SEPARATION, MAGNETIC SEPARATION

1. Principles

The application of magnetic separators relies on the behavior of individual particles under the influence of magnetic forces. When exposed to a magnetic field, all materials are affected in some way. Those that are attracted to the magnetic field are designated ferromagnetic; those that are repelled by it are called diamagnetic. Ferromagnetic materials are attracted along lines of magnetic force from points of lower magnetic field intensity to points of higher magnetic field intensity. The particles frequently retain magnetic properties after the applied magnetic field is removed. Diamagnetic materials are repelled along the lines of magnetic force from points of high magnetic intensity to points of lower field intensity. Only limited commercial use of diamagnetic effects has been made.

For practical applications, ferromagnetic materials are described as strongly magnetic (ferromagnetic), magnetic, weakly magnetic, or nonmagnetic. The limits of these groupings are not well defined and can vary in some mineral species. Values indicating the magnetic intensity required to separate a selected grouping of minerals are shown in Table 1. Only a few minerals are ferromagnetic, eg, magnetite. The dividing line between high and low intensity magnetic fields has been selected by some investigators to be one Tesla (10 kG).

Magnetic separation methods are used either to separate valuable minerals from nonmagnetic waste, or magnetic impurities or other valuable magnetic minerals from bulk nonmagnetic values. Magnetically susceptible mineral particles occur as individually discrete particles; as partially liberated particles consisting of two or more minerals, one of which is magnetically susceptible; or as particles stained or coated by a magnetically susceptible mineral such as geothite staining quartz or kaolin.

Minerals normally considered nonmagnetic may be rendered magnetic by elemental substitution of a small amount of a magnetic element in the crystal lattice. Magnetic properties may also be affected by partial alteration in weathering effects.

1.1. Definitions. Terms used in magnet evaluation are distinct from those in other processes and are defined as follows. Magnetic flux density refers to the number of magnetic lines of force passing through a unit area and is measured in Tesla (Gauss). One Tesla equals 10,000 Gauss. Magnetic field intensity, ie, the magnetizing force that induces the lines of force in the specific area under consideration, is also measured in Tesla. In addition, the term magnetic field gradient is used and refers to the rate of change of magnetic flux density from areas of low intensity to points of high intensity. This term is measured in Tesla per meter (Gauss per centimeter). Ferrous particles placed in a magnetic field can serve to focus magnetic lines of force. Thus the particles can become sites of high intensity.

1.2. Equipment. From the applications standpoint, magnetic equipment falls into one of four broad categories: tramp iron removal, magnetic particle separation and concentration, product cleaning, or eddy current separation on nonmagnetic metallics.

Tramp iron removal equipment is usually related to the material handling system involved. The most commonly applied magnetic separators include pulleys of the permanent magnetic and electromagnetic types applied in belt conveyor systems as head pulleys, suspended magnets applied over belt conveyor chutes or feeders, magnetic drums usually applied as a separately installed unit, plate magnets applied in or above chutes, and grate magnets applied in free-flowing product streams.

For magnetic particle separation and product purification, a selected plant area is determined and the feed is usually brought to that area for treatment. Magnetic separators applied include magnetic pulley separators, magnetic drums of several types, high intensity induced-roll magnetic separators, high intensity cross-belt magnetic separators, magnetic filters, wet high intensity magnetic separators (WHIMS), and special magnet types.

Eddy-current separation is usually applied to the removal of nonferrous metallics from product streams containing nonmetallic or nonmagnetic materials. These include applications such as material recovery facilities (MRF), eg, aluminum can recovery from commingled containers; both preburned and ash municipal solid waste plants; and nonferrous recovery from scrap fragmentizing operations.

2. Tramp Iron Magnetic Separation

Tramp iron magnetic separators are used to protect handling and processing equipment such as crushers, pulverizers, and material handling equipment. Separators are usually applied to dry material or material that contains only surface moisture. Iron coarser than 13 mm is usually defined as tramp iron. The size and shape of the tramp iron, together with the material handling system in place or proposed, must be considered when selecting the protective magnet. Magnetic equipment developed for tramp iron removal may involve magnetic head pulleys, suspended magnets, magnetic drums, plate, or grate magnets.

2.1. Magnetic Pulleys. An easy and simple way to achieve tramp iron removal from material handled on a conveyor belt is by means of a magnetic head pulley (see CONVEYING). Magnetic pulleys are available in both permanent and electromagnet construction. Most units are of the permanent type, although electrounits are also used for discriminatory separation where field control is required. Magnetic pulleys, relatively low in initial cost and easy to install, accomplish both continuous and automatic trap iron removal. A typical installation is shown in Figure 1.

Magnetic pulleys are available in diameters from 152 to 1524 mm and in widths that match the conveyor belt width. The material burden on the belt, belt speed, and type of tramp iron expected to be encountered are all considerations in magnetic pulley selections.

Selection. The magnetic pulley width should match that of the belt. The face width is normally 51 mm wider than the belt width up to 1067 mm wide, and 76 mm on widths in excess of 1219 mm. The speed of operation of the conveyor belt should be determined by calculating the maximum capacity to be handled. Using this information, the diameter of the pulley required to handle the capacity can be determined (Table 2). The operating belt speed must be acceptable for the diameter selected. If the recommended belt speed is exceeded, the pulley diameter that can handle the belt speed must be used.

Inclined belts provide additional areas of contact with the pulley magnetic field and can tolerate higher capacities than normal for a magnetic pulley application. Table 3, which indicates the correction factor to be applied to the capacity, can be used with Table 2 to make the magnetic pulley diameter selection for an inclined belt. The initial cost of units can be related to the capacity or volume throughput. Costs run about \$35 for each m^3/h on the smaller units; about \$50 for each m^3/h on larger units.

2.2. Suspended Magnets. Suspended magnets having either square- or rectangular-shaped base area are available. The square magnet is most commonly applied and permits installation of self-cleaning additions where such construction is desired. Suspended magnets can be installed at many points in a material handling system, at any point along a conveyor belt, at the discharge end of feeders or screens, and above chutes or launders. Suspended magnets are available in both permanent and electromagnet construction. The permanent type is largely limited to the lighter burden and lower suspension applications. Electro suspended magnets having deep magnetic fields are required when the burden on the belt exceeds the limits of a magnetic pulley.

The burden depth, belt speed, clearance required over the burden, and the size, shape, and weight of the tramp iron all determine the selection and size of the suspended magnet required. The depth of magnetic field produced using a suspended magnet is largely related to the dimensional configurations of the magnet. There is no standardization of magnet lengths or magnet widths. Each manufacturer has design parameters that influence the magnetic field obtained at a specific distance from the magnet face.

The preferred location for a suspended magnet is at an angle over the discharge of a conveyor. At this point the material moves into the magnet face and the load breaks open, making tramp iron removal easier. Suspended magnets can be installed at a variety of other points, but magnet selection must be modified for increased difficulty of tramp iron removal, owing to conditions such as ore on top of the tramp iron or a required change in direction of movement of the tramp iron.

A suspended magnet can be made continuous in the discharge of tramp iron by placing a belt over the magnet face and driving the belt across it. This discharging feature is particularly effective where long pieces of tramp iron are encountered.

Automatic discharging suspended magnets can be operated transversely (Fig. 2) or parallel to conveyor flow (Fig. 3**b** and 3**c**). Because the tramp iron must be attracted from a buried location and turned 90° from the movement of the conveyor belt, a larger and stronger magnet is required for a transverse installation. In some instances, the material handling layout, or desired operation location, dictates the use of the transversely mounted magnet.

Selection. Suspended magnet selection requires determination of the burden depth using one of the following formulas. For installation flat over the belt or transverse self-cleaned mounting, the burden design is calculated as

$$De = \frac{994C}{WV}$$

where De = burdendepth in mm, C = capacity in t/h, W = belt width in mm, and V = belt speed in m/s. Capacity for coal is measured in units of 800 kg/m^3. For installation at an angle over head pulley or parallel self-cleaned mounting, the burden depth is

$$De = \frac{821C}{WV}$$

For material having a bulk density higher or lower than 800 kg/m^3, the resulting De must be multiplied by the factor of $800/K$ where K = bulk density of material other than the coal in kg/m^3.

A suspension height, Ds, of 75 to 100 mm greater than De, or the maximum lump size, or the edge of the troughed idler in the burden is required, ie, $Ds = De + 75$ to 100 mm.

To determine the size of the magnetic field to be used, the type and size of tramp iron to be removed must be known. A general rule of thumb for 13 to 25 mm balls or cubes is that a 0.1-T (1-kG) field is required at the suspension distance. For tramp iron 50 mm and larger, a 0.05–0.08-T (0.5–0.8-kG) field is required at the suspension distance.

A much more accurate selection procedure is to determine the burden depth, suspension distance, and force index rating of the magnet and particle shape in order to determine the size and strength of the magnet required. From the manufacturer's Tesla curves, the size of magnet required to obtain the required Tesla reading at the determined suspension height can be calculated. Figure 4 shows force index readings for suspended magnets and the relationship to particle shape so that such particles can be picked up from a static bare belt. Force index values to be used in making suspended magnet selections must be obtained from the individual magnet manufacturer and applied as specified. Initial costs vary from \$42 for each m^3/h on the smallest units to \$15 for each m^3/h on the largest units.

