromagnetic components when operating at a high burden depth. These separators can operate at high capacity when utilized for tramp metal such as nuts and bolts. A 0.6-m-diameter drum can operate at a unit capacity up to 40 t/h/m of drum width. The unit capacity is reduced by 50% for the collection of iron of abrasion.

Low-intensity drum separators for mineral separation applications combine a large-diameter drum of 0.9–1.2 m, with an agitating element and a high drum speed. This combination provides a high-capacity separation with a high level of precision. The separator typically incorporates an axial agitating (alternating polarity high-gradient style) magnetic element that spans 180–210 degrees. Strontium ferrite magnets are used for the collection and recovery of ferromagnetic materials. The high drum speed in combination with many agitating magnetic poles provides a high level of agitation as the ferromagnetics are transferred along the drum surface. This results in a near-complete rejection of nonmagnetic material, subsequently producing a very clean ferromagnetic concentrate.

The magnetic drum separators operate completely enclosed in housing. The housing incorporates a feed bin with an adjustable gate to deliver a controlled feed rate across the width of the drum. The housing also has magnetic and nonmagnetic product discharge chutes. The only utility necessary is the electrical input for the drive system. The parallel shaft gearmotor that drives the drum is mounted on the housing. The drive system uses a V-belt drive, which offers protection to both the motor and the drum shell in the event of a jam from oversize material. In many cases, the drive is controlled with a variable-frequency controller to allow variations in the drum speed. The 0.9- and 1.2-m-diameter drums typically have drum widths up to 3.0 m. The drive motor ranges from 3.7 to 18.6 kW, depending on the magnetic circuit configuration drum speed and width of the drum.

Coarse particles ranging in size from –25 mm to +6 mm respond well to a magnetic circuit employing large, wide magnetic poles. This magnetic circuit generates a *deep* magnetic field, effectively capturing coarse ferromagnetic or composite minerals. Coarse iron ore (magnetite) can be treated at a relatively high unit capacity. As an initial magnetic separation, the separator rejects a nonmagnetic product relatively free of iron while recovering the magnetite as a rougher concentrate. This concentrate represents an intermediate grade, containing locked particles, and requires milling to further liberate the iron minerals.

Crushed copper slag also responds well to this separator. The major component in this slag is iron-bearing fayalite, which constitutes approximately 90% of the feed. The fayalite is recovered as the magnetic fraction while the metallic copper is rejected as a nonmagnetic concentrate. Coarse slags and

Table 3 Applications and unit capacities of rare earth drums

Application	Feed Size	Drum Diameter, m	Unit Capacity, t/h/m of drum width
Preconcentrating hematite	–6 mm	0.6	66
Recovering specularite from a gravity concentrate	–35 mesh	0.6	13
Recovering final ilmenite product from heavy mineral concentrate	–35 mesh	0.4 0.6	10–13 13–16
Recovering high-iron ilmenite from low-iron ilmenite	–35 mesh	0.6	20
Recovering ilmenite from roasted concentrate	–4 mesh	0.9	33
Tabular alumina	–6 mesh +48 mesh	0.4	23
Cleaning tabular alumina	–48 mesh +325 mesh	0.4	16
Cleaning tabular alumina	–48 mesh	0.4	10
Cleaning silica and feldspar	–28 mesh	0.4 0.6	10–13 13–16
Cleaning garnet	–48 mesh	0.4	13–16
Collecting nickel bearing pyrrhotite from crushed nickel ore	–100 mm	0.9	66
Recovering metallic nickel from slag	–10 mm	0.9	40

iron ores are treated at a unit capacity of 80–115 t/h/m of drum width on a 0.9-m-diameter drum.

Fine particles in the size range of –100 mesh respond well to a magnetic circuit employing small, narrow magnetic poles. The magnetic circuit may consist of up to 40 separate magnetic poles providing a very high degree of agitation as the material is transferred through the magnetic field. Applications in these size ranges include iron ores as well as intermediate grade concentrates, slags, fly ash, ferrosilicon, and iron carbide. Iron ores and concentrates are treated at a unit capacity up to 33 t/h/m of drum width on a 0.9-m-diameter drum. Fly ash, which is very fine and has a low bulk density, is treated at a unit capacity of 16–25 t/h/m of drum width on a 0.9-m-diameter drum.

High-Intensity Drum Type

The high-intensity rare earth drum magnetic circuit is comprised of segments of alternating rare earth magnets and steel pole pieces. The steel poles are induced and project a high-intensity, high-gradient magnetic field. The peak magnetic field intensity on the drum is approximately 7,000 G (0.7 T) and is effective in removing many paramagnetic constituents.

The rare earth drum was developed to meet several operational objectives. Initially, the project focused on the dry treatment of ilmenite and hematite. It was anticipated that the separator could provide high capacity with relatively low capital and operating cost. Test work carried out on the prototype separator demonstrated that this design effectively recovers ilmenite from a heavy mineral concentrate and hematite from siliceous gangue. The unit capacities far exceed the typical capacities of cross-belts and induced magnetic roll separators. Currently, the applications utilizing the rare earth drum magnetic separator are diverse. Although many of the units are used primarily for the recovery and concentration of paramagnetic minerals, most are used for removing deleterious iron-bearing minerals from process streams such as alumina, silica, and feldspar. These various applications have confirmed that the rare earth drum is effective in treating a wide range of particle sizes and operates at relatively high capacities. Table 3 presents the unit capacities of specific applications using the rare earth drum magnetic separator.

