J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*

MAGNETIC SEPARATION

Commercial applications using the principles of magnetic separation have been around for more than one hundred years. Magnetic separators have been used since the time of Joseph Henry (1797–1878), when electromagnets were used to remove nails from horses' feed (1). Principles of magnetic separation are widely used in commercial applications today. Typical uses range from the simple removal of coarse tramp iron and steel from garbage, to more sophisticated separations, such as the removal of weakly magnetic mineral contaminants from paper-coating clays. Technical advances in magnetic separator design have led to the commercial use of high gradient magnetic separators (*HGMSs*). These devices are capable of removing weakly magnetic particles and processing tons of material per hour. This ongoing progress has greatly broadened and enhanced the commercial magnetic separations market. For example, it is estimated that the introduction of HGMS into the purification of kaolin clay has nearly doubled the worldwide useful kaolin reserves (2) by making lower grade ores economically attractive.

Until the development of HGMS, magnetic separation techniques had been confined to manipulating mixtures that contained one or more of the three strongly magnetic (ferromagnetic) elements: iron, nickel, and cobalt. High gradient magnetic separators are potentially applicable to many more elements, mixtures, and compounds. For example, there are more than 56 weakly magnetic elements (diamagnetic and paramagnetic) listed in the periodic table. Perhaps of even greater potential benefit is the possibility of manipulating nonmagnetic substances, for example, pollutants in water—using appropriate magnetic "seeding" techniques. (The term *nonmagnetic* is typically reserved for materials that display extremely weak paramagnetic or diamagnetic properties.) Recently HGMSs, fabricated with superconducting coils, have been introduced into the kaolin industry. Superconducting HGMS devices can produce even higher magnetic fields and operate with less than one fifth the total power consumption of conventional resistive units. Higher magnetic fields translate to better particulate selectivity and increased productivity by processing more material per unit canister volume. For a more complete description of the history and development of high gradient magnetic separation, see Ref. 3.

Principles of Magnetic Separation

Magnetic Phenomena. All materials possess magnetic properties to some extent. Their relative strength varies widely among materials. Materials are typically classified into four categories based on the strength of their magnetic properties: (1) ferromagnetic, (2) strongly magnetic, (3) weakly magnetic, and (4) nonmagnetic. With the exception of the ferromagnetic, the boundary defining the difference between strongly magnetic, weakly magnetic, and nonmagnetic materials is arbitrary and typically application-dependent. Any particle exposed to a magnetic field will become magnetized. The magnetic moment of an atom results from the electron spins, their orbital angular momentum, and the change induced in the orbital angular momentum (4). Materials that exhibit positive magnetization when placed in an external magnetic field are described as paramagnetic. Materials that exhibit negative magnetization are described as diamagnetic. All materials will display some degree of diamagnetism owing to the moment induced by an applied magnetic field; however, this type of diamagnetism is relatively weak and can be negligible if other forms of magnetism are present (e.g., paramagnetism or ferromagnetism). Paramagnetism results from the electron spins and their orbital angular momentum. Atoms with unpaired electrons typically exhibit paramagnetism. Paramagnetic materials are further classified as strongly or weakly paramagnetic depending on the strength of the magnetization (magnetic moment per unit volume) when placed in an external magnetic field. Many elements and their compounds exhibit paramagnetism; some common examples are hematite (Fe_2O_3) and pyrite (FeS_2). Ordered arrays of magnetic moments result in phenomena such as ferromagnetism, antiferromagnetism, and ferrimagnetism. When domains of paramagnetism are created in some materials such that long-range order is established, the magnetization can be quite large, and the materials are described as ferromagnetic. These materials include iron, nickel, and cobalt and a relatively small number of compounds of these elements. An example of a ferromagnetic ore is magnetite (Fe_3O_4).

Basic Electrodynamics. A magnetic field and magnetic field gradient can be produced in a variety of ways, typically by current-carrying conductors (electromagnets) or by residual magnetization of ferromagnetic materials (permanent magnets) or a combination of these. The magnetic induction $\boldsymbol{B}$ in teslas (T) is a vector quantity defined in terms of the sideways force $\boldsymbol{F}_\mathrm{M}$ in newtons (N) acting on a test particle with charge q_0 in coulombs (C) and moving with a velocity v in meters per second (m/s) such that

$$\boldsymbol{F}_\mathrm{M} = q_0 \boldsymbol{v} \times \boldsymbol{B} \qquad (1)$$

where $\boldsymbol{v} \times \boldsymbol{B}$ is the outer (or cross) product between the vectors $\boldsymbol{v}$ and $\boldsymbol{B}$ (5). The space around a magnet or current-carrying conductor is defined as the site of the magnetic field. The site of the magnetic field is the space through which its influence extends and is mapped by lines of magnetic force. A magnetic field is said to be uniform and homogeneous when these lines are parallel and equally spaced. Using the International System of Units (*SI*), the magnetic induction (which is sometimes referred to as the magnetic flux density or simply the magnetic field) in teslas is calculated by

$$\boldsymbol{B} = \mu_0(\boldsymbol{H} + \boldsymbol{M}) \qquad (2)$$

where μ_0 is the permeability of free space equal to $4\pi \times 10^{-7}$ N/A^2, $\boldsymbol{H}$ is the magnetic field intensity measured in amperes per meter (A/m), and $\boldsymbol{M}$ is the induced magnetization measured in amperes per meter (A/m). The magnetic quantities $\boldsymbol{B}$, $\boldsymbol{H}$, and $\boldsymbol{M}$ are often described in many textbooks using centimeter-gram-second (cgs) units. In cgs units, the magnetic induction $\boldsymbol{B}$ is expressed in gauss (G), the magnetic field intensity $\boldsymbol{H}$ in oersteds (Oe), and the magnetization $\boldsymbol{M}$ in electromagnetic units per cubic centimeter (emu/cm^3). To convert between the two systems of units, several reference tables have been published elsewhere (6). One convenient conversion factor to recall is 1 T = 10,000 G.

The magnetic susceptibility χ_m (volume susceptibility) of a material is a dimensionless parameter and is often used to describe the relative magnetic strength of the material. The magnetic susceptibility is defined as the ratio of the induced magnetization to the magnetic field intensity and is given by

$$\chi_\mathrm{m} = \boldsymbol{M} / \boldsymbol{H} \qquad (3)$$

The magnetic induction can now be expressed in terms of the magnetic susceptibility

$$\boldsymbol{B} = \mu_0 \boldsymbol{H}(1 + \chi_\mathrm{m}) \qquad (4)$$

Table 1 shows the magnetic susceptibility of some common minerals and elements. Paramagnetic materials have positive susceptibilities, and induced moments enhance the magnetic induction. Diamagnetic materials have negative susceptibilities and reduce the magnetic induction. Ferromagnetic materials have

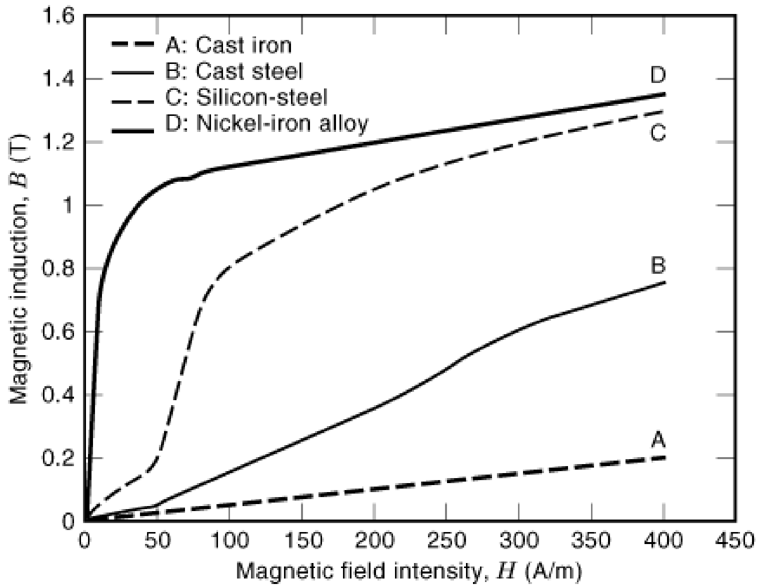

Fig. 1. Magnetization curves of four ferromagnetic materials: (A) cast iron, (B) cast steel, (3) silicon-steel, and (4) Nickel-iron alloy. Courtesy of John Wiley & Sons.

very large positive susceptibilities but become magnetically saturated above certain applied magnetic field intensities; thus, a further increase in magnetic field intensity does not produce a further increase in magnetic induction. Figure 1 shows the magnetic induction of some ferromagnetic materials as a function of the applied magnetic field intensity (4).

Magnetic Separation Dynamics.

Magnetic Forces. Several magnetic separation concepts have been proposed over the years, but they all rely on the same electromagnetic principle: a particle exposed to an external spatially varying magnetic field (i.e., a magnetic field gradient) will experience a force in newtons (N) equal to

$$\boldsymbol{F}_{\mathrm{M}} = V\boldsymbol{M}(\boldsymbol{B}) \cdot \mathrm{grad}\boldsymbol{B} \quad (5)$$

where V is the volume of the particle in cubic meters (m^3), $\boldsymbol{M}(\boldsymbol{B})$ is the magnetic field dependent magnetization of the particle in amperes per meter, and grad $\boldsymbol{B}$ is the gradient of the magnetic induction in teslas per meter. The magnetic force acting on a particle can be rewritten in terms of the magnetic susceptibility where $\boldsymbol{M}(\boldsymbol{B}) = \chi_{\mathrm{m}}(\boldsymbol{B})\,\boldsymbol{H}$ such that

$$\boldsymbol{F}_{\mathrm{M}} = \chi_{\mathrm{m}}(\boldsymbol{B})V\boldsymbol{H} \cdot \mathrm{grad}\ \boldsymbol{B} \quad (6)$$

The implications of Eq. (6) are that in order to have large magnetic separation forces, not only is the particle's magnetic susceptibility important, but a combination of high magnetic field intensity and magnetic field gradient determines the magnitude of the magnetic force.