2.3. Tramp Iron Magnetic Drums. Magnetic drum separators are used for tramp iron removal where magnetic pulleys and suspended magnets are not feasible. In effect, these are individual pieces of process equipment inserted in the process line. The magnet assembly is held in a fixed position inside the drum shell and the drum shell is driven around this magnet assembly (Fig. 5). The magnet assembly develops a field that typically covers 120–180° of the drum section. These drums can be fed at the top vertical centerline (Fig. 5**a**) or near the bottom of the drum (Fig. 5**b**). Overfeed drums produce the highest magnetic removal but result in carryover of some nonmagnetic product. Underfeed drums produce the cleanest magnetic concentrate having reduced nonmagnetic entrapment.

Magnetic drums are operated either as drums only, ie, on separately mounted framework such as those used in coarse iron cobbing and autofragmentization plants, or as drums enclosed in a housing, such as those used in tramp iron removal from smaller-sized or dusty material. Magnetic drums are selected on the basis of the volume in units of m^3/h to be handled from rated capacities in manufacturers' catalogs. The capital investment for magnetic drums can vary from \$1,500 up to \$81,000, depending on the application and whether an electro or permanent drum is required.

2.4. Plate Magnets. Plate magnets (Fig. 6**a**) are simple devices usually mounted in the bottom of a chute or duct. These magnetized plates are manufactured in various models and are normally of the permanent magnet type. The largest units provide protection to about 115 mm of material depth, at chute angles of up to 45° from the horizontal.

The plate magnet traps the tramp iron against the magnet face so that the trapped material must be periodically removed by hand. Automatic discharging-type plate magnets having timed air cylinder circuits to ensure proper cleaning are available. A chute angle not exceeding 45° is recommended and the plate magnet should be installed as close to the feed point as possible, in an effort to capture the particle before an acceleration increase.

2.5. Grate Magnets. The grate magnet (Fig. 6**b**) consists of a series of magnetized tubes, round or square, mounted in a frame or housing. The collected tramp iron must be removed periodically. Again, periodic self-cleaning mechanisms are available with times cylinders. The grate magnet, largely restricted to use on free-flowing material finer than 13 mm in size, is typically mounted at the discharge of a hopper. Grate magnet selection is made on the basis of volume to be handled, in m^3/h, from manufacturers' catalogs. Either style of unit can be supplied with a variety of permanent magnet materials, such as ceramic, Alnico, and rare earth (see MAGNETIC MATERIALS).

3. Magnetic Concentration and Purification

The magnetic responsiveness of mineral particles provides a positive means of concentrating and/or purifying ores. The type of magnetic separator used is influenced by feed condition, ie, wet or dry; the mineral to be concentrated or purified; the relative magnetic responsiveness of the mineral; the feed size; the purity to be obtained, in either the magnetic concentrate or the nonmagnetic product; the capacity to be handled; equipment operating and maintenance costs; and temperature of magnet applications.

3.1. Magnetic Separator Classification. Whereas a wide variety of magnetic equipment has evolved over the years, much of this equipment is specialized and has limited usage. A fundamental equipment classification can be made on the basis of feed condition. A wet condition involves the treatment of a slurry or slip; a dry condition involves treatment where the particles are essentially free to move as independent particles. Both conditions depend on liberation of the magnetic particles. If liberation does not occur, the magnet traps the middling particles and reduces the concentration of magnetics.

Wet or dry magnetic separators can be further divided based on the field intensity developed by the individual separator. Broadly speaking, classification by field strength is high, intermediate, or low intensity. Expressed in the magnetic unit Tesla, an arbitrary categorization of these classifications would be

>0.5 T, 0.25–0.5 T, and <0.25 T, respectively. Consideration must also be given to the size of the material being treated, the desired purity of either the magnetic or nonmagnetic product, desired capacity, and magnetic recovery.

3.2. Commercial Magnetic Separations. Various magnetic separators have been used to accomplish many mineral separations (see MINERAL RECOVERY AND PROCESSING). Some of these include iron ore, ie, magnetite and hematite concentration; abrasive cleaning using silicon carbide and aluminum oxide; garnet concentration; ilmenite concentration; barite purification; bauxite beneficiation; clay mineral cleaning; enamel slip or glaze cleaning; feldspar and kyanite cleaning; magnetite or ferrosilica media recovery in heavy-media separation (HMS) plants; manganese ore concentration; tungsten, monazite, and rare-earth mineral concentration; silica sand cleaning; and columbite and tantalite concentration.

In total numbers of installed units for mineral concentration, the wet magnetic separators generally exceed the number of dry magnetic units. Wet magnetic separators include wet drum separators for media recovery in HMS plants, wet drum separators for iron ore concentration, magnetic filters, and high intensity wet magnetic separators for mineral concentration and clay cleaning. Dry magnetic separators used in mineral concentration include magnetic pulleys for iron ore concentration as well as rare-earth magnetic pulleys for moderately responsive minerals, alternating polarity magnetic drums for iron ore concentration and miscellaneous uses, induced-roll high intensity magnetic separators for silica sand and feldspar cleaning and for ilmenite concentration, and high intensity cross-belt magnetic separators for high value mineral concentration used independently or with induced-roll flow sheets.

3.3. Low Intensity Wet Drum Magnetic Separators. Wet drum separators are used to recover ferromagnetic solids from a slurry feed. The principal areas of usage are in media recovery in heavy-media separation plants and in magnetite ore concentration. Physical construction of wet drum separators is slightly different for the two applications. The ore concentrator, which is more rugged in construction, is subject to more detailed specifications than the media recovery units. This is particularly true for feed and collection tank design, bearing construction, wear covers on the drums, magnet assembly design, and magnetic field strength ratings.

Media Recovery Wet Magnetic Drums. In HMS recovery service, the particle size of the feed, particularly the magnetic portion, is quite fine so that drum wear is not a serious problem. Maximum magnetic recovery is important and the highest magnetic purity and solids content in the magnetic concentrate are desired.

Factors to consider in selecting a wet drum separator for media recovery service are the percentage of solids in the feed slurry, the percentage of magnetics in the feed solids, the grade of media used in the operating circuit, the feed volume in m^3/h to the separator, the magnetic discharge rate in metric tons per hour (MTPH) from the separators, and the desired magnetic recovery.

Media recovery magnetic drums are conventionally available in 762 or 914 mm diameter and in drum widths to 3.05 meters, usually in increments of 305 mm. The effective magnet width is about 150 mm less than the overall drum width. In some instances 1219 mm dia wet magnetic drums have been used, but the higher capacity of these units does not usually justify the higher costs involved.

Both electro and permanent wet drum separators have been used in media recovery, but permanent-type magnet assemblies are usually preferred because of the savings obtained in the elimination of magnet energization power costs. Both concurrent and countercurrent feed arrangements (Fig. 7) have been used in media recovery plants. The concurrent drum arrangement is usually recommended to give the highest magnetic content in the magnetic discharge and regularly provides the highest percentage of solids in this discharge. The countercurrent unit gives a slightly higher recovery in some applications, particularly when the magnetic loading is heavy.

Feed Solids Content. A good HMS plant operation keeps the medium as free of fines as possible by effective screening of the heavy-media separation vessel feed. Reduced fines reduce viscosity problems in the medium and result in sharper separation of sink and float products. It also improves magnetic recovery on the magnetic drum separators and gives a cleaner magnetic concentrate. The use of cyclones in the HMS circuit, either as the heavy-media separation vessel or as a densifier for rinse or wash water, increases the solids content and must be evaluated in selecting the media recovery wet drum separators for plants in which cyclones are used.

A single wet drum separator is typically used in plants where the feed solids are in the 10–15% range. Extremely dilute feeds make magnetic recovery more difficult and feed volume should be reduced by a factor of 0.5–0.75 for such dilute feed. For solids in the 20–25% range, either single-drum 914-mm units or double-drum 762-mm units are recommended. Above 25% solids, 914 mm dia double drums are recommended.

Magnetic Content of Feed Solids. The magnetic content of the solids is typically $\geq$60%. Conventional selection procedures can be used in such cases. When the magnetic content of the solids falls below 60% the feed volume should be reduced and multidrum separators considered in order to maintain higher magnetic recovery.

Media Size. Media are supplied in several size grades and the grade used varies at each plant. The finer grades improve media stability, but finer particles are more difficult to recover and the feed rate of these finer-grade slurries should be reduced by a factor of 0.5–0.75 to maintain magnetic recovery. A typical size analysis as used in various heavy-media separation plants treating coal (qv) is given in Table 4.

Recommended Feed Volumes. Both feed volume and magnetic solids discharge rate should be balanced in selecting media recovery drum size. The feed rates typically recommended for single and double wet drum separators depend on drum diameter. For a 762 mm dia single drum, the recommended feed rate is 50–55 $m^3/(h \cdot m)$; for either a 914 mm dia single drum or a 762 mm dia double drum, 55–70 $m^3/(h \cdot m)$; for a 914 mm dia double drum, 70–95 $m^3/(h \cdot m)$.