High-Intensity Roll Type

The rare earth roll, generating peak magnetic field strengths in excess of 21,000 G (2.1 T), is very effective for concentrating or removing weakly magnetic minerals from a dry process stream. The rare earth roll magnetic separator is designed to provide peak separation efficiency and is typically used when a high-purity product is required. The roll is constructed of disks of neodymium–boron–iron permanent magnets sandwiched with steel pole pieces. The steel poles are magnetically induced to the saturation point of approximately 21,000 G (2.1 T). Magnetic roll diameters are typically 100 and 150 mm, although separators as large as 300 mm in diameter are available.

The machine is configured with a head pulley in the separator. A thin belt, usually measuring 0.125–0.50 mm (5–20 mil) thick, is used to convey the feed material through the magnetic field. When feed material enters the magnetic field, the nonmagnetic particles are discharged from the roll in their natural trajectory. The paramagnetic, or weakly magnetic, particles are attracted to the roll and are deflected out of the nonmagnetic particle stream. A splitter arrangement is used to segregate the two particle streams. The magnetic rolls are constructed up to 2 m wide. Typical feed rates to the separator range from 2 to 8 t/h/m of roll width. Coarse 6-mm material, such as chromite or hematite, can be treated at a very high rate, whereas fine material, such as silica, feldspar, nepheline syenite, or alumina, must be treated at lower rates. Sized silica sand can typically be treated at a rate of 4–6 t/h/m of roll width.

The separator can be configured with several magnetic rolls in series to provide a multiple-stage separation. Two to three magnetic rolls are typically placed in series (modular design) to provide optimum separation efficiency. When cleaning a nonmagnetic material, the rolls are usually arranged in a nonmagnetic repass configuration. The nonmagnetic material from the first stage of separation is delivered to the second roll to further remove residual paramagnetics. The rolls can also be arranged in a magnetic repass configuration to provide a cleaning stage of the magnetic fraction.

The rare earth roll is enclosed in a housing or framework. All product contact areas are fabricated from 304 stainless steel. The framework incorporates an electromagnetic feeder to provide a consistent feed rate across the entire width of the roll. A hopper is mounted over the feeder to contain and deliver incoming feed. Magnetic and nonmagnetic product discharge chutes are also used. A wide range splitter is used to segregate the magnetic fraction from the nonmagnetic product. A dust hood is mounted over each roll.

The only utility necessary is the electrical input for the electromagnetic vibratory feeder and the drive system. The vibratory feeder extends the entire width of the magnetic roll to provide a uniform distribution of feed. The vibratory feeder on a separator using a 1-m-wide magnetic roll draws ~0.8 kW. Each magnetic roll is driven independently. A 1-m-wide magnetic roll utilizes a 0.75-kW gearmotor. The roll speed is variable, controlled with a variable frequency drive. Belt speeds in a production mode typically range from 0.6 to 0.9 m/s. Treating silica sand on a 1-m-wide roll at a feed rate of 5 t/h and a belt speed of 0.8 m/s results in a burden depth of ~1 mm.

Wet Magnetic Separators

Wet magnetic separators include both low- and high-intensity drum-type machines.

Low-Intensity Drum Type

The wet drum magnetic separator is used extensively in iron ore and heavy media applications. It is also used for collecting magnetite or *black sands* from gold-bearing ores and tailings as well as pyrrhotite in sulfide mineral applications. The wet drum magnetic separator is well established with literally thousands of separators in current operation.

The wet drum magnetic separator consists of a rotating magnetic drum situated in a tank that receives the feed slurry. The magnetic drum consists of a stationary, shaft-mounted permanent magnetic circuit completely enclosed by a rotating drum. The magnetic circuit is comprised of segments of alternating permanent magnets that spans an arc of 120 degrees. The peak magnetic field intensity on the drum is approximately 2,000 G (0.2 T) and is effective in removing ferromagnetic minerals.

The magnetic drum is mounted in a tank. Slurry is fed to the tank and subsequently flows through the magnetic field generated by the drum. The magnetic minerals are attracted to the drum shell by the magnetic circuit and are rotated out of the slurry stream. The magnetic minerals discharge from the drum shell when rotated out of the magnetic field. Wet drum tanks are in three basic styles. Tank selection is based on the specifics of the application.

In a wet drum separator, the magnetic force acting on a ferromagnetic particle is predominately opposed by hydrodynamic drag force. This feature, when properly applied, provides the vehicle of separation, washing away the nonmagnetic particles while the ferromagnetic particles are collected in the magnetic field. The hydrodynamic drag force is also responsible for any losses of ferromagnetics.

Following are the variables that affect the collection of ferromagnetics in a wet drum magnetic separator:

- **Magnetic field strength.** The magnetic field strength must be sufficient to effectively collect ferromagnetic minerals.
- **Hydraulic capacity.** Ferromagnetic recovery is directly related to the flow rate through the separator. As the flow rate increases, the slurry velocity and, consequently, the fluid drag force increase, which tends to detach more magnetite particles from the opposing magnetic field.
- **Percent solids.** The percent solids of the feed directly affects the selectivity of the separation. As the percent solids increases, the slurry becomes more viscous, minimizing the effects of the fluid drag to assist in the separation of the silica.
- **Ferromagnetic content.** Any given wet drum magnetic separator has the characteristic of removing a limited amount of ferromagnetics based on the diameter of the drum, peripheral speed, and the magnetic field strength. This is referred to as the *magnetic loading*. Exceeding the limits of this magnetic loading results in increased magnetite losses.

Two distinct applications for wet drum magnetic separators exist. One application is the recovery of magnetite or ferrosilicon in a heavy media process. The other is the concentration and recovery of magnetite from iron ore. The use of wet drum magnetic separators has been well documented in each of these applications.

Drum Separators for Heavy Media Applications

Wet drum magnetic separators are extensively used for the recovery of fine magnetite in heavy media applications. The separator recovers the magnetite from a slurry stream toward the end of the gravity separation circuit and returns it to the heavy media separator.