Fluid Dynamic Effects. For many magnetic separation processing techniques (i.e., wet processing), the particles are often mixed in an aqueous fluid (slurry) that moves past the high gradient collector. Typically, the high gradient collector is a mesh fabricated from thin ribbons or wires of highly permeable stainless steel, which concentrates the magnetic field lines. In general, magnetic field gradients are large near sharp edges or

Table 1. Magnetic Susceptibility of Some Common Elements and Minerals

Substance	Susceptibility (10^{-6} cgs)	Substance	Susceptibility (10^{-6} cgs)
Aluminum	+10.5	Ferberite	+39.3
Al_2O_3	−37	Galena	−0.4
Apatite	+1.0 to + 18.0	Garnierite	+30.7
Aragonite	−0.4	Gold	−28.0
Asbolan	+150.0	Ilmenite	+15.45 to +70.0
Azurite	+12.2 to +19.0	Lead	−23
Anatase	+0.96 to +5.60	Malachite	+10.5 to +14.5
Beryl	+0.4	Millerite	+0.21 to +3.9
Braunite	+35.0 to +150.0	Molybdenite	+4.9 to +7.1
Biotite	+40.0	Molybdenum	+89.0
Barite (pure)	−71.3	Rutile	+0.85 to +4.78
Brannerite	+3.5	Scheelite	+0.13 to +0.27
Chromium	+180.0	Siderite	+65.2 to +103.8
Chromite	+125.6 to +450.0	Titanium	+150.0
Cobalt	Ferromagnetic	Tungsten	+59.0
Cobaltine	+2.0	Uranium	+395.0
Cobaltite	+0.34 to +0.64	Vanadium	+255.0
Columbite	+32.6 to +37.2	Vanadinite	−0.2 to +0.27
Copper	−0.1	Wolframite	+42.2

corners. Thus, the magnetic force (given in Eqs. (5) and (6)) acting on the particle can be quite large. The mesh acts as a filtering mechanism by trapping magnetic particles attracted to the wire and allowing nonmagnetic particles to pass freely. While traveling within this fluid, however, each particle in the mixture is acted on by several other competing forces, including magnetic force ($\boldsymbol{F}_{\mathrm{M}}$), fluid viscous drag force ($\boldsymbol{F}_{\mathrm{D}}$), gravitational force ($\boldsymbol{F}_{\mathrm{G}}$), and fluid buoyant force ($\boldsymbol{F}_{\mathrm{B}}$). If the buoyant force of the particle is ignored, Newton's law of motion for a particle in a fluid is given by (7)

$$\rho V(d^2r/dt^2) = \boldsymbol{F}_{\mathrm{M}} + \boldsymbol{F}_{\mathrm{D}} + \boldsymbol{F}_{\mathrm{G}} \qquad (7)$$

where ρ is the particle density in kilograms per cubic meter, V is the particle volume in cubic meters, r is the position coordinate in meters, t is the time in seconds, and the magnetic force is as defined in Eqs. (5) and (6). To a first-order approximation, the viscous drag force is given by

$$\boldsymbol{F}_{\mathrm{D}} = 3\pi\eta \boldsymbol{v} a \qquad (8)$$

where $\boldsymbol{v}$ = fluid velocity (m/s)a = particle diameter (m)η = fluid viscosity (N·s/m^2)

Figure 2 illustrates the forces acting on a magnetic particle as described in Eqs. (5) and (6). For a magnetic particle to be collected at the surface of the wire within the magnetized volume of the separator, the following condition must be met:

$$\boldsymbol{F}_{\mathrm{M}} \geq \boldsymbol{F}_{\mathrm{D}} + \boldsymbol{F}_{\mathrm{G}} \qquad (9)$$

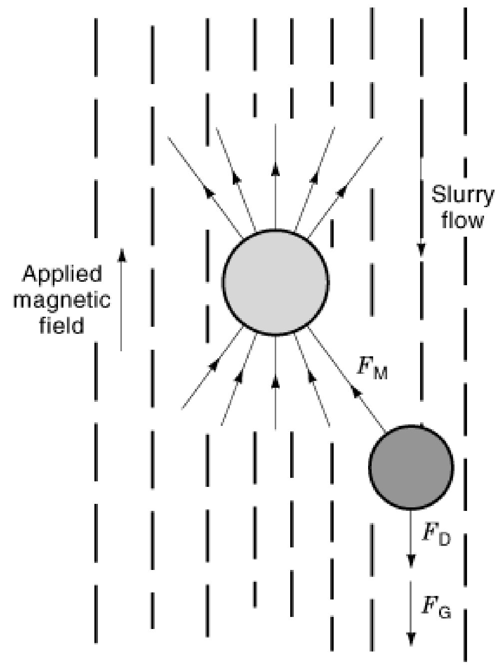

Fig. 2. Schematic representation of a magnetic fiber in a high gradient magnetic separator and the forces acting on a magnetic particle. Courtesy of Plenum Publishing Company.

In this analysis, both the density and particle size (diameter) are extremely important in the magnitude of the magnetic and viscous drag forces. The magnetic force varies as the cube of the particle diameter (a^3). The viscous drag force varies linearly with the particle diameter. This implies that separations between particles with similar magnetic susceptibilities are possible only when significant size and density differences exist.

Open Gradient Magnet Systems. The large magnetic field gradients used in separation devices are typically created using two different methods. The first method is known as the open gradient magnet system (*OGMS*). The second is the matrix/filter method. Open gradient devices separate particles with different magnetic susceptibilities by preferentially directing them into open spaces using magnetic forces. In the open gradient technique, the conductor geometry or suitably designed pole pieces generate magnetic field gradients and hence the magnetic forces on the particles. The magnetic forces are often in competition with other forces such as gravity, electrostatics, drag, and buoyancy. A significant shortcoming of open gradient systems is that the magnetic field gradients that can be generated are typically less than 2 T/cm. Typically, these low magnetic field gradients limit the use of OGMS devices to the separation of strongly magnetic minerals and metal scrap.

Open gradient systems have an advantage in high-volume processing. No magnet matrix or filter is required to trap the magnetic particle mechanically. In standard operation, the particle stream is passed down the bore, and magnetic particles are either pushed radially inward or outward depending on whether they are diamagnetic or paramagnetic. The particles can then be physically separated further down stream. For example, a quadrupole (four-pole) magnet could be used in an open gradient system. The conductor windings in a quadrupole magnet generate a magnetic field that is near zero at the center of the bore and increases radially outward. The magnet has four distinct racetrack-shaped windings located within each quadrant at the perimeter of the bore. These racetrack-shaped windings generate the four poles of the magnet (see Fig. 3). Shown in Fig. 3 is a two-dimensional cross-sectional view of a superconducting quadrupole magnet with a 40 mm bore. In Fig. 3, the direction of the particle stream flow is into the page. The plus (+) symbol indicates

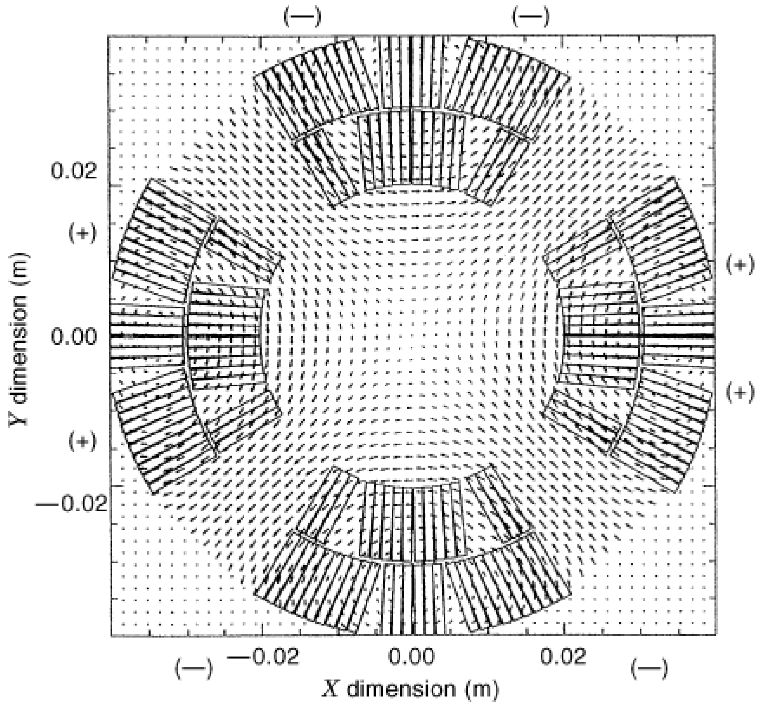

Fig. 3. Two-dimensional cross-sectional view of a quadrupole magnet with a 40 mm bore. The size of the arrows denote the relative magnetic field strength. The plus (+) symbol denotes current flow into the page; the minus (−) symbol denotes current flow out of the page.

current flow into the page, and the minus (−) symbol indicates current flow out of the page. The arrows in the figure represent the relative magnetic field strength generated by the conductor windings and illustrate the magnetic field gradient. The longer the arrow, the higher the magnetic field strength. The conductor windings are fabricated with a high aspect ratio (width/thickness) superconductor. In order to match the rectangular-shaped conductor with the cylindrical geometry of the magnet, V-shaped metal wedges are placed at strategic locations within the cross section. The magnetic field within the bore is periodic and fourfold symmetric and can be described mathematically by a $\cos(2\theta)$ function.

Matrix/Filter Systems. The second most often used method for generating magnetic field gradients in separation devices is by use of a magnetic matrix or filter. Frantz patented the conceptual basis for the modern ferromagnetic filament-type collector matrix (8) in 1937. The Frantz magnetic filter (Frantz Ferrofilter™) used a matrix of ferromagnetic type 430 stainless steel screens fabricated from thin sharp ribbons. In general, magnetic field gradients are large near sharp edges or corners. The introduction of a large number of spheroids, wires, or a mesh of wires will similarly create regions of high gradients near the wires. The magnetic field gradient near the vicinity of the wire can be as high as 10,000 T/cm. A magnetic particle traveling past the wire will experience two magnetic fields: one from the background ambient field ($\boldsymbol{B}_0$) of the magnet and the other from the collector wire ($\boldsymbol{B}_c$), where the total magnetic field is the vector sum of the two contributions, namely, $\boldsymbol{B}_t = \boldsymbol{B}_0 + \boldsymbol{B}_c$. A more detailed analysis of how matrix shape affects the capture cross section of a particle can be found elsewhere (9).

One method to increase the separation efficiency is to increase the magnetic field gradient. To obtain the highest possible field gradient, it is important to use the finest possible matrices (filamentary type). The most cost-effective separations occur when the filament diameter of the matrix and hence the range of the magnetic field gradient is matched with the diameters of the particulates being processed. If the particle is much larger than the range of the gradient, then only a small portion of the particle will feel the effect of the force. On the other hand, if the particle is small compared with the range of the gradient, then the difference of the magnetization across the particle will not be large. If the difference in magnetization across the particle is small, then the resulting magnetic force acting on the particle will also be small.