Magnetic Discharge Rate. In order to maintain high magnetic media recovery, the magnetic discharge rates should not exceed 9 MTPH/m for 762 mm dia drums or 15 MTPH/m for 914 mm dia drums.

Wet Drum Operating Considerations. Selection of wet drum separators using the selection criteria discussed produces a media recovery in the

99.6–99.9% efficiency range. Significant operating considerations must be maintained, however, to ensure these recoveries. Some of the most important are as follows: (*1*) maintenance of a reasonably uniform feed rate and feed distribution across the drum; (*2*) maintenance of the magnetic discharge point at the proper position. This magnetic discharge point can usually be adjusted slightly, but loose clamp bearings can cause the magnet assembly to fall out of position; (*3*) maintenance of a proper operating level in the separator tank, ie, loss of level or excessive overflow rates can cause serious loss of magnetic recovery efficiency; and (*4*) periodic inspection of drums and tanks to determine if holes have developed, which results in leakage into the drum or out of the tank. Wet drum-type magnetic separators for heavy-media separation had an initial cost of about $8000/m of width in 1995.

Wet Magnetic Drums for Ore Concentration. The depletion of direct shipping-grade ore bodies and the demand for higher grade iron ore concentrates have led to the usage of magnetic drum separators in the concentration of magnetite ores. These relatively low magnetic strength drums can also be used to concentrate other minerals having ferromagnetic properties.

Typically, ore bodies are relatively low in iron content. Iron minerals are finely divided in a gangue matrix. Wet grinding is usually required to liberate the iron minerals, although some beach sands may have liberated iron mineral values. Wet drum separators are limited to the treatment of material $\leq$10 mm. The magnetic drum separators applied are usually related to the grinding circuit required to liberate the iron mineral, and are typically designated by application as cobbers, roughers, or finishers.

Cobbers. Magnetic drums used in cobbing services are designated to obtain maximum rejection of a nonmagnetic product and maximum recovery of the iron mineral. Typically, cobbers are applied on a rod mill discharge product. Because the objective is to obtain maximum capacity, these drums are 914 or 1219 mm in diameter and incorporate wear covers on the drum shells to take the wear introduced by the relatively coarse feed size.

Most iron-ore-concentrating drums are applied in a multidrum configuration in order to obtain maximum rejection of nonmagnetic particles. In cobbing service, two drums are typical but as many as four have been used. These drum concentrators incorporate a repulping box ahead of each drum in order to provide the next drum with a feed that can accomplish nonmagnetic rejection.

Laboratory or pilot plant tests are usually conducted on individual ores to determine the number of drums required to obtain optimum concentration results. Drums that are 914 or 1219 mm in diameter are usually used in cobbing service.

Roughers. Magnetic drums used in roughing service, ie, roughers, sometimes called cleaners, are applied after further size reduction has been accomplished on the cobber concentrate. Because the cobber has produced significant upgrading of the ore, the magnetic loadings on these drums is significantly increased. Replaceable drum covers are usually used. The objective is to obtain rejection of nonmagnetics while maintaining magnetic recovery. Typically, a double-drum separator is used in this rougher service, and in some plants countercurrent or combined concurrent and countercurrent drums are used to maintain magnetic recovery under heavy loads. Drums 914 or 1219 mm in diameter are used in roughing applications.

Finishers. Magnetic finishing drums are designed to produce the highest possible iron content in the concentrate. Typically, the feed size has been reduced to a nominal size of −74 μm (−200 mesh) or −44 μm (−325 mesh) in a ball mill circuit. The feed tank and feed arrangement of the finisher separator is usually of the semicountercurrent design. The objective is to disperse the feed particles in order to obtain maximum rejection of nonmagnetic particles. Both 762 and 914 mm dia drums have been used in finisher applications. Drum covers frequently are not used in finisher construction because of the material size.

Feed Factors in Wet Drum Concentrator Selection. Feed factors in selection of wet drum concentrators include the rate (MTPH), size (10 mm dia max), and volume (m^3/h of pulp), as well as the magnetic content, ie, projected magnetic discharge rate (MTPH), and the degree of liberation at each stage, which effects the size distribution. Also important are the desired magnetic recovery and required magnetic field strength. Maximum feed rate varies with the type of separator being considered, ie, cobber, rougher, or finisher. In concentration applications, capacity must be balanced with magnetic recovery and nonmagnetic rejection.

Feed rates for the various types of separators are as follows:

	Rate, MTPH/m	
Type	Maximum	Recommended
cobber	75	45
rougher	60	45
finisher	15	15

Owing to the feed pan distance usually maintained on wet drum cobbers, the wear encountered with coarser particles, and the feed velocities required to move coarse particles, the recommended upper size limits for cobber separators is 10 mm in diameter. Individual ore characteristics required to obtain liberation determine the feed size in rougher and finisher feeds. For finishers, where all the nonmagnetics must be overflowed, a sufficiently fine size to accomplish the overflow must be obtained. Typical feed sizes for cobbers are from −841 μm (−20 mesh) to 10 mm; for rougher, −420 μm (−35 mesh) to −297 μm (−48 mesh); and for finishers, −63 μm (−270 mesh) to −44 μm (−325 mesh). The magnetic content of the iron ores to be concentrated varies over fairly wide limits. Ores as low as 10 wt% Fe have been successfully treated, as have ores having up to 50 wt% or more iron.

Because liberation is not complete at the cobber stage, a substantial amount of attached gangue is carried into the cobber concentrate. Typically, the cobber concentrate contains 50% Fe and accordingly the magnetic content of the rougher feed is quite high. Finisher feed contains 2–5% nonmagnetics and has a high magnetic content, ultimately producing magnetic concentrates near 70% Fe.

Complete liberation of most iron ores is usually finer than 149 μm (100 mesh). Some ores have to be reduced to −44 μm (−325 mesh) for successful concentration. In many instances, reduction to a size suitable for pelletizing is required (see SIZE REDUCTION).

Desired Magnetic Recovery. In ore concentration, maximum recovery is desired at all times. Rejection of middling particles, although sometimes desired, is difficult to accomplish on wet magnetic drum separators.

Magnetic Strength Required. There is considerable debate as to the magnetic field pattern required for the various stages of ore concentration. Several styles of magnet assemblies and a variety of pole combinations are available. Average 50-mm readings, ie, average based on readings taken at 50-mm distance and made at the center of each gap and center of each pole, of 0.08–0.12 T are available on 914 and 1219 mm dia wet drum separators. Magnetic drums of this strength have operated successfully in commercial plants. Finisher drums are frequently 762 mm in diameter and develop average 50-mm readings of 0.05 T.

Wet Drum Ore Concentrator Specifications. There is a high degree of individual preference among users for specific construction features in the wet magnetic drums purchased for ore concentration plants. Specifications usually include number of drums, drum diameter, drum shell thickness and material of construction, drum head construction and material of construction, tank type and arrangement, type of magnet assembly, bearing type and lubrication arrangement, type and thickness of wear covers, and effective magnet width.

Drums. Typical selection for the number of drums used in the various applications is two to four for cobbers, one or two for roughers, and two or three for finishers. The inner drum shell, usually 3 mm thick, is specified Series 302 or 304 stainless steel. Drum heads are usually of high tensile strength aluminum alloy or brass. Recessed head bolt construction having an effective seal is specified.

Drum diameters are typically 762, 914, or 1219 mm, all of which have been used in the various basic applications. In some instances, standardization of diameter is specified because of maintenance considerations. Because these separators are constructed more ruggedly and require repulping stages, capital costs are higher than heavy-media separators. Costs in 1995 were approximately \$10,000/m of width for single-drum modules and multiples of the single-drum module.

Tanks. Three basic tank types have been used in ore concentration: concurrent, where feed slurry moves in the same direction as the drum rotates (Fig. 8**a**); countercurrent, where feed slurry moves in the direction opposite to drum rotation (see Fig. 7**b**); and semicountercurrent, where there is uprising feed with the drum moving in a selected direction and all tailings rejected through the tank overflow on the opposite side of the magnetic discharge (Fig. 8**b**).

An all-stainless steel tank, Series 302 or 304, is frequently specified, but composite tanks of stainless and carbon steel have also been used successfully.

Magnet Assembly. Several types of magnet assemblies and pole combinations have been used successfully. Both electro and permanent magnet assemblies have also been employed. The permanent assembly is frequently preferred because of the power savings effected. Typical pole specifications for the various applications are five or six poles for cobbers as well as for roughers, and from four to ten (normally five) poles for finishers.

The effective magnet width is always less than the total drum width and must be considered when determining the expected capacity of the unit.

Bearings and Wear Shells. Ball-, roller-, and sleeve-type bearings have all been used successfully. Lubrication through the shaft without stopping drum rotation is preferred. A butt of lapped-type wear shell constructed of nonmagnetic stainless steel is preferred for cobber and rougher units. Shells of 3- to 6-mm thickness have been specified, although the shell thickness does influence the surface strength of the magnetic drum and should be taken into consideration when the Tesla pattern is specified. Finishers have been operated using both stainless and soft rubber covers and without any cover at all.