Heavy media operations commonly employ wet drum magnetic separators, measuring 0.9 and 1.2 m in diameter, ranging up to 3.0 m in drum width. There can be two different tank styles—concurrent and counter-rotation. These tank styles are illustrated in Figures 13 and 14.

The drum rotates in the same direction as the slurry flow in the concurrent tank style. The slurry enters the feedbox and is channeled underneath the submerged drum. The slurry then flows into the magnetic field generated by the drum. The magnetite is attracted by the magnetic field, collected on the drum surface, and rotated out of the slurry flow. A shortcoming of this basic design is that any magnetite that is not immediately collected exits the tank with the nonmagnetics.

The counter-rotation wet drum tank style is preferred for heavy media applications. The drum rotates against the slurry flow in the counter-rotation tank style. The slurry enters the feedbox and flows directly into the magnetic field generated by the drum. The magnetite is attracted by the magnetic field, collected on the drum surface, and rotated out of the slurry flow. Any magnetite that is not immediately collected passes through to a magnetic scavenging zone. The short path that the magnetic material must be conveyed between the feed entry point and the magnetics discharge lip, combined with the magnetic scavenging zone, results in high magnetite recoveries.

Extensive sampling of wet drum magnetic separators in heavy media applications has indicated that the industry standard for magnetite losses is 0.25 g of magnetite per liter of nonmagnetic product. Figure 15 demonstrates the typical performance of a wet drum magnetic separator operating in a coal preparation plant employing a heavy media circuit. The wet drum magnetic separator is 0.9 m in diameter with a counter-rotation (Eriez Climaxx) style tank. This separator was isolated in the dilute heavy media circuit. The feed rate was incrementally increased with samples of the nonmagnetic

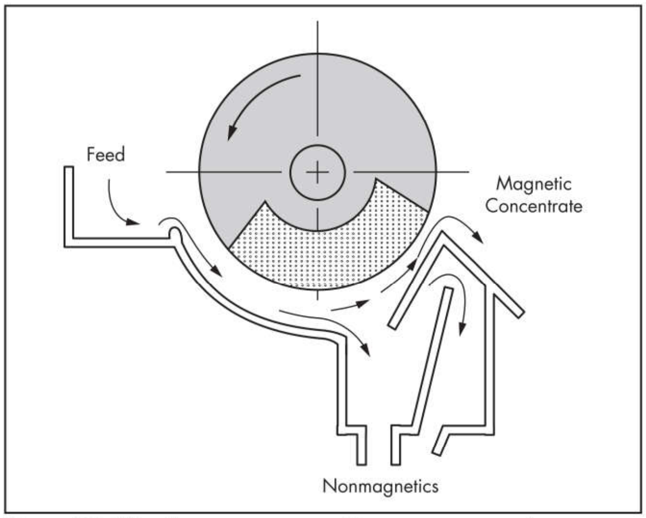


Figure 13 Wet drum separator with concurrent tank

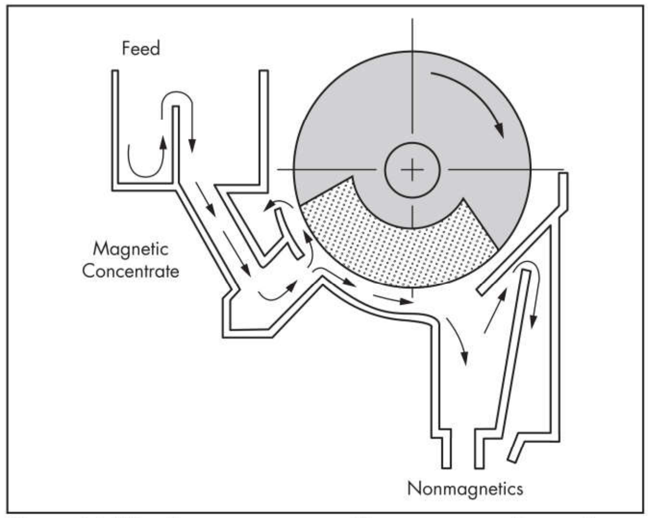


Figure 14 Wet drum separator with counter-rotation tank

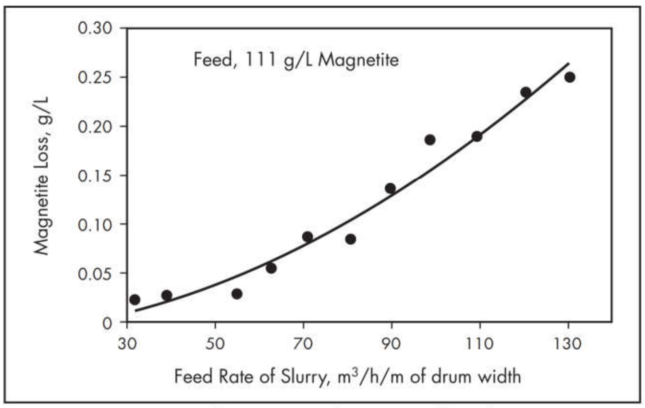


Figure 15 Magnetic losses as a function of feed rate

Table 4 Wet drum magnetic separator sizing parameters

Drum Diameter, m	Sizing Parameter	
	Hydraulic, m^3/h/m of drum width	Magnetic Loading, t/h/m of drum width
0.9	90	16
1.2	110	24

product taken at each level. The magnetite level was measured in each nonmagnetic product sample.

The magnetite losses were then compared to the corresponding feed rate to the separator. The magnetite content of the feed was maintained at 111 g/L or 10.2% solids as magnetite. The graph demonstrates that the magnetite losses are relatively low throughout the range. The maximum magnetite losses of 0.25 g of magnetite per liter of nonmagnetic product occur at the maximum feed rate of 130 m^3 of slurry per meter of drum width.