By increasing the magnetic field gradient using a high permeability matrix, the required magnetic field intensity ($\boldsymbol{H}$) is correspondingly reduced. Reducing the required background magnetic field intensity has a twofold positive impact on the cost of the separation system. First, it lowers the initial capital cost of the magnet system by requiring a lower ambient field. Second, it lowers the operating cost of the separations systems by reducing the amount of electricity required to power the electromagnet. In a resistive electromagnet, the magnetic field intensity that is generated is proportional to the square root of the electric power. Therefore, as the magnetic field intensity increases, the amount of electricity required to power it increases rapidly.

A significant disadvantage of the matrix/filter system is the problem of magnetic particle build-up. A magnetic separation device that uses a matrix/filter to mechanically trap magnetic particles must be periodically cleaned to prevent clogging. This means that during the cleaning of the matrix/filter, the magnetic field must be reduced to zero (or near zero) to minimize the magnetic trapping force. Periodically cycling the magnetic field or removing the matrix/filter from the magnetic field in order to clean it reduces processing efficiency.

Characteristics of High Gradient Magnetic Separation

The efficiency of a magnetic separation device is typically expressed in two ways (10). First, it may be characterized by the so-called grade, which is defined as the percentage ratio of the desired component's mass relative to the total mass of the magnetic fraction (mags). Second, the separation efficiency can be characterized by the so-called recovery, which is defined as the percentage ratio of the amount of magnetic material recovered relative to the total amount of magnetic material in the feed. The two measures are independent quantities and together determine the efficiency of the separation. For most separation devices, there is a relation between the grade and the recovery of the processed material. By adjusting the operating parameters of the separator, the grade can be increased at the expense of the recovery, and vice versa. For example, Fig. 4 shows processing data for the magnetically trapped product of a taconite ore. The percent recovery and grade is plotted as a function of the slurry flow rate at a constant applied field of 2 T. As the recovery of the magnetically trapped product decreases with increasing flow rate, the grade correspondingly increases.

Key Processing Variables

The key process variables in paramagnetic mineral separations are (a) magnetic field strength, (b) high gradient matrix, (c) retention time, and (d) minimizing the competing forces acting on the particle (11, 12).

Magnetic Field Strength. The magnetization $\boldsymbol{M}(\boldsymbol{B})$ [see Eqs. (5) and (6)] of a particle is a general function of the ambient magnetic field. Maximizing the magnetic field in a separator also increases the magnetic attractive force. For ferromagnetic materials, this effect generally saturates at fields above 2 T (see Fig. 1). For paramagnetic materials, the magnetic moment increases with increasing magnetic field well beyond 2 T. For these materials, larger magnetic fields enhance the magnetic trapping force.

Magnetic Field Gradient. The magnetic field gradient is the spatial variation of the magnetic field strength over the microdistance adjacent to the (filament) collector surface. The key factor in the generation of the magnetic field gradient is the transition of the magnetic flux from the highly permeable magnetic medium, typically type 430 stainless steel wool with a permeability > 500, to the surrounding medium containing

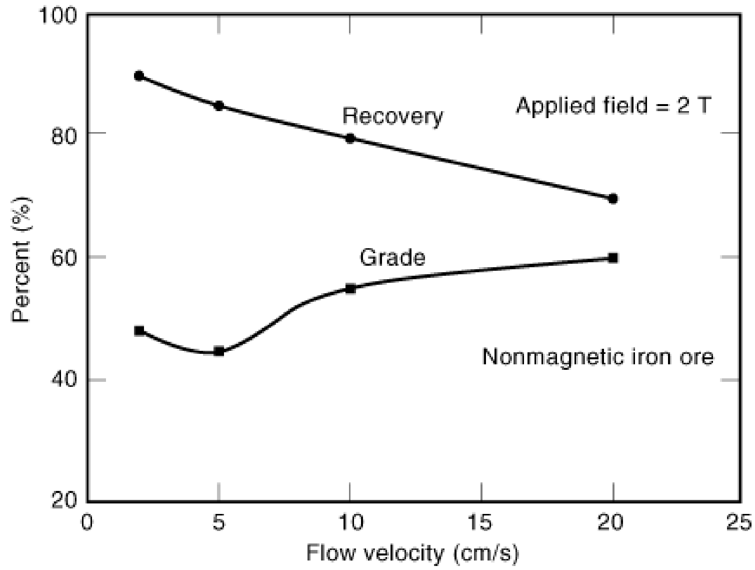

Fig. 4. Grade and recovery of a nonmagnetic iron ore (nonmags) versus slurry flow velocity at a constant applied field of 2 T. Courtesy of Plenum Publishing Company.

the particulates, typically air or water with a permeability of 1. The geometry of the conductor (e.g., sharp points), also plays a significant role is establishing the magnetic field gradient. The greater the number of such interfaces, the more effective the collecting power of the matrix. The smaller the diameter of the filament, the higher the magnetic gradient, but the shorter the range of its influence. High collection efficiencies have been demonstrated by a variety of magnetic fibers and small magnetic spheres. Stainless steel wool is an exceptionally efficient low-cost collector and is widely used in the commercial processing industry. In particular, 430 stainless steel is often used because it is magnetically "soft" and does not have a high residual field. Having a low residual field is necessary during the cleaning/flushing process of the matrix, where the magnetic trapping force on the particle must be as small as possible. The advantage of this type of filter is that it has a high collection surface but occupies a relatively small portion of the total magnetized volume, leaving the remainder of the space for material to be processed. The amount of stainless steel per magnetized volume is application-specific but typically varies between 6% and 12%.

Retention Time. The retention time is a measure of how long a particle contained within a slurry is influenced by the magnetic field. The retention time is calculated by dividing the canister length by the velocity of the fluid flow or alternatively by dividing the canister volume by the flow rate per minute (11, 12). The concept of retention involves control of the flow rate in the canister volume to balance the magnetic force of attraction to the filament collector surface with the viscous drag of the medium of suspended particles. Retention time influences both product quality and production rate. The retention time used in commercial processes is application-specific and is usually chosen by a trial- and-error approach with many factors such as system back pressure and slurry flow distribution through the canister also being considered. Typically, commercial slurry feed times used in the purification of kaolin clay vary between 2 min and 4 min. Experimental results demonstrating the effects of retention time and applied magnetic field are shown in Figs. 5 and 6. Figure 5 is a plot of the percent recovery for the magnetic fraction versus the applied magnetic field for three different values of flow rate. The test material consisted of 10 μm cupric oxide and aluminum oxide powder slurried in water, where the magnetic material being separated is the cupric oxide. Figure 6 shows the recovery of iron

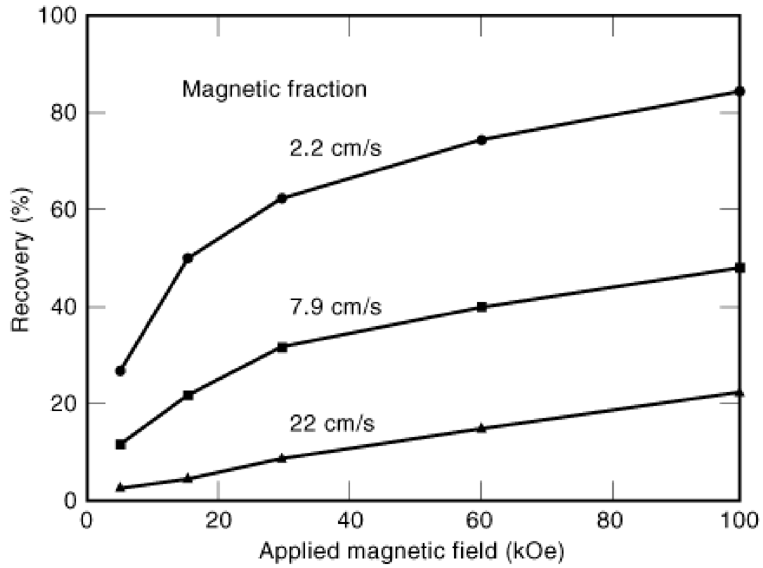

Fig. 5. Recovery percent of desired component of magnetic fraction (mags) relative to feed material versus applied magnetic field for three different values of slurry flow rate.

for a nonmagnetic taconite ore versus the applied magnetic field for two different values of flow rate. In both Figs. 5 and 6, at constant flow rates the percent recovery increases with increasing applied field. This can be attributed to the increase in the magnetic force acting on the particle in the fluid [see Eq. (6)]. At constant applied magnetic field, the percent recovery decreases with increasing flow rate. This can be attributed to the increase in the viscous drag force, which is proportional to the velocity of the slurry [see Eq. (8)]. The trade-off between the magnetic field and the flow capacity is ultimately dictated by the economics of the application. Higher magnetic fields translate to higher particulate recovery, but at a higher capital equipment cost. Higher flow rates translate to increased capacity, but at lower particulate recovery.

Minimizing Competing Forces. Many magnetic separators that process minerals suspended in fluids try to minimize the competing gravitational and fluid dynamic forces. As seen from the right-hand side of Eqs. (7) and (9), minimizing the viscous drag force and gravitational force increases the chances for magnetic capture and correspondingly increases the separation efficiency. To minimize the unwanted gravitational effects, unprocessed slurry is typically fed upward (i.e., introduced from the bottom of the canister).

As seen from Eq. (7), the viscous drag force is proportional to the product of the viscosity and linear flow velocity. To reduce the viscous drag force, a considerable effort is made to select a suitable dispersant to add to the slurry in order to minimize the fluid viscosity. For example, kaolin clays are typically dispersed in water with 0.2% tetrasodium pyrophosphate in order to provide deflocculated slurries. To further minimize the viscous drag force, the slurry is fed at as low a linear velocity as practical while maintaining allowable commercial processing rates (see also the previous section entitled “Retention Time”). A final consideration in the reduction of the viscous drag force is the percent solids content of the slurry itself. Slurries with high solids content are more viscous, which decreases particle capture. However, slurries with low solids content process less material per canister volume and have much quicker particulate settling times, which can lead to clogging in the feed, transfer, and distribution piping. Typically, trial and error is used to find the optimal processing conditions to accommodate these two competing effects. In kaolin clays for example, the percent solids content of the slurry typically varies between 20% and 40%.

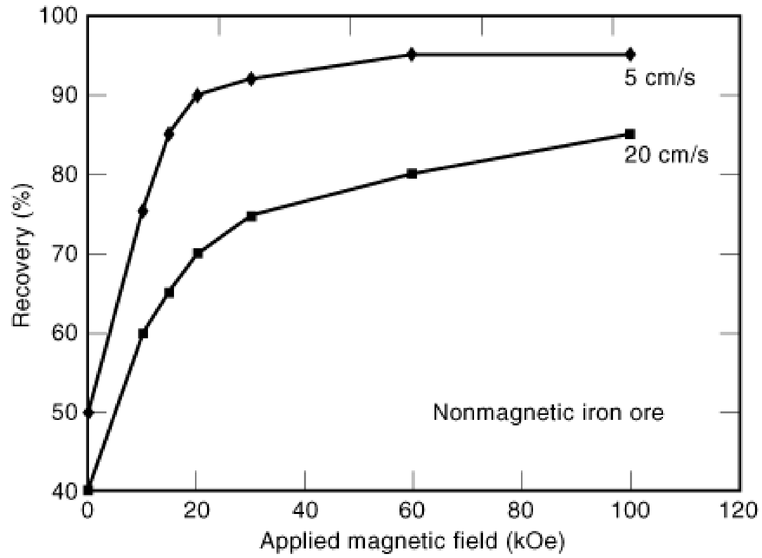

Fig. 6. Recovery of nonmagnetic iron ore (nonmags) versus applied field at two different values of slurry flow rate.