3.4. Wet High Intensity Magnetic Separators. There are several types of relatively new, wet high intensity magnetic separators (WHIMS) commercially available. The first units were developed in England for clay purification. This early separator, ie, Jones' separator, was a cycling-type machine that later evolved into the continuous carousel unit (Fig. 9). The Jones' unit has been used to concentrate itabirite in Brazil. These units are capable of developing magnetic field intensities of 2.0 T. Other units have been applied in the purification of silica sand, feldspar, and fluorspar. Concentration of ilmenite, monozite, tourmaline, and chromite has also been achieved by WHIMS separators.

Other wet high intensity units provide configurations that have rotating matrixes similar to wet drum units having cooled electro coils. Still others fall into the category of filters using cryogenically cooled coils and stationary matrixes (Fig. 10).

3.5. Magnetic Filters. Small magnetic filters are simple devices in which an electrically energized coil or permanent magnets are used to magnetize a magnetic steel grid. The grids develop high points of magnetic strength on their edges. The material to be cleaned is passed through this series of magnetized grids and magnetic particles are attracted to and held onto the grid edges. Periodic cleaning of the magnetic filter is required.

Magnetic filters have been used to clean paint slips and liquids. Filters that are open to the atmosphere or closed, ie, pressure type, are available where the filter inlets are matched to standard pipe connections from 10 to 50 mm, for low capacity applications.

Filter selection, based on the feed capacity, m^3/h, to be handled, varies from 1 to 45 m^3/h in the many sizes available. A permanent magnetic filter is shown in Figure 11.

3.6. Dry Magnetic Separators. Commercial types of dry magnetic separators fall into two broad areas. Low intensity magnetic pulley separators (see Fig. 1) and several types of magnetic drums (Fig. 12) have been used to concentrate iron ore, sponge iron, and to recover iron values from steel mill slags. These separators have effective working magnetic field strength of under 0.1 T and are largely limited to the recovery of ferromagnetic materials. However, rare-earth rolls are available that produce 0.6 T and effectively separate moderately responsive minerals.

High intensity dry magnetic separators include two basic types: the induced-roll and the cross-belt magnet. A high intensity inductively magnetized disk has been used in some areas of the world, but this is not well known in the United States. In addition, high intensity ring-type units have been developed and are used in Australia and Europe, but generally are not used commercially in the United States.

3.7. Magnetic Pulleys. Magnetic pulleys of special design are used in the concentration of magnetite and other ferromagnetic minerals. For best results, the feed should be screened into various-sized fractions and each fraction treated on a separate pulley separator unit. Typical feed size is $100\times 50\ mm^2$, $50 \times 25\ mm^2$, and $25 \times 6\ mm^2$. When treating material of -10 mm, an axial pole magnetic pulley should be utilized, as this provides uniformity of field across its width.

The magnetic pulley selection is largely dictated by the tonnage to be handled. The feed should be as uniform as possible across the pulley width. Feed size dictates the diameters of the magnetic pulley used. The larger diameter pulley develops larger magnetic holding capability, as well as a larger radius, which improves holding action of the magnetics on the pulley face. Pulley diameters recommended for various feed sizes are as follows:

Feed size, mm^2	Recommended pulley diameter, mm	Capacity, MPTH/m
100×50	762–914	240–400
50×25	460–610	160–240
25×6	305–460	75–135

3.8. Magnetic Drums. Two types of magnetic drums, which vary in the construction of the magnet assembly inside the drum, are used in concentration service. The first incorporates a magnet assembly in which the poles vary in polarity across the drum width. This type of drum develops a strong holding force and is used in treatment of ore up to 200 mm in diameter. The second magnetic drum is used for the concentration of finer material, usually -25 mm or smaller in size, and incorporates a magnet assembly of from six to as many as 55 poles that vary in polarity around the circumference of the drum.

Typically, the magnet assembly of the first type, the coarse ore concentrator, has a magnet arc of $120-180^{\circ}$; the assembly of the fine ore concentrator has a magnet arc of $180-240^{\circ}$. The alternating polarity of the fine ore concentrator causes agitation and reorientation of the magnetic particles as the particles traverse the magnet arc, producing the maximum cleaning effect.

Coarse Ore Treatment. Coarse ore concentrating drum selection is based on capacity to be handled and the size of the particle to be treated. As in the case of magnetic pulleys, a sized feed is desirable for optimum operation. Recommended capacity and diameters for coarse ore drums are as follows:

Feed size, mm^2	Recommended drum diameter, mm	Capacity, MTPH/m
200×150	1524–1829	895–1190
150×100	1067–1219	750–900
100×50	762–914	240–400
50×6	305–460	75–135

Fine Ore Treatment. The alternating polarity drums, used for the concentration of −25−mm ores, are available in both electro and permanent magnet types. The permanent units are usually used on ore finer than 13 mm. The field strength of the electro drum assembly can be regulated by putting a control resistor in the magnet circuit. Control of the permanent drum performance can be regulated to some degree by using a variable-speed drum drive motor to create variations in centrifugal forces exerted on the particles.

A variety of magnet pole configurations are available. The alternating polarity drums are usually available in 460−914 mm diameter and have from seven to 55 poles. Multidrum treatment is frequently used to obtain both additional magnetic recovery and improved magnetic cleaning. The physical arrangement of multipole drums depends on the objective of the separation. The primary magnetic concentrate is retreated on the secondary drum when maximum cleaning is required; the primary nonmagnetic product is retreated in the primary drum when maximum recovery is required (see Fig. 12).

Magnetic drum selection of alternating polarity drum separators is based on the capacity to be handled and the particle feed size. Recommended capacity and drum-type selections for permanent magnets are as follows, where 0 indicates fines:

Feed size, mm^2	Drum diameter, mm	Number of poles	Capacity, MTPH/m
25×13	610−762	6−8	75−90
13×6	762	8−30	45−75
6×0	914	10−55	15−60

The drums for a feed size of 25×13 mm^2 may consist of either electro or permanent magnets.

3.9. High Intensity Induced-Roll Magnetic Separators. Induced-roll magnetic separators are typically used for cleaning such materials as silica sand and feldspar. Both overfeed and underfeed roll designs have been built. The latter is used to obtain a higher degree of cleaning at a relatively high capacity. Owing to the narrow magnetic operating gap, the feed size to induced-roll separators is limited to material finer than 3-mm size. Furthermore, because of the surface activity of very fine material, there should be little 74-μm (−200−mesh) material present, unless the loss of this material in the magnetic concentrate can be tolerated.

Induced-roll separators have also been used in the concentration and cleaning of heavy minerals found in beach sands. Examples are the rutile and ilmenite beach sands of Florida and New Jersey. Induced-roll separators are frequently used in combination with high tension or electrostatic separators.

For selective removal of minerals that vary in magnetic response, or for maximum removal of contaminants in silica sand or feldspars, multistage induced-roll separators are applied. Induced rolls from a single roll to as many as seven rolls arranged in series are available. The roll width is limited to 760 mm, largely because of deflection forces exerted on the induced roll by the strong magnetizing sources utilized. Field strengths up to about 2.0 (20°kG) are developed in the working gap.

Induced-roll magnetic separator selection is influenced by the objective of the separation and the capacity to be handled. There is no standard roll diameter, although 100 mm dia rolls are most frequently used in magnetic cleaning services, such as silica sand cleaning. The principle of operation of the induced-roll magnetic separator is shown in Figure 13. Recommended capacities for 100-mm roll diameters are 2–4 MTPH/m of width for cleaning operations, and 1–2 MTPH/m of roll width for concentrating service. The number of magnetic fields to be used varies with the application and is largely determined by preliminary testing. For silica sand cleaning operations, a three-roll or a five-roll machine is recommended in most cases. The primary roll of most induced-roll separators usually utilizes leak paths of flux from the high strength energizing coil in order to develop a moderate strength primary roll. This roll removes ferromagnetic particles that tend to accumulate and block the secondary rolls if not removed. These units can have a high initial cost per ton treated. Prices amount to about $15,000 per roll on a 762-mm wide unit.

3.10. High Intensity Cross-Belt Magnetic Separators. For very selective concentration of weakly magnetic minerals, the high intensity cross-belt separator has been utilized. This separator utilizes a feed belt on which a thin layer of the feed material is introduced to a high intensity magnetic field. The magnetic materials are lifted to the upper pole of this field and transferred by a cross-belt to a collective hopper.

To obtain the high field gradient required for separation of the weakly magnetic minerals, the upper pole is shaped to a point or series of points for improved capacity. The bottom pole is flat. In cases where a variety of weakly magnetic minerals are to be concentrated, a series of high intensity poles is utilized, which have increasing coil strength at each succeeding pole, or by using a variation in the air gap. A high intensity cross-belt magnetic separator is shown in Figure 14.