Based on in-plant testing, general sizing parameters for heavy media wet drum magnetic separators have been established, as shown in Table 4. This is for a counter-rotation style tank and heavy media sized (grade E) magnetite feed slurry at less than 13% solids. The hydraulic capacity and the magnetic loading represent maximum sizing parameters. The separator should be sized on one of the parameters without exceeding the other parameter.

Drum Separators for Concentrating Applications

Wet drum magnetic separators are the most vital part of the upgrading process in magnetite concentration. The upgrading of primary magnetite is always accomplished with wet drum separators. Mill feed is typically upgraded to 65%–66% magnetic iron using a series of wet drum magnetic separators. The number of magnetic separation stages required to upgrade the ore is dependent on the magnetite content and the liberation characteristics of the ore.

Feed to the concentration process is crushed and milled in preparation for magnetic separation. The size distribution of the wet drum feed may have a top size of ~6 mm with the distribution extending down through 25 µm. The selected size distribution provides the minimum degree of liberation necessary for satisfactory magnetite recovery and silica rejection.

Upgrading the magnetite may require several stages of wet drum separation to achieve a final product while minimizing milling costs. To reject a substantial amount of weight prior to reprocessing, the initial magnetic separation or *cobber* stage is conducted on coarse milled ore. The concentrate is then reground to liberate the magnetite and subjected to additional cleaner and finisher stages of separation to produce a final concentrate.

Most cobber separators are double drums (concentrate re-treatment) to provide a two-stage separation and reject a maximum amount of weight. Counter-rotation style wet drum tanks are used in the cobber stage to provide a high level of recovery of the coarse ore. The magnetic element should generate a deep magnetic field for the collection of coarse locked or composite particles. High iron recoveries are achieved with the interpole-type magnetic element.

The cobber concentrate is reground to provide a high degree of liberation and subjected to additional wet drum separation stages. These subsequent stages are referred to as *finisher* stages. Most finisher separators are either double or triple drums (concentrate retreatment) to again provide a multiple-pass separation. The finisher stage produces a final magnetite concentrate. Countercurrent-style wet drum tanks are used in the finisher stage. A schematic of a countercurrent wet drum tank is illustrated in Figure 16.

The feed enters the separator at the bottom of the tank and flows concurrent to the drum rotation. Like the counter-rotation tank, this tank also has a magnetic scavenging zone. The nonmagnetics must migrate through the magnetic field to a full-width overflow. This design is most effective for producing a clean magnetite concentrate. The magnetic element incorporates several agitating magnetic poles (high-gradient design) to provide a high degree of cleaning.

Although most magnetite concentrators employ cobber and finisher magnetic separation stages, there is diversity among them. Specific features of the ore, variability in the ore body, and operating practices may require additional stages of magnetic separation. Many concentrators employ intermediate magnetic separation stages referred to as the *rougher* or *cleaner* stage. These intermediate stages typically treat a reground product to provide additional weight rejection prior to the final regrind stage.

Wet drum magnetic separators in iron ore concentrating operations are commonly 0.9 and 1.2 m in diameter, ranging up to 3.0 m in drum width. The vast majority of the wet drums supplied for magnetite concentration have been 1.2 × 3 m although drums as large as 1.5-m diameter × 5 m-wide have been built. Based on in-plant testing, general sizing parameters for iron ore (magnetite) concentrating wet drum (1.2 m in diameter) magnetic separators have been established, as shown in Table 5. The hydraulic capacity and the magnetic loading represent maximum sizing parameters. The separator should be sized on one of the parameters without exceeding the other parameter.

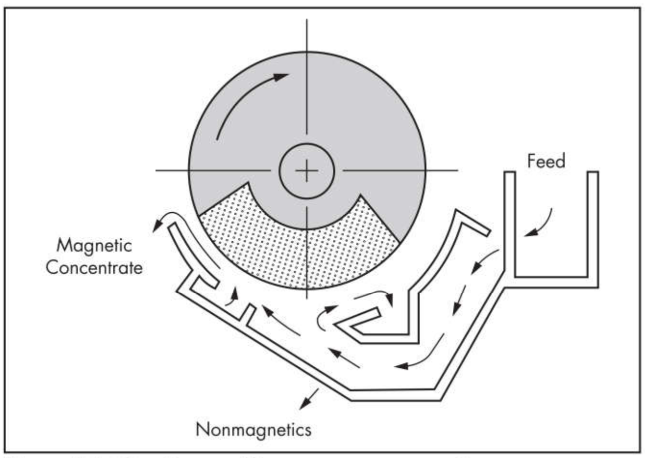


Figure 16 Wet drum with countercurrent tank

High-Intensity Drum Type

The wet drum magnetic separator can also employ a rare earth magnetic element to significantly increase the magnetic field strength. The salient pole rare earth magnetic element used in the dry drum is also used in the wet drum magnetic separator. The magnetic field strength on the drum surface is approximately 7,000 G (0.7 T).

The primary variables affecting separation efficiency are the same as described for the low-intensity magnetic drum separator. The increase in magnetic field strength extends the range of applications. Although the low-intensity magnetic drum is limited to the collection of ferromagnetic materials, the rare earth drum effectively collects many paramagnetic minerals. The drum is effective when used in a scalping operation prior to high-intensity or high-gradient matrix-type magnetic separators. Typical applications of the rare earth wet drum magnetic separator are the recovery of iron-bearing minerals, such as martite and hematite, as well as the collection of ilmenite from heavy mineral concentrates. It is also used in specialty minerals applications such as the magnetic cleaning of high-purity zinc and nickel for battery feedstock.

The rare earth wet drum is available in 0.6- and 0.75-m diameter with drum widths ranging up to 3.0 m. General sizing parameters for a counter-rotation style tank are provided in Table 6.