Table 2. Potential Applications of Magnetic Separators

Device	Magnet	Maximum Field (T)	Matrix	Maximum Gradient (T/cm)	Required Susceptibility	Particle Size (mm)
Grate	Permanent	0.05	Rods	0.05	Ferromagnetic	<12
Pulley	Permanent	0.02	—	0.01–0.1	Ferromagnetic	<50
Drum	Permanent	0.05–0.1	—	0.05–0.1	Ferromagnetic	0.02–20
Belt	Electromagnet	0.01–0.1	—	0.01–0.1	Ferromagnetic	0.15–30
Induced roll	Electromagnet	2	—	20	Paramagnetic	0.03–3
Carpco	Electromagnet	2	Steel balls	4.5	Paramagnetic	0.01–1
C-frame; Jones	Electromagnet	2	Grooved plates	20	Paramagnetic	0.01–2
Marston Sala	Electromagnet Superconducting	2–5	Steel wool	2500	Paramagnetic weak	0.0001–2

Magnetic Separation Equipment

Several terms are often used to characterize magnetic separation devices. These include permanent magnet, electromagnet, high gradient, open gradient, etc., but the devices themselves basically fall into two separate categories: (1) batch type and (2) continuous type. Table 2 summarizes some common types of magnetic separators and their ranges of potential applications. The following information concerning commercial magnetic separations units can be found in more detail in Ref. 1.

Batch Type. Batch-type separators are most useful when the unprocessed feed materials contain a relatively small amount of magnetic material to be trapped in the collection volume. This allows for a convenient duty cycle for the device. Batch-type separation devices are most often fabricated using iron-bound solenoid electromagnets surrounding a cylindrical canister. The cross section of the canister is circular in order to minimize the amount of conductor used to magnetize the collection volume. Utilizing a long coil where the height of the coil exceeds the canister height further maximizes the efficiency of a batch-type solenoid electromagnet. Iron pole pieces of the magnet are then designed to extend into the top and bottom of the solenoid. Batch-type

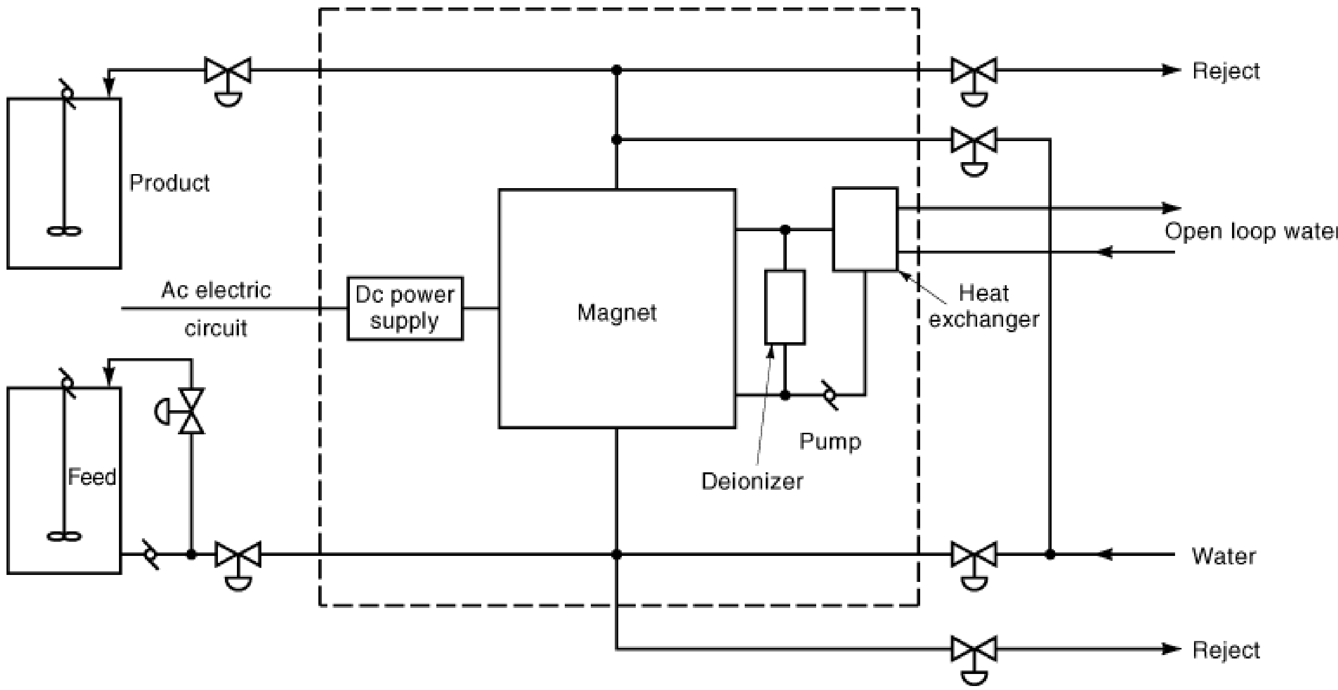

Fig. 7. Schematic of batch-type process used in magnetic separation. Courtesy of Aquafine Corp.

separators operate on the principle of cycling the magnetic field from a maximum value down to zero applied field. It is important to have a magnetically soft material with a low remanent field as the collection matrix, so that when the applied field is reduced to zero the force acting on the magnetic particles is minimized. In normal operation, typical duty cycles for mineral separations vary between 10% and 80% and consist of five basic steps (see Fig. 7 for illustrative purposes). (1) The current in the magnet is increased to obtain the desired operating magnetic field level. During this step the collection matrix (typically compressed 430 stainless steel wool) is magnetized. (2) While maintaining the desired operating magnetic field level, the appropriate valves are opened/closed and the unprocessed clay (feed) is introduced and flows through the magnetized collection volume. The nonmagnetic material which passes through the magnetized volume is collected separately, whereas the magnetic material remains trapped on the 430 stainless steel collection matrix. (3) By shutting off the appropriate valves, the flow of the unprocessed feed material into the collection volume is stopped, and the collection volume is subsequently displaced with water. (4) The current in the magnet is decreased to zero (or near zero). This step demagnetizes the collection matrix and minimizes the magnetic force acting on the captured magnetic particles. (5) Appropriate valves are opened/closed, and the (now demagnetized) collection matrix is subjected to a high velocity water rinse/flush and the magnetic by-product that is liberated from the matrix is collected separately. The steps of the process are then repeated based upon some established procedure. A schematic representing this process is shown in Fig. 7 (13).

Induced-Pole Separators. In induced-pole separators the magnetic field gradient is generated by the application of background magnetic field to a ferromagnetic filter matrix. The word “induced” is somewhat misleading because there are no ac fields present. The name “induced-pole” refers to the magnetic poles that are induced around the ferromagnetic matrix/filter edges by the application of the background magnetic field. The orientation of the magnetic field to the edge of the matrix determines whether the device is a parallel or perpendicular field-to-flow. These batch separators are manufactured in two basic configurations: (1) C-frame and (2) solenoid. Solenoid electromagnets represent a major area of development in magnetic separation and are described in detail in the following three sections of this article.

C-frame magnets employ a ferromagnetic matrix placed between two poles of an electromagnet. The ferromagnetic material used to transfer the magnetic flux from pole to pole typically occupies between 40% and 80% of the magnetized volume. A disadvantage of this type of device is the nonuniformity of the background ambient field. With even the smallest amounts of ferromagnetic particulates present in the feed material, these devices are subject to clogging in the flush region where the fringe field is the highest.

Resistive Solenoid Electromagnets.

Installed Systems. In March 1973, the first large-scale HGMS was installed at Freeport Kaolin Company in Gordon, Georgia (2). The separator was a 2.1 m diameter resistive electromagnet fabricated by Pacific Electric Motor Company. The separator could generate magnetic fields up to 2 T and process nearly 3800 liters of slurry per minute or 60 metric tons per hour (dry basis). The central magnetic field was 2 T, with an electric power consumption of nearly 500 kW. The conductor consisted of 16 hollow water-cooled copper coils surrounded by a vaultlike steel enclosure that was 3.65 m $\times$ 3.65 m $\times$ 2.44 m (13). For its day, this magnet represented a 13-fold increase in process capacity over the largest previous commercial magnetic separator. Continued improvements in magnet design have led to similarly sized units operating at 2 T with less than 300 kW of electric power consumption. In 1982, the first 3 m diameter resistive electromagnetic separator went into operation. This enormous unit could process 130 tons of kaolin per hour with about 400 kW of electric power consumption. To date, there have been 29 resistive electromagnets (2.1 m and 3 m diameter) installed in the United States and 8 others in the rest of the world for the purification of kaolin clay.

Low-Temperature Superconducting Solenoid Electromagnets.

Background. In a low-temperature superconducting (*LTS*) magnet, the magnetic field is generated in exactly the same way as in a conventional resistive electromagnet. The only real difference between the two is that the conductor in the LTS magnet must be maintained at a suitably low temperature in order to remain in its superconducting state. The key benefits offered by superconducting magnets are (1) very low power consumption, resulting from zero resistance in the conductor windings (see next section), and (2) much higher magnetic fields resulting in better selectivity of particles and higher separation efficiency. However, the zero resistance property of a superconductor is only true for direct current (dc). For applications where the electromagnetic field is changing in time (ac), a superconducting material no longer operates with zero electric resistance. Therefore, for batch-type magnetic separators, which periodically cycle the magnetic field, there is a practical limitation on the maximum allowable magnetic field ramp rate for these devices.

Several LTS materials have been studied, but the most prominent in terms of conductor fabrication and commercial implementation is an alloy of niobium and titanium (*NbTi*). In order to enhance electric and thermal stability of the superconductor, the NbTi is typically embedded in a normal metal matrix of copper or aluminum. This allows for greater heat transfer through thermal conduction and also provides a low-resistance electric path in the event that the superconductor comes out of its superconducting state. One disadvantage of the normal metal matrix is in ac applications. In ac applications, additional Joule heating is caused by the generation of induced currents in the normal metal matrix. To fabricate these composite superconductors, fine filaments of NbTi are either drawn or extruded with the aluminum or copper. The filament size of the NbTi can vary between about 5 μm and 30 μm depending upon the application. Copper and aluminum-clad superconducting windings using NbTi conductor are now commonplace in the research community and have been used in applications such as motors, generators, transformers, and magnets.