The cross-belt separator has been used to concentrate such high value minerals as ilmenite, wolframite, monazite, xenotime, columbite, and tantalite. The use of a lift action provides a high degree of selectivity and a minimum amount of entrapped nonmagnetic minerals. Because the accumulation of magnetics at the high intensity point creates a buildup across the belt width, the cross-belt magnet widths are limited to a maximum of 610 mm. The feed is, at most, a few particles deep and accordingly feed rates are limited to about 2 MTPH/m of feed belt width. Lower capacities are required for the cleaning of very weakly magnetic minerals.

A variable-speed drive is usually used on the feed and cross-belt drives to exercise control in separator operation, although the speed is not usually changed once the optimum operating condition is established. Feed rates and the selection of the number of magnetic poles are usually determined by preliminary laboratory tests. The mineral types involved in the feed largely determine the number of poles selected. High intensity cross-belt separators are frequently used in combination with induced-roll or electrostatic separators.

3.11. Eddy-Current Separation of Nonferrous Metallics. The advent of material recovery facilities (MRFs) has increased the need for automatic removal of metallic values tenfold. Although many small facilities rely on hand sorting of commingled refuse, ie, glass, aluminum, tin, and plastic, as these plants grow in size, ways of reducing labor costs become more important. Suspended magnets are used to remove ferrous material. The removal of aluminum is relegated to a form of eddy-current separation. A typical processing system is illustrated in Figure 15.

The eddy-current concept was the basis for a separator patented by Thomas Edison in 1889 (1). Only since the mid-1980s has this type of separator been utilized, however, because of the growth in the recycling (qv) and scrap industries. Although the recycling area is of main consideration, there are other areas of usage. These separators are used both in foundries and in autoshredder operations for the removal of nonferrous metallics from foundry sand and from shredder fluff, respectively. In addition, when applied to aluminum dross (slag), these separators effect the recovery of nonferrous metallics after crushing and sizing; when applied to electronic scrap, they effect the recovery of nonferrous values from shredded circuit boards.

Principle of Operation. Electrical current flows are induced in all conductors when exposed to an a-c field. These currents generate a magnetic field surrounding the conductors which oppose the field being produced by the a-c field with a force sufficient to repel the conductor. Figure 16 illustrates this principle by showing a rotor consisting of many poles.

The force exerted by a machine is proportional to the field intensity, H^2, and the frequency. In a rotating device, the frequency is proportional to the number of poles and the rotor rpm. For example, a unit having 10 poles and moving at 3000 rpm produces15 kilocycles. With the advent of improved rare-earth magnet material, the field intensity for this type of rotor configuration can be greatly increased compared to other types of magnet material, such as ceramic, Alnico, and the early rare earth. Energy products that are nearly seven times greater than those employing a ceramic rotor can be attained.

On a given metallic particle, the repulsive force, F, is dependent on particle mass, M; electrical conductivity, σ; density, ρ; and shape, s.

$$F \approx \frac{M\sigma}{\rho s}$$

The force is proportional to the ratio of a particle's conductivity to its density. Table 5 lists these ratios for several metals.

It is evident from Table 5 that if there were two particles of the same shape and mass, one aluminum, the other copper, the aluminum would have about twice the reaction in repulsive force than would the copper. Both metals have high conductivity, but the densities are nearly three to one.

Particle shape is also important. Disk-shaped as well as cylindrical-shaped conductors have a high response because large induced current loops are formed. Small randomly shaped conductors, such as those present in crushed slag, also respond favorably. Sphere-shaped particles generate small-current loops, however, and do not have a high response. Multiple-current loops occur in conductors that have irregular bends, producing counteractive forces that tend to nullify each other.

4. Manufacture

Magnetic separators are produced worldwide. Some of the principal manufacturers of equipment are as follows:

Manufacturer	Location
Boxmag Rapid	Birmingham, U.K.
Carpco Magnetics	Jacksonville, Fla.
Dings Magnetics	Milwaukee, Wis.
Eriez Magnetics	Erie, Pa.
S. J. Frantz Co.	Trenton, N.J.
Humboldt Wedag	Bochum, Germany
Krupp Industries GmbH	Rheinhausen, Germany
Master Magnets	Birmingham, U.K.
O. S. Walker Co.	Worcester, Mass.
Readings & Lismore Pty., Ltd.	New South Wales, Australia
Stearns Magnetics	Maple Heights, Ohio
Zelba	Spisska Novaves, Czechoslovakia

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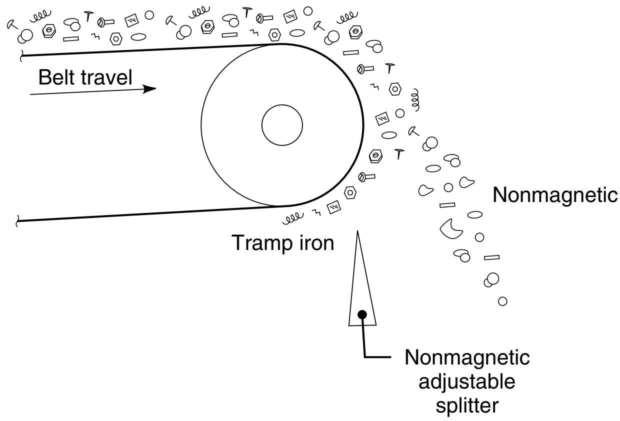

Fig. 1. Principle of operation for magnetic pulleys.

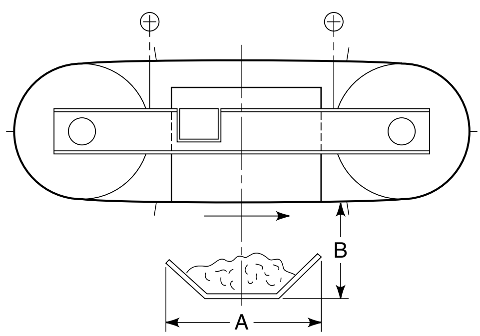

Fig. 2. Self-cleaning suspended magnetic separator over conveyor run (cross-belt), where A = conveyor belt width; B = distance to magnetic belt.

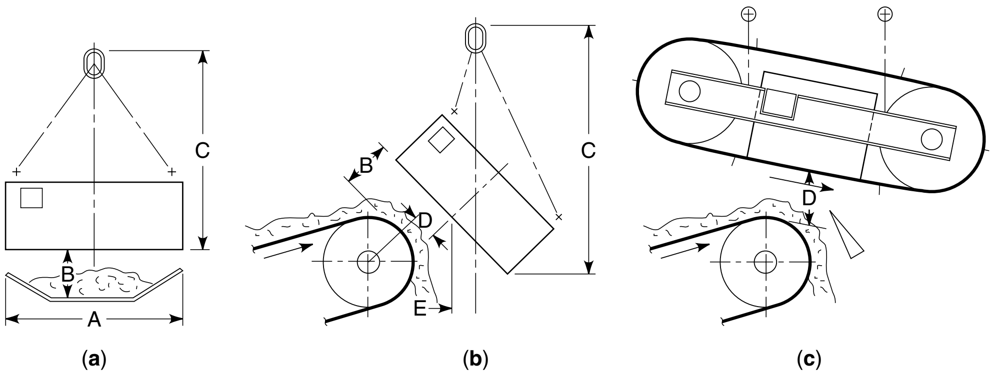

Fig. 3. Suspended magnets, where A = conveyor belt width; B = suspension height; C = overall height; D = distance to magnet centerline; and E = location of lift point. (**a**) Manually cleaned over conveyor run system, (**b**) manually cleaned over head pulley, and (**c**) self-cleaning separator over head pulley (in-line).

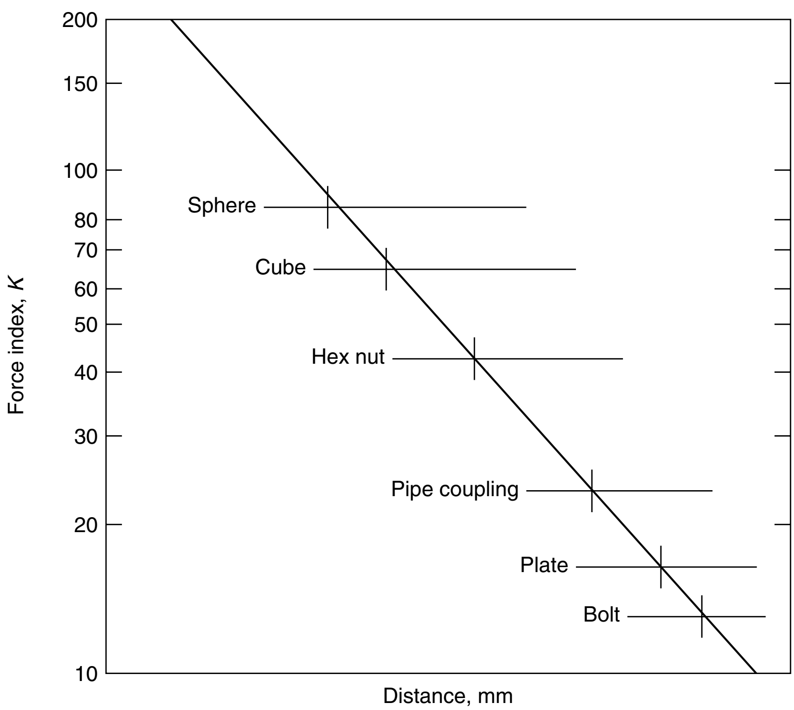

Fig. 4. Static force index (Tesla(ΔTesla/Δdistance)) for varying particle shapes, where K is the bulk density of material in kg/m^3. The plate has dimensions of $6 \times 76 \times 76$ mm^3; the bolt has dimensions of 6×25 mm^2. The horizontal line represents the distance from the magnet face.