High-Intensity and High-Gradient Separators

Wet high-intensity magnetic separation (WHIMS) and high-gradient magnetic separation (HGMS) machines employ high-intensity electromagnets and a flux-converging matrix. These separators are utilized for the collection of fine paramagnetic minerals. Technically, WHIMS is distinguished from HGMS by the direction of slurry flow being perpendicular to the line of magnetic flux rather than parallel. In practical terms, WHIMS has come to refer to any continuous-feed carousel-type wet magnetic separator, whereas HGMS is associated with the canister-type filter that is batch operated.

Both WHIMS and HGMS use an electromagnet to generate a magnetic field. The magnetic field induces a matrix that creates a region of high magnetic gradient and provides the mineral collection zone. As slurry flows through the magnetized matrix, the paramagnetic particles are collected and held. The nonmagnetic particles flow through the matrix unaffected.

Table 6 High-intensity (rare earth) wet drum magnetic separator sizing parameters

Drum Diameter, m	Sizing Parameter: Hydraulic, $m^3/h/m$ of drum width	Sizing Parameter: Magnetic Loading, t/h/m of drum width
0.6	34	10
0.75	45	13

Table 5 Wet drum magnetic separator sizing parameters for magnetite concentration

Application	Feed Size	Tank Style	% Solids	Sizing Parameter: Hydraulic, $m^3/h/m$ of drum width	Sizing Parameter: Magnetic Loading, t/h/m of drum width
Cobber	–5 mm; –4 mesh	Counter-rotation	50	135	40
Rougher	–500 μm; –35 mesh	Counter-rotation	40	110	30–33
Cleaner or finisher	Nominal 75 μm; nominal 200 mesh	Countercurrent	35	105	26

Courtesy of Mineral Technologies
Figure 17 Wet high-intensity magnetic separator

The paramagnetic minerals are segregated as a separate product. This occurs when the magnetic field is de-energized and the paramagnetic minerals are flushed from the matrix.

The matrix is a ferromagnetic material that provides a high level of magnetic induction. It also has a high degree of open area to provide slurry flow without physical entrapment. The function of the matrix is actually threefold:

1. Amplifies the background magnetic field
2. Produces localized regions of extremely high gradient
3. Provides the collection sites for paramagnetic particle capture

Matrix material consists of screen cloth, expanded metal, wedge wire, steel balls, grooved plates, and steel wool. The matrix is selected based on the size distribution of the ore. The optimum matrix for a given application should provide a high magnetic loading capacity, high magnetic gradient, and have a relatively open structure for flow-through capacity. The matrix should be coarse enough to allow the largest particle to pass through unimpeded, yet fine enough to generate high magnetic field gradients and provide sufficient collection sites.

Wet high-intensity magnetic separation. WHIMS machines are built in two general configurations. They both consist of an annular ring that contains the matrix that rotates through the poles of an electromagnetic field. As the ring rotates through the electromagnet, the matrix is magnetically induced. Feed is continually delivered to the magnetized matrix. Paramagnetic minerals are captured while nonmagnetic minerals pass through unaffected. As this section of the matrix rotates out of the magnetic field, the paramagnetic minerals are rinsed out of the matrix and separately collected. The earliest-designed WHIMS machines all employed a horizontal carousel. These separators are widely used for concentrating hematite or for preconcentration of ilmenite from beach sands. Figure 17 show a particular WHIMS application that provides a rougher-cleaner magnetic separation.

Most recently, separators have been built with carousels each with magnetic feed zones. These 265-t separators have a capacity of 1,400 t/h of hematite tailings. The Chinese have developed a separator consisting of a vertical ring. The feed is introduced into the lower section of the ring, which is submerged. A jigging action is introduced in this area, which helps to rinse off any nonmagnetic particles. The Chinese have built thousands of these separators for concentrating paramagnetic ores, such as hematite, and removing paramagnetic contaminants from industrial minerals. Many have replaced earlier horizontal ring separators. Most of these separators are 2 m or less in diameter, but most recently, a 4-m-diameter separator has been installed. The rated capacity of this unit is 175–275 t/h. One manufacturer is providing two separate jigging mechanisms on each separator.

Permanent magnets are also used to generate the magnetic field in a WHIMS. The ferrous wheel is a matrix-type separator that generates a high-gradient magnetic field using a fine matrix and conventional barium ferrite or rare earth permanent magnets. The ferrous wheel utilizes a relatively fine matrix to produce high magnetic gradients. A 14-mesh screen cloth is used for the collection of fine hematite. A conceptual illustration of the ferrous wheel is shown in Figure 18. This particular application provides a rougher-cleaner magnetic separation.

The separating ring is vertical and rotates clockwise. The separating ring holds the matrix. The depth of the matrix is 0.15 m. The separating ring is open in the middle to allow the removal of the separated products. Magnets are mounted on each side of the separating ring and generate a magnetic field through the matrix. Two magnetic stations, each with ~60-degree magnetic arcs, are used on the separating ring.