An important aspect of the design of an LTS magnet is the choice of refrigeration or cryogenic cooling system that will be used to cool the conductor windings. There are two basic refrigeration routes that have been used successfully. The first and most prevalent route is the use of liquid or gaseous cryogens. The NbTi conductor windings are typically cooled by either immersion in a bath of liquid helium or by forcing cold, two-phase (liquid–vapor) helium gas around the conductor. Helium gas will liquefy at 4.2 K at atmospheric pressure. The helium gas that is boiled off or heated by ac-loss is recirculated through a liquefier, cooled, and recondensed into liquid or a two-phase (vapor–liquid) mixture. The second method used to cool superconducting windings is through indirect cooling using a refrigerator. These refrigerators are commonly referred to as cryocoolers. Cryocoolers, based on various thermodynamic cycles, allow cooling to extremely low temperatures. One such device commonly used in the cryogenic industry is the Gifford–McMahon (*G–M*) cryocooler. Recent advances in G–M cryocooler technology permit these units to generate temperatures of 4 K or lower. The units enable superconducting windings to be cooled indirectly and without the presence of liquid or gaseous cryogens and are particularly advantageous in small-scale systems where the cost of a liquefier cannot be justified. The two major drawbacks to these systems are: (1) the constant supply of electrical power that is essential for reliable operation and (2) the relatively small cooling capacity of cryocoolers (typically a few watts) at 4 K.

Energy Efficiency. One of the major drawbacks of conventional resistive-type magnetic separators using water-cooled copper conductor windings is their high operating cost owing to their large electrical power consumption. The power consumption in a conventional copper magnetic separator can be as high as 400 kW in a 3 m diameter unit. In a superconducting unit, the primary source of power consumption is the refrigeration unit. An equivalent 3 m diameter LTS unit is rated at about 50 kW. In production environments, these units operate approximately 8000 h/yr with an expected lifetime between 5 and 10 years. In the southern United States, where most of the processing plants are located, the present average price of electricity is approximately $$0.05/kWh. This translates to an annual cost saving of about $140,000 with a lifetime saving of $1.4 million for a superconducting magnet over its resistive counterpart. For processing plants located in nonindustrialzed countries, the savings in annual operating cost is even more substantial as price and availability of electrical power is at a premium.

Installed Systems. The first large-scale LTS magnetic separator went into operation in 1986. The device had a 2.1 m diameter bore and was fabricated by Eriez Magnetics of Erie, Pennsylvania (14). The device was installed at the J. M. Huber Company in Georgia and is used for the benefaction of kaolin clay (see Fig. 8). The installed cost of this device was around $2 million. To date, 12 batch-type LTS magnetic separation systems have been installed in the United States. Eight of the 12 LTS systems installed have been retrofits, where the existing resistive electromagnets have been replaced with superconducting windings. Worldwide, five other batch-type LTS magnetic separation systems have been installed for the benefaction of kaolin clay in Australia, Brazil, China, England, and Germany. Low-temperature superconducting magnetic separation systems appear to be displacing their conventional resistive counterparts.

High-Temperature Superconducting Solenoid Electromagnets. In 1986, Bednorz and Mueller (15) discovered a ceramic oxide compound that would superconduct at higher temperatures than the previously well-studied LTS materials. Before this discovery, the highest recorded superconducting transition temperature was about 23 K. Since 1986, several more ceramic oxide materials, which superconduct at even higher temperatures; have been discovered. This class of ceramic oxide materials has been given the name high-temperature superconductors (*HTS*). At the time of this writing, the highest recorded superconducting transition temperature of an HTS material at atmospheric pressure was approximately 140 K. High-temperature superconducting materials may offer substantial benefits in the practical commercialization of superconducting devices because of the higher temperatures at which these materials superconduct. Higher superconducting transition temperatures translate to higher (Carnot) refrigeration efficiencies. For example, an LTS material operating at 4 K in a bath of liquid helium would require more than 20 times the amount of electric power for every watt of cooling versus its HTS counterpart operating in a bath of liquid nitrogen at 77 K.

Presently, magnetic separation represents one of only two industrial applications of large-scale superconducting devices; the other is magnetic resonance imaging (*MRI*). Consequently, one of the first prototype industrial devices fabricated using HTS wire was an HGMS. In 1996, the first successful demonstration of kaolin benefaction using an HTS magnetic separator was reported (16). In this report, five different types of kaolin clays representing major worldwide deposits were processed in a 5 cm diameter warm bore HTS magnet in fields up to 2.5 T. Results indicated brightness improvements varying from one to five GE brightness units, depending on the particular clay processed. Most likely, HGMS will be one of the first industrial areas impacted

Fig. 8. Low-temperature superconducting batch-type magnetic separator with a 3 m bore. Note the liquid helium refrigeration system to the right of the magnet. Courtesy of Eriez Magnetics.

by HTS technology and may represent the future migration of HGMS to this technology. However, because of the higher cost of the HTS wire per ampere-meter compared to its LTS counterpart, it is unclear at this time if the economic benefits from increased refrigeration efficiency will outweigh the additional capital cost of the HTS wire.

Continuous Type. One of the primary shortcomings of the batch-type separator is processing efficiency. Batch-type separators operate on a duty cycle, so there is a period of time where material is not being processed. Continuous-type separation devices are designed to maximize the duty cycle and minimize the processing time. Continuous-type separators are advantageous when the magnetic fraction of the unprocessed feed material is relatively high.

Drum and Pulley Magnets. In the earliest magnetic separators, and in many that are still applicable for attracting strongly magnetic materials, permanent magnets were used in an open single-surface device. These devices consisted of suspended magnets, pulleys, conveyors, or drums. These devices produced fields in the neighborhood 0.06 T and gradients of the order of 0.05 T/cm. Drum and pulley type magnetic separation equipment has been used since the time of Thomas Edison who used a magnetic pulley for the concentration of nickel ore. These are among the most common types of magnetic separators in the world today. They can be made from either permanent or electromagnets and process either wet or dry feeds. Dry magnetic drums can be designed to perform as lifting magnets or pulleys. Magnetic drum devices have stationary magnets, whereas pulley drums rotate. Schematics for these types of devices are shown in Figs. 9 and 10.

Grate-Type Magnets. Grate-type magnets consist of a series of stainless steel tubes packed with ceramic magnets that are mounted in a trap perpendicular to the flow of the material. Grate magnets are used in both wet and dry processing for the removal of both coarse and fine tramp iron. Various types of designs such as self-cleaning grates, permanent magnets, vibrating grates, and rota-grates, have been proposed and implemented. These trap-type separation devices come in a variety of shapes and sizes and have been used in such applications as food processing, chemical processing, paper and plastic processing, and recycling. Grate magnets are most

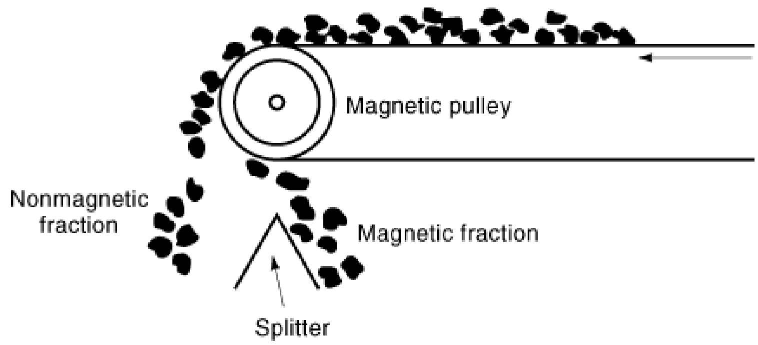

Fig. 9. Conventional pulley-type separator. Courtesy of McGraw-Hill Publishing Companies.

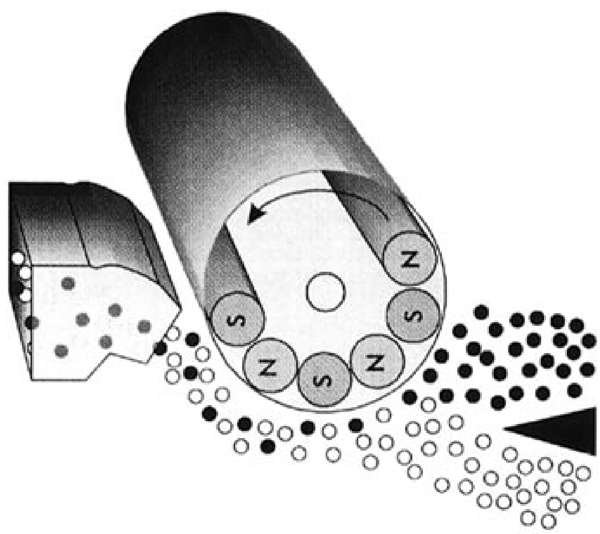

Fig. 10. Conventional rare-earth permanent magnet drum-type separator. Courtesy of Carpco, Inc.

often implemented in production lines to prevent accidents or contamination from tramp iron where dry or wet pulverized material is processed.

Lifting Magnets. Lifting magnets are used in both continuous and batch operation depending upon the particular application. Continuous devices typically carry the unprocessed material along a conveyor belt that is located directly under the lifting magnet. The lifting magnet itself has a belt that moves over its lifting magnetic poles. The magnetic material is lifted from the first belt carrying the unprocessed material to the second belt moving over the magnetic poles of the lifting magnet. The magnetic material on the second belt is then carried away to a region of low magnetic field where it is cleaned. These devices can be either high or low intensity depending upon the design of the pole pieces. Lifting magnets are used primarily in the removal of tramp iron. The lifting magnet is typically positioned about 5 cm to 10 cm from the highest point of the convor transporting the unprocessed material. Typical conveyor speeds vary between 1.75 m/s and 2.5 m/s depending on the application and whether the device is self-cleaning or not.