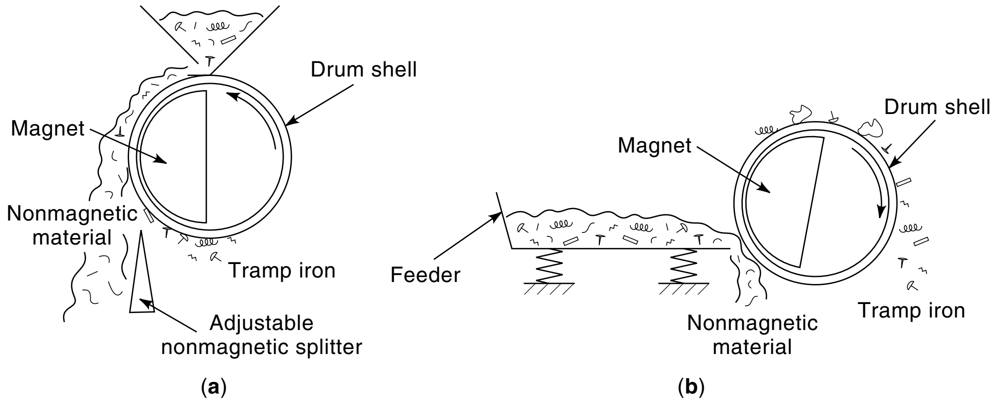

Fig. 5. Arrangements for magnetic drums: (**a**) overfeed and (**b**) underfeed.

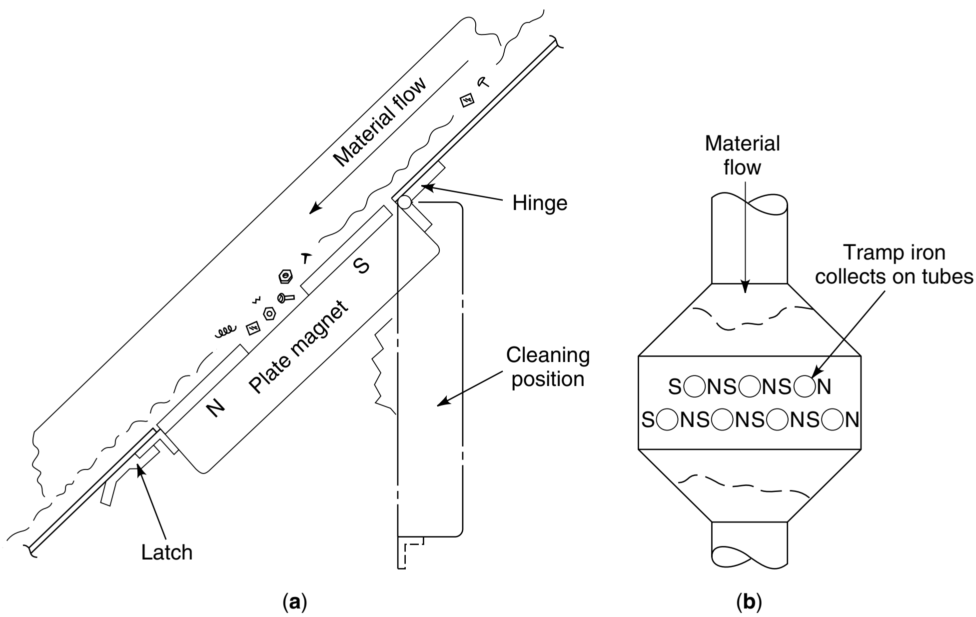

Fig. 6. Schematic of magnetic separation systems where N and S denote the poles of the magnets: (**a**) plate and (**b**) grate magnet.

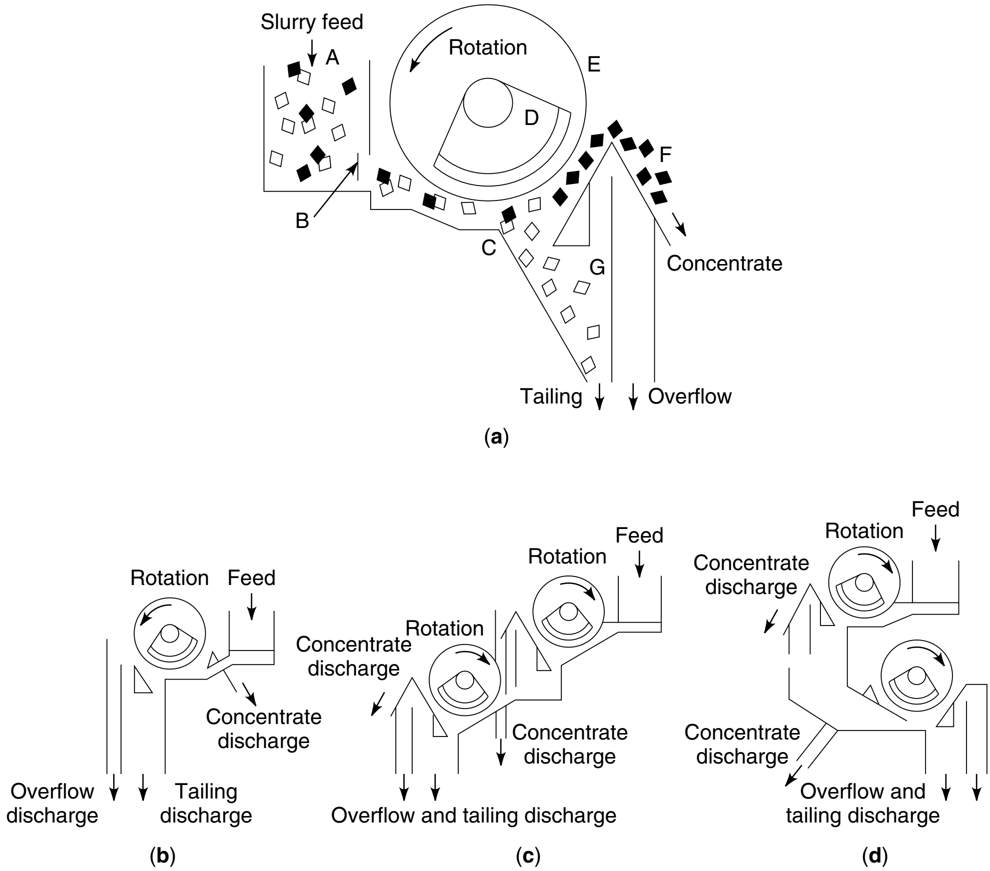

Fig. 7. Magnetic wet drum tank configurations of single and multiple drums: (**a**) operational features of a concurrent tank, where A represents the slurry distribution box of nonmagnetic stainless steel; B, the tramp screen for oversize material; C, the all-stainless steel tank construction; D, the high strength strontium ferrite magnet assembly; E, the nonmagnetic stainless steel drum shell with O-ring seals for water-tight construction; F, the high density, 60% solid magnetite discharge; and G, the dead box for preventing magnetite accumulation losses; (**b**) countercurrent tank style; (**c**) double-drum concurrent/concurrent tank style; and (**d**) double-drum concurrent/countercurrent tank style.