The ferrous wheel magnetic separator provides a two-stage separation in the single vertical separating ring. The separator can be configured as either a rougher-scavenger or a rougher-cleaner. The feed enters the matrix in the magnetic field at the top of the separating ring. In this first separation stage, the feed enters from outside the separating ring and flows inward toward the center. The nonmagnetic particles pass through the matrix and are channeled out of the separator. This product represents the rougher tailings. The magnetic

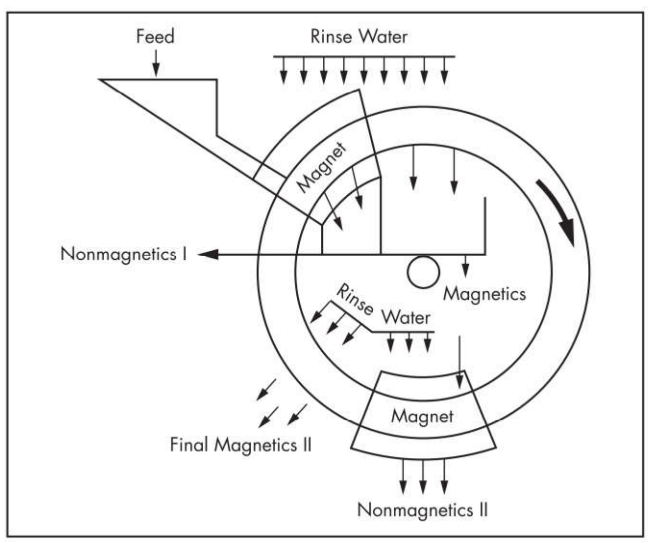


Figure 18 Ferrous wheel

(hematite) particles are collected and held in the magnetized matrix. As the matrix rotates out of the magnetic field, the magnetic particles are rinsed out of the matrix and collected in a hopper in the center of the separating ring. This magnetic product from the rougher separation stage is then repassed in a cleaner stage to wash out residual gangue minerals and further upgrade the hematite.

In the cleaner stage, the feed enters from inside the separating ring and flows outward. Again the nonmagnetic particles pass through the matrix and are channeled out of the system as a final tailing. The magnetic particles are collected and then rinsed out of the matrix. This cleaner magnetic product is channeled out of the separator and represents the final concentrate.

Several separating rings can be mounted together to form a single drum to provide the necessary production-capacity feed rates. Production separators have been fabricated with 15 separating rings in a single unit. The permanent magnets are placed between each ring to generate the magnetic field. The feed distributor consists of a box that runs the length of the separator. Each separating ring has a single feed pipe attached to the distributor box to accept new feed.

High-gradient magnetic separation. HGMS is associated with the canister-type filters that are batch operated. HGMS is also a common term for high-capacity magnetic filters used in the beneficiation of clay and other associated fine-grained earthy minerals. These separators were developed with specific features to provide peak separation effectiveness while operating at feed capacities ranging up to 227 m^3/h slurry. HGMS is operated with a controlled slurry flow rate through the matrix. The slurry is pumped into the bottom of the matrix canister and discharges out of the top. In this manner, the retention time in the matrix is controlled. The slurry must be well dispersed and the particles held in suspension to operate in this manner. Most applications are limited to fine-particle processing in the range of –10 µm, using a steel wool matrix.

The magnet in an HGMS system can either incorporate a hollow-core conductor coil that is water-cooled or a superconducting coil. In either system, the magnetic separation is performed in the exact manner; the only difference is the method of generating the magnetic field.

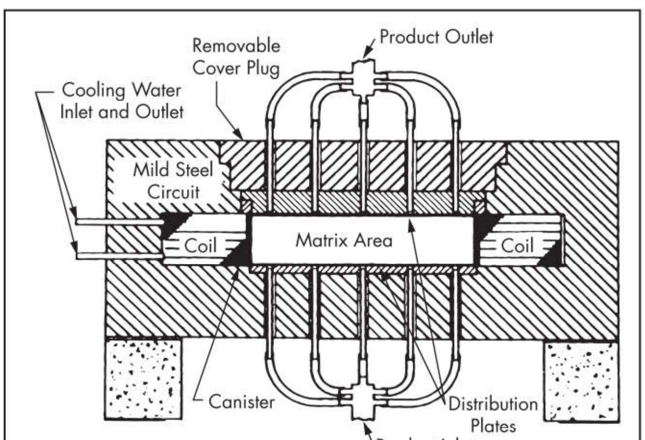


Figure 19 Production-scale high-gradient magnetic separator

Figure 20 Conventional water-cooled high-gradient magnetic separator

Conventional water-cooled high-gradient magnetic separation. The major components of a water-cooled hollow-core conductor system are illustrated in Figure 19, which depicts a production-scale high-gradient magnetic separator. The steel wool matrix is held in a canister in the center of the magnet. A solenoid coil surrounds the canister. The conductor is square with a hollow core to allow the passage of cooling water. Cooling water is pumped through the solenoid coil during operation. An external hydraulic system with heat exchangers provides continuous cooling of the water through the coils. The coil is enclosed in a steel circuit that provides magnetic field uniformity in the bore and minimizes stray magnetic fields. The feed slurry is pumped to the matrix from the bottom and collected at the top. This feed arrangement permits an even distribution of slurry through the matrix and allows control of the retention time through the matrix.

HGMS operates in a batch mode. Feed material is pumped through the separator for a predetermined amount of time. During this operating cycle, the matrix collects magnetics. Eventually the collection sites of the matrix are loaded with magnetics. At this stage, the magnet is de-energized and the matrix flushed of the magnetics. The *duty cycle* refers to the operating time of the HGMS in the separating mode.

Many hollow-core conductor or conventional HGMS systems are in operation. The standard canister size is 2.1 and 3.0 m in diameter. A conventional water-cooled HGMS system used for magnetically cleaning kaolin clay is shown in Figure 20. The power supply is shown on the left, and the magnet and feed distribution system are on the right.

The magnet incorporates a 2.1-m diameter canister with an operative height of 0.5 m. The nominal processing rate through the canister is 114 m^3/h feed slurry. The system consists of a power supply, iron enclosed magnet, and hydraulic cooling system. The magnet generates a field strength of 20,000 G (2 T) with a direct current input of 3,500 amperes, resulting in 400 kW. The solenoid coil is enclosed in an iron circuit to provide magnetic field uniformity within the canister. The magnet weighs 373 t. The open-loop cooling system requires ~1.14 m^3/min of water. The auxiliary system

Figure 21 Superconducting high-gradient magnetic separator

Courtesy of Outotec

Figure 22 Superconducting Cryofilter

also includes feed and discharge manifolds to provide even slurry distribution throughout the canister and remotely activated valves, timers, and controllers to properly activate the rinse cycle.