Plate Magnets and Magnetic Humps. Plate magnets operate by removing tramp iron from materials moving pneumatically or by free falling gravity flow. The tramp iron is removed by attaching itself to a

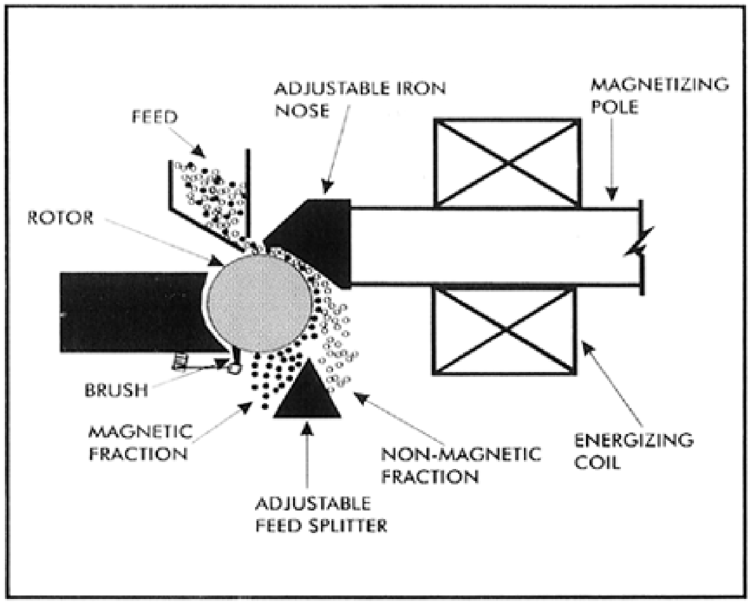

Fig. 11. Conventional induced-pole separator. Courtesy of Carpco, Inc.

magnetized plate that is periodically scraped and cleaned. Chute angles of 45° are recommended, and the magnetic plate should be located as close to the feed point as possible to minimize velocity effects of the incoming stream. Plate magnets are fabricated using both permanent and electromagnets. For permanent magnet versions of this device, plate widths can extend up to 1.23 m; electromagnet versions of this device can increase plate widths to 2.85 m. The capacity of these devices varies as function of the chute angle and the size of iron particulates being removed.

Induced Roll Separators. Induced roll separators have been in commercial use since 1890. These devices can only handle dry granulated weakly magnetic material and are similar to drum separators with the primary difference being that the cylinder rotates in the gap of an electromagnet. An example of an induced roll separator is shown in Fig. 11. The magnetic field gradient is created by making sharply edged ridges of the surface of the cylinder or by constructing a cylinder of alternating magnetic and nonmagnetic disks. Industrial devices are built with multiple cylinders that operate in either series or parallel. By varying the configuration, these devices can be used as either concentrators or purifiers. Typical cylinder widths vary between 0.25 m and 0.75 m. Installed cost for these devices is relatively low compared with other units with similar capacity.

Wet Drum Magnetic Separators. Wet drum separators are used exclusively for the processing of wet feed material for the separation of strongly magnetic coarse particles. The key processing variables that determine the size and processing capacity of the device are slurry volume, percent magnetics and solids in the slurry, and the required recovery and concentration of magnetic particles. Several vendors manufacture these devices. Typical drum sizes vary from 0.023 m to 1.2 m in diameter with heights up to 3 m. Wet drum devices can come in either a single- or concurrent-type arrangement (see Fig. 12). A concurrent arrangement is where two or more drums are placed in series. Unprocessed feed material is introduced into the first drum, which is used to remove the strongly magnetic coarse particles. The processed material is then fed into the second drum for the removal of finer magnetic particles. Units with single drums can process slurry with magnetics up to 20% by weight and units with two drums can process slurry with up to 45% magnetics by weight. Recommended maximum particle size is 6 mm. Concurrent devices can process finer particles down to about 0.8 mm (20 mesh)

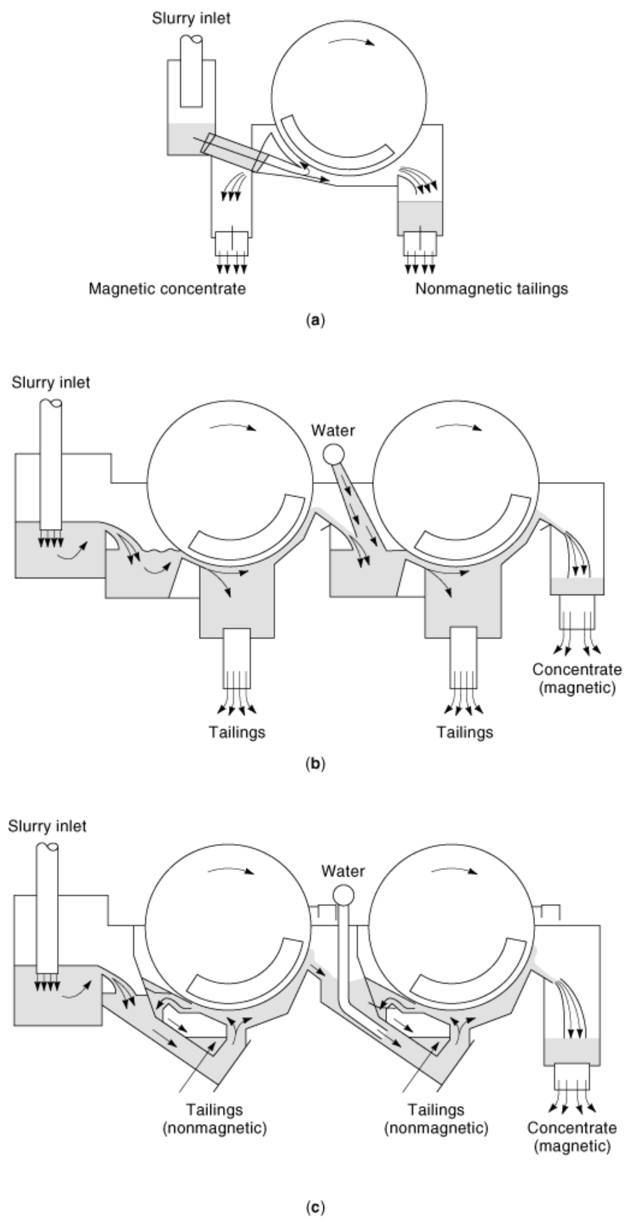

Fig. 12. Wet drum magnetic separator arrangements: (a) counter-rotating-type, (b) concurrent double-drum-type, and (c) countercurrent double-drum-type. Courtesy of Svedala Industries AB Pumps and Process.

with an optimum solids content of about 30% by weight. Wet drum separators have the advantage of being able to process material with a wide variation of particle size and throughput. The installed cost of a single wet drum-type separator can vary between \$25,000 and \$75,000 per meter of magnet width. Multiple drum cost increases in direct proportion to the number of drums required.

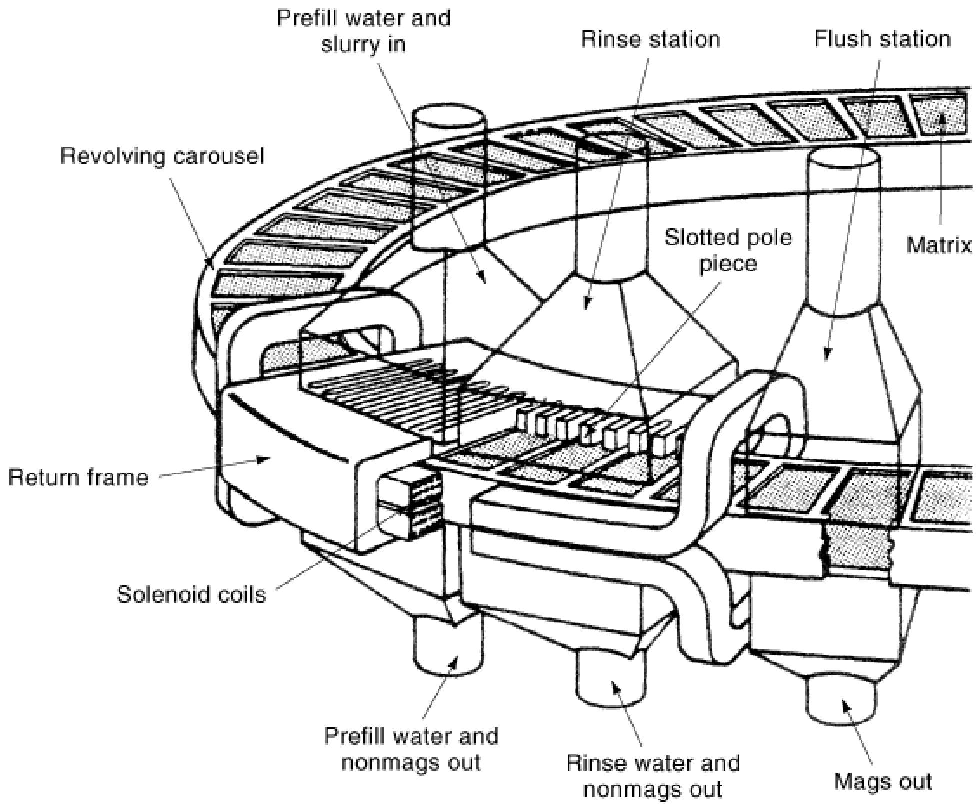

Fig. 13. A schematic representation of a carousel-type magnetic separator. Courtesy of Svedala Industries AB Pumps and Process.

Carousel Electromagnets. One of the first high-intensity continuous-type separators was developed around 1963. This device was a rotating carousel version of the wet high-intensity magnetic separator (*WHIMS*) developed earlier by Jones in 1957 (18). This device consists of a cylinder subdivided into equally spaced compartments that rotate about a vertical axis. Each compartment is packed with 430 stainless steel wool. The magnetic field is generated using an electromagnet that produces a magnetic field in the axial direction perpendicular to the rotating compartments. Unprocessed feed material is introduced into the compartments in the low field region (see Fig. 13). These compartments are then rotated into the high field region. In this region, the magnetic particles are trapped in the cells, and the nonmagnetic particles are washed out. Once the compartment cell has rotated to a region of low field, the magnetic particle is then washed out with a high-velocity rinse (19).

LTS Reciprocating Magnet System.