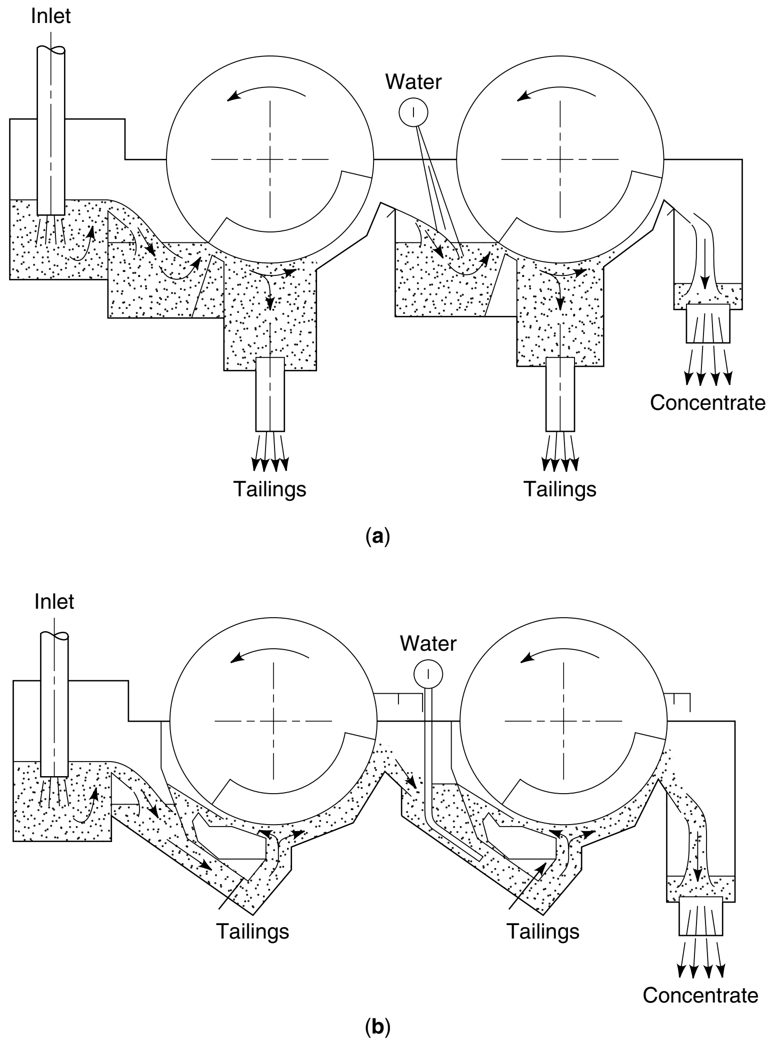

Fig. 8. (**a**) A double-drum concurrent cobber arrangement; (**b**) a double-drum counter-current (Steffenson) finisher arrangement.

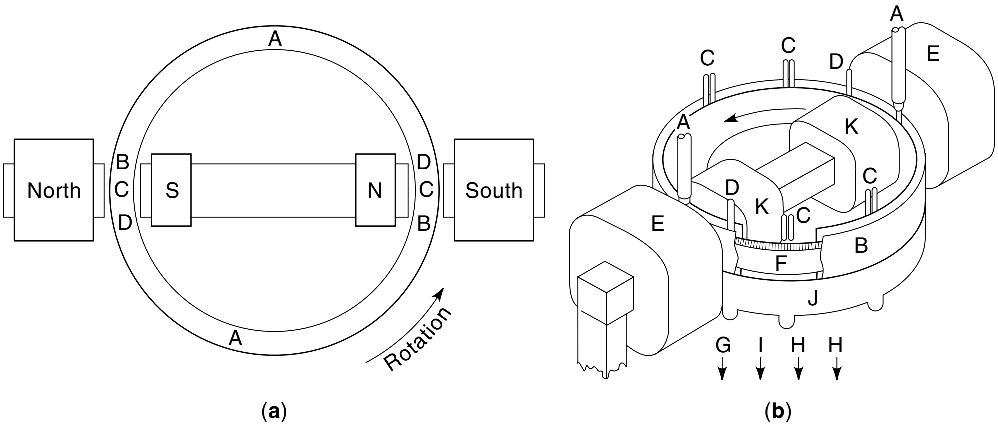

Fig. 9. Continuous carousel wet high intensity magnetic separator where for (**a**) A is the high pressure scour point (magnetics discharge); B, feed point; C, nonmagnetic discharge; and D, low pressure wash point (middlings discharge); for (**b**), A is the feed pipe; B, rotor; C, high pressure and D, low pressure water jets; E, outer coil; F, matrix; G, nonmagnetics, H, magnetics, and I, middlings discharge; J, trough; and K, inner coil.

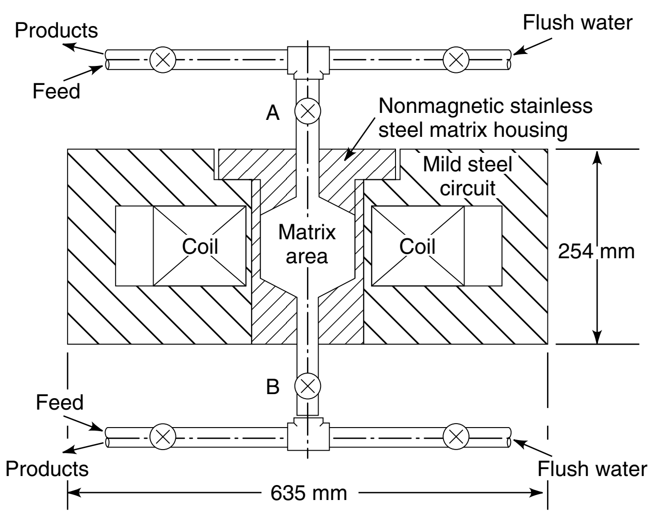

Fig. 10. Wet high intensity magnetic separator using cryogenically cooled coils and a stationary matrix where A is the feed control for top-fed or retention time control for underfed operation and B is the feed control for underfed or retention time control for top-fed operation.

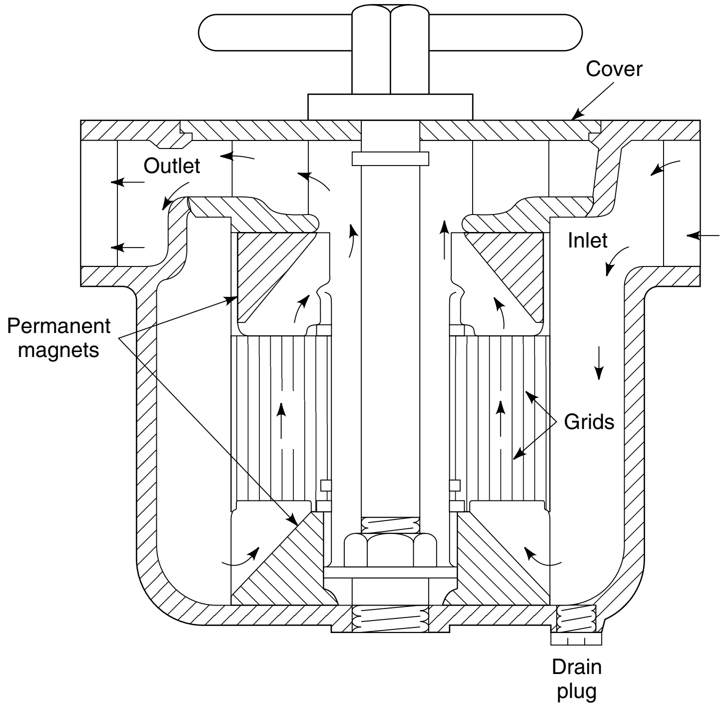

Fig. 11. Magnetic filter.

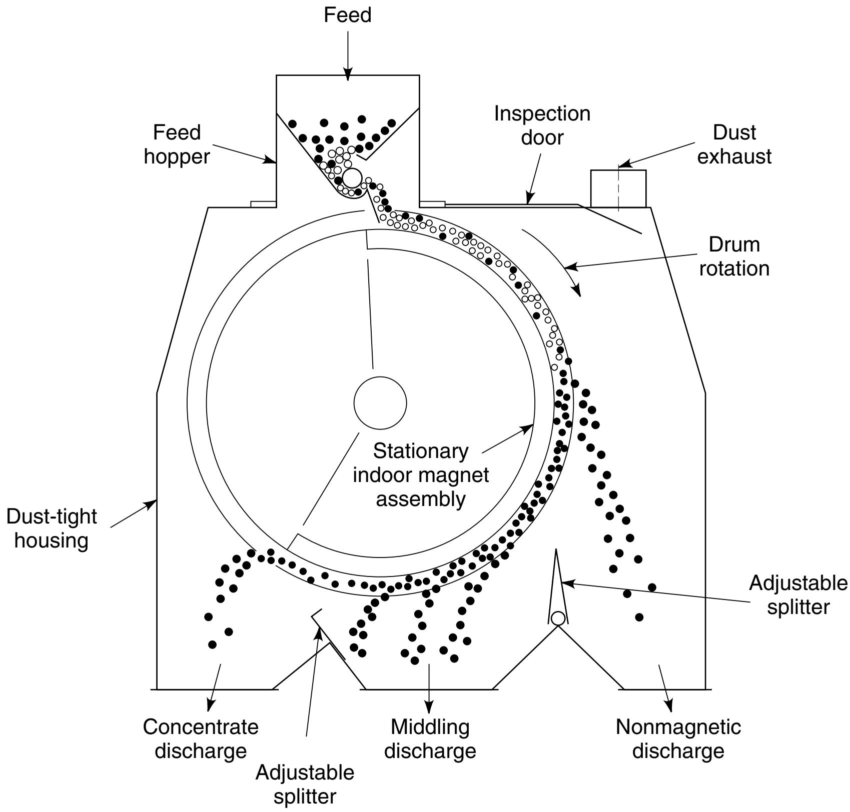

Fig. 12. Magnetic drum for dry feed principle of operation.