Superconducting high-gradient magnetic separation. HGMS systems incorporating superconducting electromagnetic coils were developed in the 1990s to significantly reduce power consumption. The first superconducting separators were similar in design to the conventional HGMS systems with the exception of the superconducting coil rather that a hollow conductor water-cooled coil.

A superconducting HGMS system with a 3.0-m diameter operating bore is shown in Figure 21. The system consists of an enclosed magnet, helium liquefier, power supply, compressor, and reservoirs for the liquid helium and liquid nitrogen. The magnet generates a field of 20,000 G (2 T). The niobium-titanium superconducting coil is cooled to –269°C with liquid helium. At this temperature, the conductor has no resistance to electrical current and consequently requires no power to generate the magnetic field. The helium is contained in a closed-loop refrigeration system that converts helium gas to liquid to supply the magnet. The refrigerator is precooled with liquid nitrogen. The refrigerator compressor requires approximately 60 kW for operation.

The power supply is used briefly at the start of each operating cycle to energize the magnet. Once the current in the coil reaches set point, the voltage input from the power supply shuts off. The magnet generates 20,000 G (2 T) with a direct current input of 840 amps at 0 V.

Recently, there have been advances in superconducting technology. The development of the Cryofilter by Carpco advanced the technology of magnetic field generation and the operating mode. The Cryofilter utilizes high-temperature superconducting leads and operates in a persistent mode (always energized), enabling the use of a compact cooler instead of a helium liquefier. The design of this system also results in magnetic field strengths up to 50,000 G (5 T).

The Cryofilter utilizes reciprocating canisters that allow a continuous-feed operation as opposed to batch mode operation. Two separate canisters are reciprocated in and out of the magnet. While one canister is in operation, the other canister is being flushed of magnetics. This essentially permit a continuous duty cycle resulting in an increase in capacity. It is reported that the Cryofilter operating on kaolin clay has reached feed rates of 100 t/h of feed slurry, consuming less than 15 kW (Figure 22).

EMPIRICAL BENCH-SCALE SEPARATORS

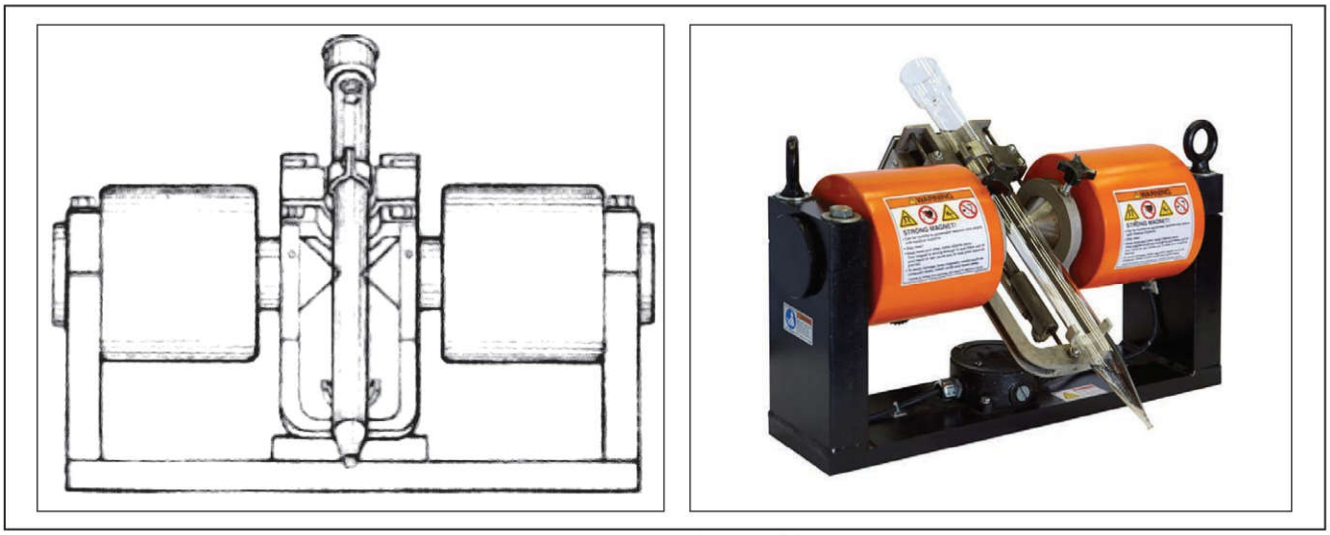
The initial step in assessing the magnetic separation of a mineral sample is to measure the response of the mineral to a magnetic field. The most common approach is to hold a hand magnet to the mineral sample. This is simply the first indicator to the presence of ferromagnetic material.

Two different bench-scale separators are commonly used for the quantitative analysis of magnetic minerals. These separators are specifically designed to provide a separation based on magnetic susceptibility. Both separators provide a high level of control and selectivity. The Davis tube tester provides a measure of ferromagnetic minerals, whereas the Frantz Isodynamic or barrier separators provide a measure of paramagnetic minerals.

Figure 23 illustrates a Davis tube tester consisting of a 25-mm-diameter glass tube that is agitated within an electromagnetic field. An electromagnetic coil on each side of the tube generates the magnetic field. The magnetic field strength in the separating zone can be varied.