Background. As early as 1975, studies were carried out on a new type of magnetic separator design that benefits from the zero resistance property of superconducting coils (20). In 1989, Carpco introduced the first commercial reciprocating magnetic separator. Unlike its LTS batch-type predecessor that cycles its magnetic field, this magnet maintains the field at a constant level and instead cycles the matrix/filter canister in and out of the active magnetic field region. This design allows for semicontinuous processing and reduces ac losses by not cycling the magnetic field. The magnet operates in what is known as the persistent mode. Below the superconducting transition temperature, a superconducting magnet can be energized and then

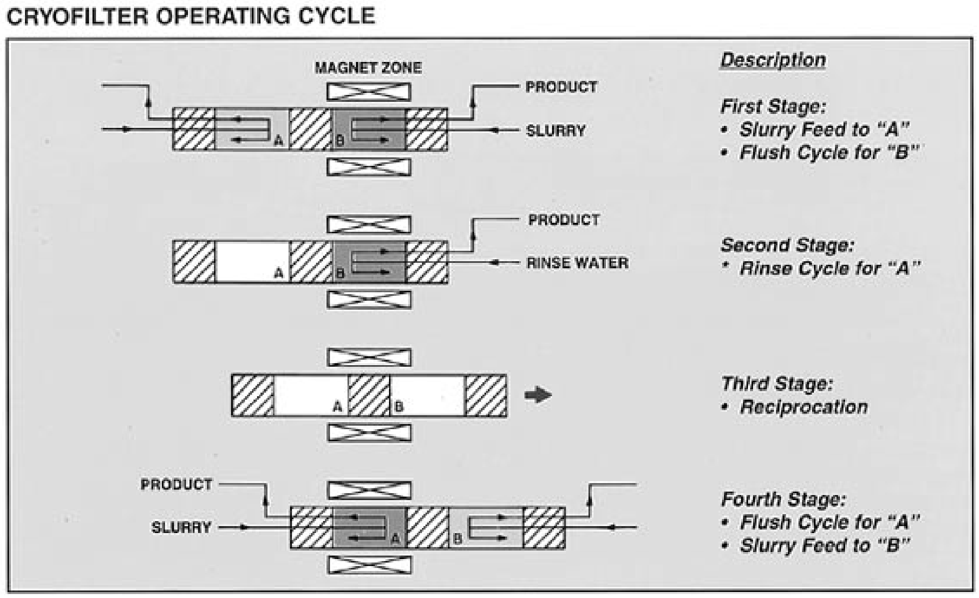

Fig. 14. A schematic representation of a reciprocating-type operating cycle. Courtesy of Carpco, Inc.

disconnected from the power supply, and current will continue to flow without additional power input. The basic processing cycle for the reciprocating magnetic separator is shown in Fig. 14. The key feature is that while one matrix canister is processing material in the central magnetic field region; the other matrix canister is being cleaned/flushed in the low field region (21).

Installed Systems. In 1989, the first LTS reciprocating magnetic separations unit used in the purification of kaolin clay went into operation in Cornwall in the United Kingdom. This unit consists of a NbTi conductor winding operating in a bath of liquid helium. It has a warm bore diameter of about 0.28 m with a maximum central field of 4 T and can process between 2 tons and 5 tons of kaolin per hour. In 1992, the second LTS reciprocating magnet system was installed in southern Germany for the purification of kaolin clay. This unit has a 0.26 m warm bore diameter with a maximum central field of 5 T and can process up to 5 tons of kaolin per hour. To date, 15 more industrial-scale LTS reciprocating magnetic separators have been installed worldwide. Reciprocating systems with warm bore diameters up to 1 m and central fields of 5 T are presently in operation (see Fig. 15). Ten smaller-diameter LTS reciprocating units, operating in research laboratories and pilot-scale production lines, have also been installed. One might expect that the complexity of superconducting technology would restrict the commercial viability of these units to developed and industrialized areas. In reality, the simplicity and reliability of the low-loss cryogen technology coupled with the reciprocating canister principle has enabled operation of these units in Munguba and Rio Caprim (21), which are remote areas of the Amazon rain forest.

HTS Reciprocating Magnetic Separator. Similar to its batch-type counterpart, it is possible to fabricate a reciprocating magnetic separation system using HTS coils. The commercial advantage of such a system would be the elimination of the use of liquid and gaseous cryogens even for very large-scale systems. It is too early to speculate on the commercial viability and technical feasibility of such a device.

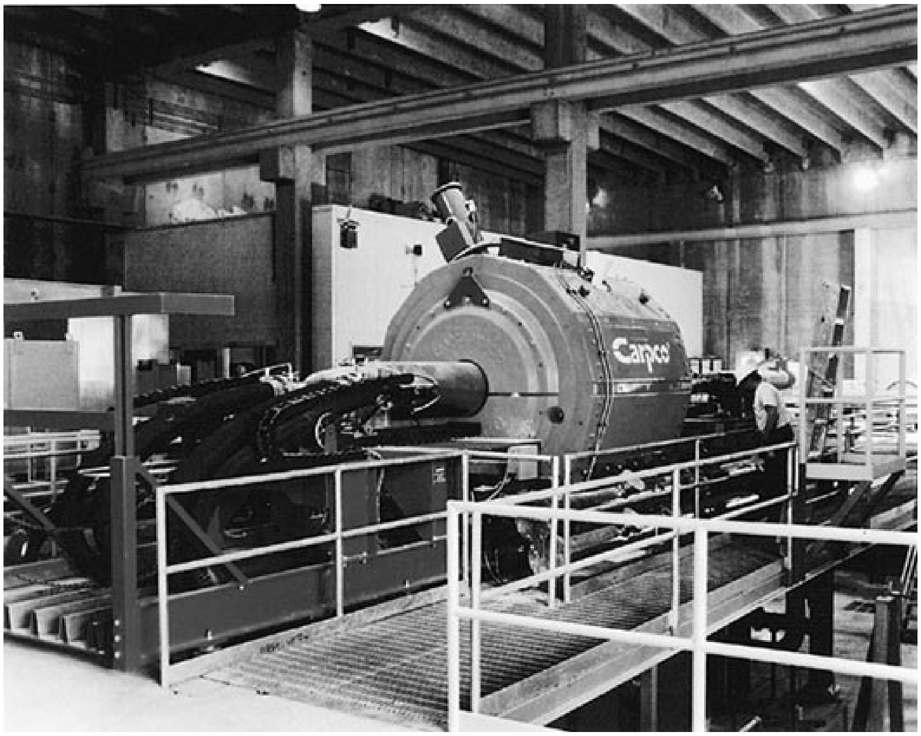

Fig. 15. A 5 T low-temperature superconducting reciprocating magnet with a 0.5 m bore, installed in Georgia. This magnet can process 20 tons of kaolin clay per hour. Courtesy of Carpco, Inc.

Applications of Magnetic Separation

Background. There are several commercially available mineral separation technologies that use specific gravity, magnetic separation, electrostatic separation, and column flotation, among others. All of these techniques exploit various discernible properties among mixtures of minerals. A comparison of different separation methods as a function of particle size range is shown in Fig. 16. Each separation technology has its own particular strength; however, typically a combination of techniques provides the best industrial minerals separation processes. Commercial magnetic separators come in a variety of shapes and sizes depending upon the required application. To select the most appropriate magnetic separator for a specific application requires an evaluation of several variables including the type of material being processed, wet or dry processing, particlesize, magnetic characteristics, and processing rate.

Kaolin Processing. Kaolin is a naturally occurring white clay consisting of microscopic platelets of aluminum silicate. The United States is the largest producer and exporter of kaolin in the world, with over 10 million tons valued at over $1.3 billion produced in 1993. Georgia generates 80% of the tonnage and 90% of the value of kaolin in the United States (16). Kaolin is used in the manufacture of fine porcelain and as a base filler in the manufacture of high-grade paper.

One of the most widely recognized industrial applications of high gradient magnetic separation is in the purification of kaolin clay. Magnetic separation has been used in the kaolin industry for over 25 years. The primary benefit is increased whiteness or brightness of the kaolin product in paper or ceramic applications. Magnetic separation has offered additional benefits to kaolin processing such as improved viscosity or rhe-

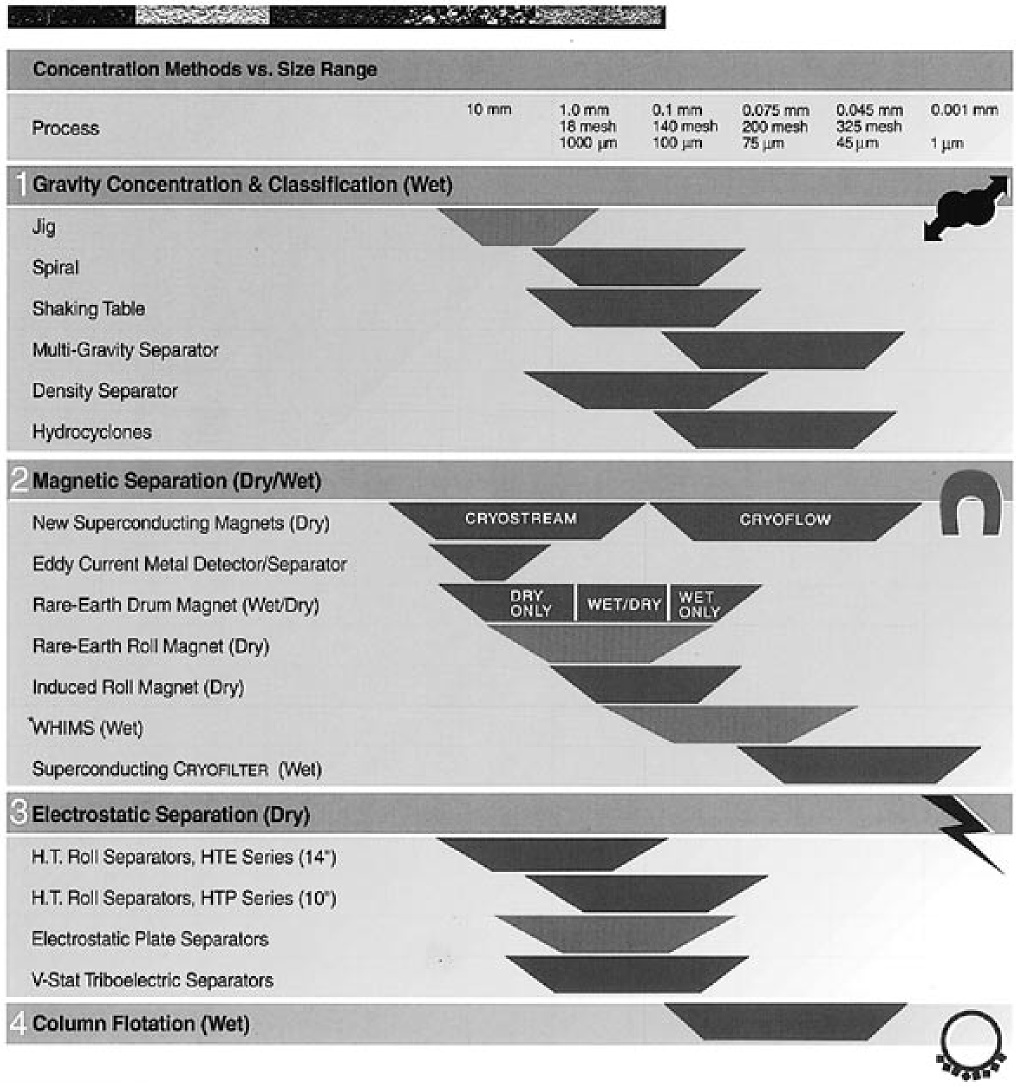

Fig. 16. A comparison of separation methods as a function of particle size. Courtesy of Carpco, Inc.