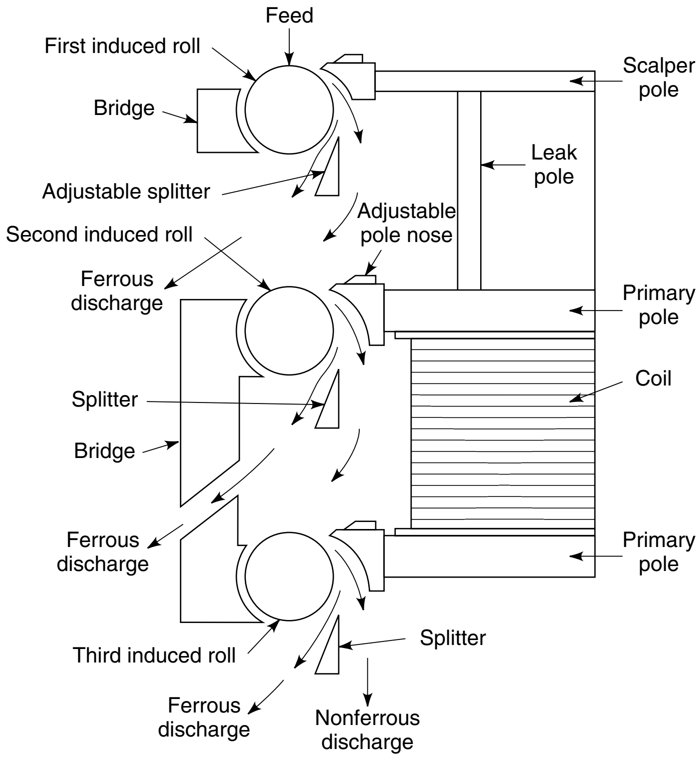

Fig. 13. Induced-roll magnetic separator.

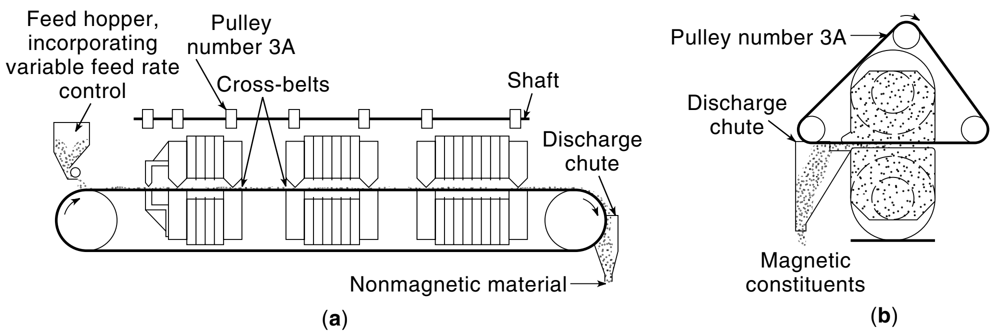

Fig. 14. (**a**) Schematic of a high intensity cross-belt magnetic separator, and (**b**) cross-section at pulley number 3A.

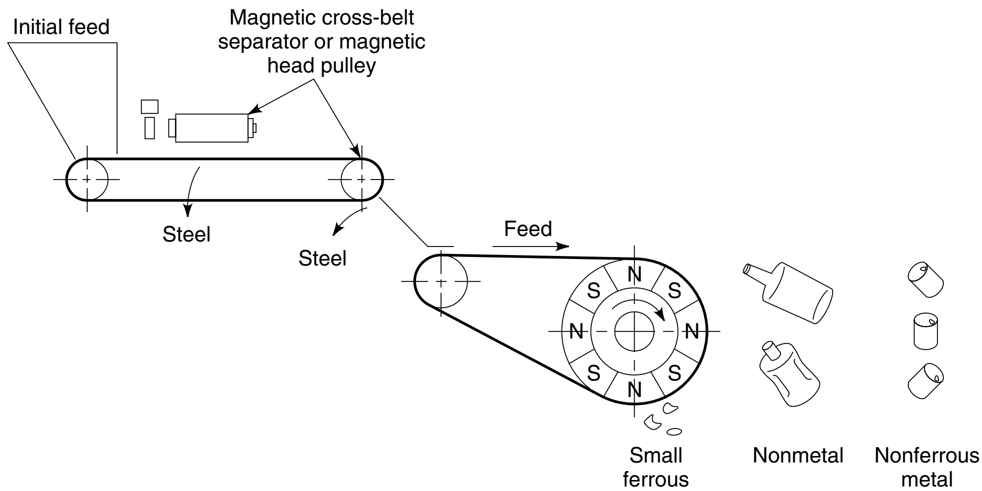

Fig. 15. Schematic of a processing system for a recycling operation.

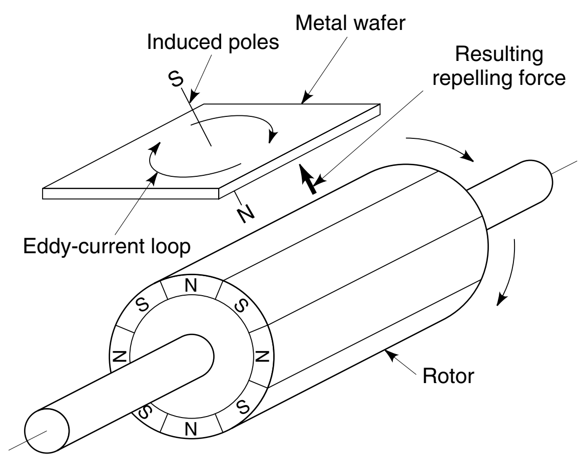

Fig. 16. Eddy-current separation theory of operation.

Table 1. **Magnetic Induction Required to Extract Discrete Minerals**

Mineral	Magnetic intensity, T[a]	Mineral	Magnetic intensity, T[a]
alabandite	1.5–1.8	limonite	1.6–2.0
ankerite	>1.3 –<1.6	maghemite	0.3–0.5
apatite	1.4–1.8	magnetite	≪0.1
bastnasite	1.5–1.7	martite	0.2–0.6
biotite	1.0–1.8	monazite	<1.4 – 2.0
braunite	1.4–1.8	muscovite	1.5–2.3
chromite	1.0–1.6	olivine (fayalite)	1.1–1.5
chrysocolla	2.0–2.4	pyrochlore	1.2–1.6
columbite	1.2–1.6	pyrolusite	1.5–1.9
columbite–tantalite	1.2–1.6	pyrrhotite	0.1–0.4
davidite	1.2–1.6	renierite	1.4–1.8
epidote	>1.4 – 2.0	rhodochrosite	1.5–2.0
euxenite	1.6–2.0	rhodonite	1.5–2.0
ferberite	>0.1 – 0.4	samarskite	1.6–2.0
franklinite	< 0.3 –< 0.5	siderite	<1.0 – 1.8
garnet	1.2–1.9	staurolite	1.2–1.9
goethite	1.5–1.8	serpentine	>0.4 – >1.8
haematite	>1.3 – 2.0	tantalite	1.2–1.7
hornblende	>1.6 – 2.0	titaniferrous magnetite	<0.1 – 0.3
ilmenite	0.8–1.6	tourmaline	1.6–2.0
ilmenorutile	1.5–1.8	uraninite	1.8–2.4
itabirite	0.8 – < 1.4	wolframite	1.2–1.6
		xenotime	1.1–1.6

[a]To convert T to G, multiply by 10^4.

Table 2. **Capacities of Magnetic Pulleys for Tramp Iron Removal[a], m^3/h**

Pulley dia, mm	Width of belt, mm									Normal belt speed, m/s
	305	457	610	762	914	1067	1219	1372	1524	
305	30	50	100							0.9
381	40	60	115	180						1.0
457	45	80	130	200	300	420				1.1
508		90	140	220	330	470				1.3
610		110	160	260	380	540	750			1.4
762			190	290	440	620	860			1.7
914			210	330	480	690	950	1230		1.8
1067				360	530	760	1040	1350	1670	2.0
1219				390	580	820	1130	1460	1820	2.2
1372					630	900	1240	1600	1990	2.4
1524						950	1300	1680	2090	2.5

[a]Normal conveyor operation.

Table 3. **Correction Factors for Inclined Conveyors**

Parameter	Values							
incline, deg	5	6	7	8	9	10	11	12
correction factor	0.955	0.946	0.937	0.928	0.919	0.910	0.901	0.892
incline, deg	13	14	15	16	17	18	19	20
correction factor	0.883	0.874	0.865	0.856	0.847	0.838	0.829	0.820

Table 4. **Screen Analysis of Ground Magnetite**

U.S. Standard sieve[a]		Grade 2, % fine	Grade 3, % medium	Grade 4, % coarse
μm	Mesh size			
+297	+50	trace	trace	8.8
−297+213	−50+70	3.8	7.1	8.2
−213+149	−70+100	4.4	8.8	4.3
−149+125	−100+140	6.2	11.0	14.1
−125+74	−140+200	7.6	10.0	12.0
−74+44	−200+325	13.5	14.7	19.9
−44	−325	64.5	48.4	32.7

[a]The + sign indicates retention on the screen; the − sign indicates passage through the screen.

Table 5. **Conductivity–Density Ratio for Metals**

Metal	ς/ρ^{a}
aluminum	14.0
magnesium	12.9
copper	6.7
silver	6.0
zinc	2.4
gold	2.2
brass	1.7
nickel	1.4
tin	1.2
lead	0.4

[a] σ = conductivity; ρ = density.