Magnetic separations in chemistry and biochemistry

Have you ever really thought about all the energy forms you might use? The authors have

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We begin with three observations:

- Methods for separating chemicals, materials, and objects are a critical part of chemical technology.
- Magnetic interactions can achieve separations that are impossible or impractical to achieve by other techniques.
- Magnetic separations are infrequently used in chemistry.

How is it that chemistry, which has cheerfully exploited separations based on almost every type of physical interaction, has managed to neglect magnetic interactions almost entirely? This question has two answers: First, magnetic separations are applicable to a smaller set of chemical problems than the more common methods. In general, magnetic separations are restricted to separations of *particles* from (or in) suspension, and are not applicable to separations of *molecules* from (in) solution. They are not particularly useful in systems containing only organic species. Second, chemists are too unfamiliar with magnetic separation to recognize promising areas of application.

In this article we direct ourselves to the problem of unfamiliarity. We summarize the physical principles underlying the two major techniques for separations based on magnetic interactions, outline representative problems in which these techniques have been successfully used, and suggest types of problems to which they might be applied in the future. After reading this article, you should be able to judge whether magnetic separations might contribute to the solution of separation problems you face.

Like other separations, magnetic separations require partitioning the materials of interest between different regions of space (Table 1). Separation may be based on rates of equilibria and may involve one or many stages. Regions may be in the same or different phases. Magnetic separations are usually effective only for particles (i.e., collections of molecules) because the strength of the interaction of magnetic fields with single molecules is ordinarily much less than thermal energies in solution ($RT \simeq 0.6$ kcal mol^{-1}). Macromolecules may prove an exception in special circumstances (*2*).

Since few chemists have an intuitive understanding of magnetic susceptibility (χ), let us give a brief, nonrigorous explanation of a few terms (*3*, *4*). Molecules and materials may be divided into two groups: those with unpaired electrons and those whose electrons are spin-paired. Members of the first group are attracted to regions of high magnetic field (χ positive). Members of the second group are repelled from high field regions (χ negative) (Figure 1). An electron has a magnetic moment. We interpret this observation in terms of a model in which the electron

Table 1. **Separations are based on partitioning between different regions of space (A,B) (*1*)**

Separation technique	Separated	Region A	Region B
Distillation	Molecules	Liquid	Vapor
Sublimation	Molecules	Solid	Vapor
Molecular Sieve	Molecules	Inside the sieve	Vapor or liquid outside the sieve
Chromatography	Molecules	Stationary phase	Moving phase
Dialysis	Molecules	Inside membrane	Outside membrane
Electrophoresis	Molecules or particles	Electric field +	Electric field −
Filtration	Particles	On the filter (precipitate)	Past the filter (filtrate)
Screening	Particles	On the screen (particles, diameter > screen)	Past the screen (particles, diameter < screen)
Magnetic	Particles	High magnetic field	Low magnetic field

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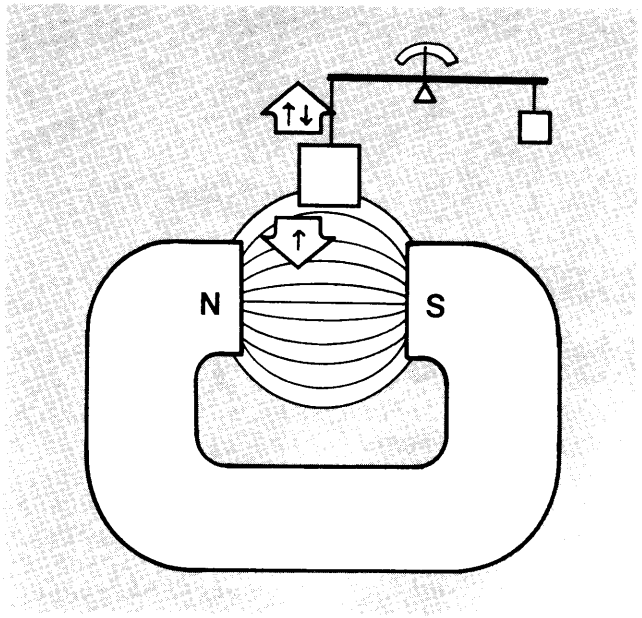

Figure 1. **Materials with unpaired electron spins are attracted to regions of high magnetic field; those with only paired spins are repelled from high-field regions. Magnetic susceptibility is determined by measuring the apparent change in mass of the sample (compared to a standard) when the magnetic field is applied**