ology. Magnetic separation is used primarily to remove small paramagnetic impurities of titanium and iron compounds that discolor the clay. The impurities content typically makes up between 2% and 5% of the weight of kaolin. The quality of the processed clay is determined by the resulting brightness. The industrial association that establishes the brightness standards for the kaolin industry is the Technical Association of the Pulp and Paper Industry (*TAPPI*). Brightness is typically measured using a reflectance technique, and the results are compared with industry standards (e.g., TAPPI T 646 om-94 for pulverized material with 45°/0° geometry) (22). The improvement in brightness after magnetic separation depends upon many processing variables such as the initial quality of the unprocessed clay, magnetic field strength, mesh size and density, and retention time. Typical improvement between 1 and 5 brightness units can be expected as a result of processing kaolin in a magnetic field. Essentially all kaolin is processed through magnetic separators. The most common separator

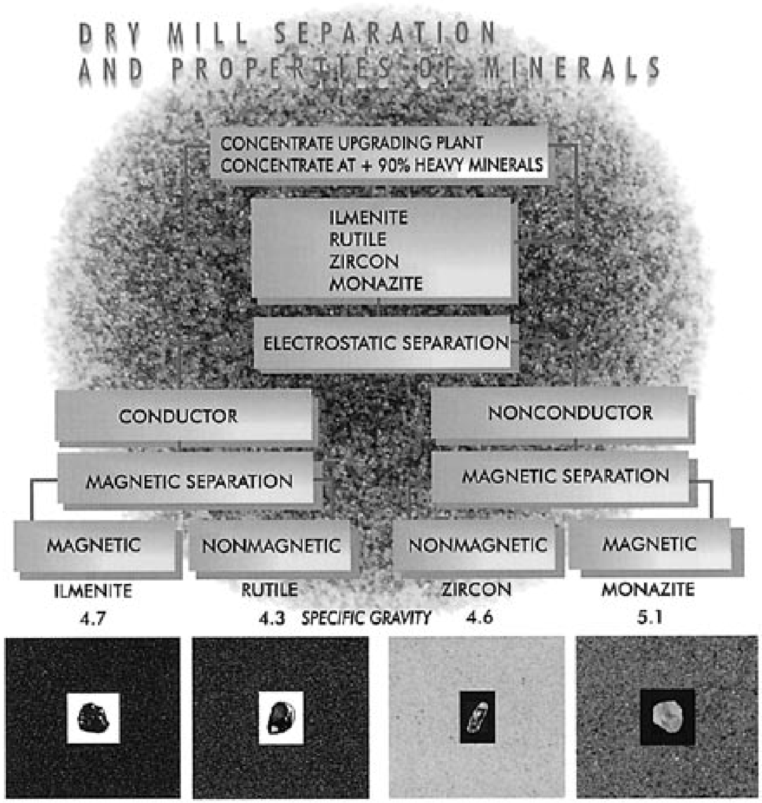

Fig. 17. Dry mill separation process of rutile and ilmenite. Courtesy of Carpco, Inc.

size in current use can process kaolin slurry at typically 70 m^3/h to 120 m^3/h, which translates to a production rate of approximately 23 metric ton/h to 45 metric ton/h (dry basis). Most of the magnetic separation devices used in the purification of kaolin clay are resistive magnets that operate in batch mode. However, both batch-type and reciprocating-type superconducting magnets are quickly displacing their resistive counterparts.

Titanium Dioxide. Rutile and anatase are naturally occurring ores containing microscopic particles of titanium dioxide (TiO_2), which is the most effective white pigment used in the paint, paper, and plastics industries. It is widely used because it efficiently refracts visible light imparting whiteness, brightness, and opacity when incorporated in a huge variety of fabricated products. Titanium dioxide is chemically inert, insoluble, and thermally stable under the harshest processing conditions. Titanium dioxide is produced commercially in two crystal forms—anatase and rutile. Rutile-based pigments are preferred because they refract light more efficiently, and are more stable and less photoreactive. Worldwide, over 2.2 million metric tons of TiO_2 are produced annually. The United States is both the largest exporter and consumer of TiO_2; however, the United States is also a net exporter of TiO_2. Asia is the fastest growing segment for both production and consumption of TiO_2. DuPont is the largest producer of TiO_2 in the world. A typical method for the separation of titanium dioxide is shown in Fig. 17. Magnetic separation is used in both the front-end screening process as well as the final processing of the “fines” of the product. As shown in Fig. 17, both ilmenite ($FeTiO_3$) and rutile (TiO_2) are electrically conductive; however, successful separation is possible because ilmenite is strongly paramagnetic and rutile is very weakly paramagnetic.

Table 3. Effect of Magnetic Treatment on Water Quality

	Charles River				Deer Island	
	Surface Control	Treated	Bottom Control	Treated	Control	Treated
Coliform Bacteria (per 100 ml)	16,000	0	16,000	300	2.8×10^6	18,000
Tubidity (JTU units)	20	2	1,700	1	50	3
Color (color units)	105	3	3,700	1	150	20
Suspended Solids (mg/L)	7	5	690	5	45	9

Chemical Processing. Reports of substantial improvements in material properties of polymers, particularly the spatial orientation of polymers, during the polymerization process by the application of a magnetic field, are intriguing to chemical and polymer manufacturers even though the reports do not represent typical magnetic separation techniques. For instance, Dow Chemical Company has reported an enhancement in the orientation of synthetic fibers extruded in the presence of a strong magnetic field (23). Significant increases in epoxy tensile strength of 80%, microhardness of 25%, and bending strength of 35% have been reported when materials of A-glycidyl ether are extruded in applied magnetic fields (24). In addition, increases in electrical conductivity and polymerization rates have been reported for conducting polymers of polyacetylene processed in magnetic fields. This has the implication of improved product quality as well as productivity increases. However, the benefits and feasibility of controlling spatial orientation on a molecular level while conducting high-volume manufacturing are presently unknown.

Water Treatment. Various studies have been performed demonstrating the successful treatment and clean up of wastewater using magnetic separation techniques. One study performed by Harvard University and Sala Magnetics showed that HGMS was highly effective in the removal of suspended solids, turbidity, coliform, color, viruses, and heavy metals from wastewater that had been treated with colloidal magnetite (25). In this study, ferromagnetic magnetite (Fe_3O_4) was chemically combined with traditionally nonmagnetic materials (i.e., pollutants in water). Using this “seeding” technique with magnetite and aluminum sulfate as a flocculent, coliform bacteria and other solids were successfully removed. For example, Table 3 shows the feed and magnetically processed data for surface and bottom samples from the Charles River and the Deer Island Sewage treatment plant in Boston, MA (10). Dissolved ions can also be separated from water systems in a similar manner. Another study (26) involved the evaluation and optimization of magnetic filters on boiler water. In this study, it was shown that magnetic separation was a highly effective technique for the removal of heavy metal contaminants of iron and copper oxide from boiler water. Results indicated that an expanded metal filter provided the highest efficiency, coupled with the lowest clogging incidences. Flow velocities up to 800 liters per minute were studied in magnetic fields of 0.5 T. Particle capture up to 98% was achieved under optimal conditions.

In terms of commercial activity, two companies in the United States, Aqua Magnetics International (27) and Fluid-Tech International Corporation (28) sell magnetic equipment for the descaling of boiler water as well as conventional filtration. Note that extensive research has been conducted in the former Soviet Union on the magnetic treatment of wastewater and that several thousand installations use the magnetic treatment of water from steam boilers.

Solid Waste Remediation. Magnetic separation techniques have received new interest in two specific areas of solid waste clean up. The first is in the area of ferrous metallic recovery (for recycle) from municipal solid waste. The Bureau of Mines reports that approximately 8% of municipal solid waste is comprised of ferromagnetic metallics. Each year up to 11 million tons of ferrous metallics are discarded domestically. Using magnetic separation techniques, the present recovery rate is about 180,000 tons per year (24).

Another area that has generated recent interest is the removal of uranium compounds from contaminated soil. Successful removal of uranium compounds from contaminated soil using magnetic separation techniques in a superconducting magnetic separator has been reported (29). This research has been limited to laboratory-scale quantities. The economic feasibility of using HGMS in large-scale solid waste cleanup (e.g., a government-qualified superfund site) has not been determined.

Coal Purification. Coal is the largest fossil fuel resource in the United States, with approximately 180 billion tons of currently recoverable reserves (30). One of the major difficulties with widespread coal use is the pollution problem, particularly with sulfur oxide emissions. Sulfur in coal occurs in three forms: pyritic, sulfate, and organic. Pyritic sulfur (FeS_2) accounts for 40% to 80% of the total content of most coals. In the bituminous coals from Illinois, for example, the mean total sulfur content is 3.57% of which 2.06% is pyritic sulfur. Pyrite occurs in coal as discrete particles varying in size from tens of micrometers to the submicron level.

Coal is diamagnetic, and pyrite is paramagnetic in nature. If coal is crushed and pulverized fine enough to liberate the pyrite, then separation by magnetic means is possible. High gradient and open gradient separators have been shown to remove between 80% and 90% of the pyritic sulfur and between 20% and 50% of the ash. The economic feasibility of magnetic separation of sulfur from coal is however highly questionable, compared with conventional processes.

Summary

Magnetic separation has been used in the processing of materials for more than one hundred years. Magnetic separation has a variety of modern uses ranging from the simple removal of tramp iron to the highly sophisticated removal of weakly paramagnetic minerals from clays. Several different types of magnetic separation devices are available. The choice and type of magnetic separator best suited for a particular application depends on several variables such as wet or dry processing, magnetic susceptibility of the materials present, magnetic fraction of the feed materials, particle size, and processing rate. The introduction of high gradient magnetic separation greatly expanded the role that these devices play in the mining of minerals. It has been estimated that the introduction of HGMS has nearly doubled the worldwide useful reserves of kaolin clay, by allowing the mining of lower grade material. It is clear that in large-scale high gradient magnetic separators, low-temperature superconducting technology is displacing conventional water-cooled copper magnets. With the recent discovery of high-temperature superconductivity, it remains to be seen if these new ceramic-oxide superconductors will replace the traditional intermetallic low-temperature superconductors.

Magnetic separation techniques are being explored in many nontraditional applications such as wastewater cleanup, the removal of pyritic sulfur and ash from pulverized coal, chemical processing, and the removal of uranium-oxide compounds from contaminated soil. The use of magnetiseeding techniques on nonmagnetic materials may open an entirely new area of benefits and applications. As more research and development is being performed, magnetic separation techniques continue to find new areas of potential environmental and commercial benefit.

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