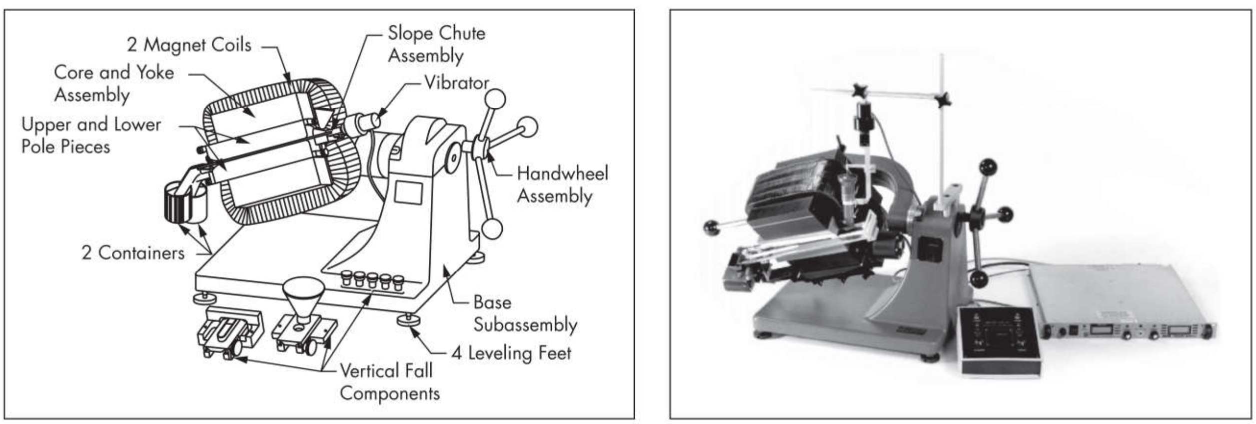
The sample to be tested is slurried and introduced to the glass tube. The magnetic field holds the ferromagnetics within the tube during agitation. Wash water flowing through the tube removes the nonmagnetics. This apparatus essentially provides a perfect separation of the ferromagnetics. The variables controlling the selectivity of the separation are the magnetic field strength, wash-water volume, agitation, and slope of the glass tube. The Davis tube tester is extensively used in measuring the performance of wet drum magnetic separators in both the iron ore industry and in heavy media recovery applications. Samples of the nonmagnetic effluent are tested for magnetite content indicating recovery performance. The Davis tube also provides a measure of product quality for magnetite concentrates. Because the Davis tube essentially provides a perfect separation, any diluents (commonly silica and alumina) in the magnetite concentrate occur as locked particles.

The Frantz Isodynamic or barrier separators are used to separate paramagnetic minerals based on magnetic



Courtesy of Eriez

Figure 23 Davis tube tester



A. Frantz Isodynamic laboratory separator

B. Frantz magnetic barrier laboratory separator

Courtesy of S.G. Frantz Company

Figure 24 Frantz Isodynamic and barrier separators

susceptibility. These instruments selectively separate minerals into products with a very narrow range of magnetic susceptibilities. Figure 24 illustrates the Frantz separators, which consist of a steel C-frame circuit coupled with electromagnetic coils. The magnetic field strength in the separating zone is variable.

The Frantz separator treats dry granular mineral samples. The gap or separating zone in the C-frame circuit is at a downward slope is shown in Figure 24. The mineral sample is fed through the magnetic field on an incline chute running the length of the electromagnetic circuit. As the mineral grains pass through regions of high magnetic gradient, those minerals with a selected threshold magnetic susceptibility are diverted from the mineral stream. The nonmagnetic minerals pass through the magnetic field unaffected. Several passes can be made through the separator at increasing magnetic field strength to perform a fractionation of the entire sample based on magnetic susceptibility. This particular series can yield several magnetic fractions with decreasing magnetic susceptibility. The variables controlling the selectivity of the separation are the magnetic field strength and the slope and pitch of the incline chute. This instrument is also used for assessing liberation. The various size fractions of a mineral sample are treated separately on the Frantz Isodynamic or barrier separator. A comparison of the chemical analysis of the magnetic products throughout the size range indicates the extent of liberation. The level of diluents contained with the magnetic fractions delineates the relative amount of locking.

PILOT-SCALE MAGNETIC SEPARATION

Pilot-scale magnetic separation tests provide the means to predict production plant performance. Once the bench-scale testing has defined the basic separation parameters, larger-scale test work provides other benefits to flow-sheet development.

Pilot-scale magnetic separation test work should closely resemble the production process and provide a higher degree of confidence for flow-sheet development. Several specific items can be identified from pilot-scale testing. These items can also be regarded as a particle characteristic or a separator characteristic. Several mineral characteristics can be assessed through pilot-scale test work:

- Magnetic susceptibility
- Concentration
- Recovery
- Variability of the ore
- Extent of liberation
- Temperature
- Moisture
- Interaction with different minerals (overlapping magnetic susceptibilities)

These characteristics are functions of the mineral. Some of these characteristics, such as magnetic susceptibility, are inherent to the mineral and can only be changed with some degree of difficulty. Other characteristics, such as extent of liberation, temperature, or moisture content, are specific to the sample preparation and can be altered in a straightforward manner. Conversely, there are a few separator characteristics that can be assessed through pilot-scale test work:

- Magnetic field strength
- Magnetic gradient
- Unit capacity

Several secondary variables related to unit capacity are separator characteristics. These relate to the design and operation of any specific separator. Many aspects of the feed parameters affect the capacity of the separator, such as percent solids, flow rate, drum speed, or belt speed.

SUMMARY

The field of magnetic separation is dynamic. The advent of rare earth permanent magnets and superconducting electromagnets coupled with new materials of construction have changed the scope of magnetic separation. New types of magnetic separators have been developed, making many older-style separators obsolete. Gone are the induced magnetic roll, cross-belt, and electromagnetic drum-type separators, to name a few. Many more new modifications and developments in magnetic separators will occur if the past is any indication of the future.

ACKNOWLEDGMENTS

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