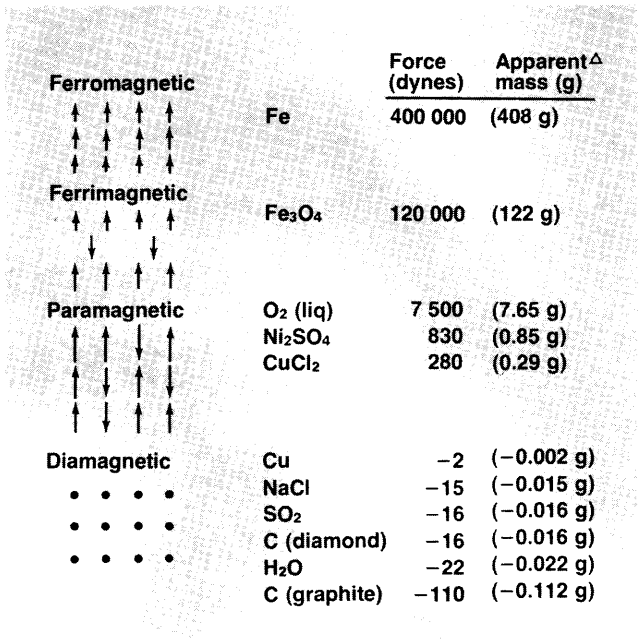

Figure 2. **Schematic representation of the ordering of electron spins in different types of materials. Magnetic force (dynes) exerted on and apparent change in mass (grams, see Figure 1) of one-gram samples of various materials with H = 18 kOe and dH/dX = 1.7 kOe/cm**

possesses a spin that causes it to behave as a magnetic dipole. The magnetization (**M**) of a material (that is, a macroscopic collection of molecules) in an applied magnetic field (**H**, Oersteds [Oe]) is given, to a first approximation, by Equation 1, in which χ_v is the volume magnetic susceptibility (emu/Oe · cm^3) of the material (see box insert).

$$\mathbf{M} = \chi_v \mathbf{H} \qquad (1)$$

The magnetization (emu/cm^3) is a measure of the alignment of the individual unpaired electrons of the material when the material is placed in an applied field (and χ_v is a measure of the susceptibility of the electrons to such alignment).

Materials are classified into four groups according to the strength of their interaction with applied magnetic fields (Figure 2).

Ferromagnets (e.g., metallic iron, nickel, and cobalt). In these materials each atom has several unpaired electronic spins. As a result of a quirk of electronic and atomic structure, the spins on adjacent atoms interact strongly and align themselves in a parallel fashion in a magnetic field. As a consequence of the parallel alignment of the individual moments, the materials have large magnetizations and hence very high magnetic susceptibilities.

Ferrimagnets (e.g., magnetite [$FeO{\cdot}Fe_2O_3$], CrO_3). Many of the atoms in these materials have strongly interacting unpaired spins. In magnetite, there are two subgroups of oriented spins and the net magnetization of each of these subgroups partially cancels. These materials are still attracted very strongly by magnetic fields.

Paramagnets (e.g., $NiSO_4$, many other transition metal complexes, NO, O_2, organic free radicals). The electronic spins of each molecule interact weakly or not at all with the spins of other molecules. The material behaves as a collection of independent spins and thus possesses a low magnetic susceptibility and magnetic moment. Paramagnetic particles are attracted to a magnetic field much more weakly than ferro- or ferrimagnetic particles, but still strongly enough to be used in magnetic separations.

Diamagnets (e.g., SiO_2, NaCl, graphite, alumina, most organic compounds). These materials have no unpaired spins and are weakly repelled by magnetic fields.

The potential energy of interaction of materials with an applied magnetic field is given by Equation 2:

$$E = -V\mathbf{M} \cdot \mathbf{H} = -V\chi_v \mathbf{H} \cdot \mathbf{H} \qquad (2)$$

Glossary

The nomenclature and units of magnetism often perplex the novitiate (*4*). A unit pole is one that exerts a force of one dyne on another unit pole at a distance of one centimeter. A magnetic field, **H,** of unit strength exerts a force of one dyne on a unit pole and by definition has the intensity of one oersted (Oe). Magnetization, **M,** although fundamentally the same, is commonly measured in emu/cm^3, which is magnetic dipole/unit volume. The magnetic field, **B,** inside an object in an applied magnetic field is the sum of the magnetization, **M,** and the applied field, **H,** and is measured in gauss (G).

$$\mathbf{B} = \mathbf{H} + 4\pi\mathbf{M}$$

Different definitions of susceptibility are often used in tables. The volume susceptibility is given by the following equation in units of emu/Oe·cm^3:

$$\chi_v = \mathbf{M}/\mathbf{H}$$

Other susceptibilities are defined:

$\chi_m = \chi_v/\rho$ = mass susceptibility (emu/g·Oe), ρ = density

$\chi_A = \chi_m{\cdot}A$ = atomic susceptibility (emu/g atom·Oe), A = atomic weight

$\chi_M = \chi_m{\cdot}M$ = molecular susceptibility (emu/mol·Oe), M = molecular weight

where V is the volume of the material. If we simplify Equation 2 by assuming that the material is free to align with the field, and that the magnetization is uniform, we obtain the attractive magnetic force acting on the material (Equation 3), where χ_v^0 is the magnetic susceptibility of the suspending medium.

$$\mathbf{F} = -(dE/dx) = (\chi_v - \chi_v^0)V\mathbf{H}(d\mathbf{H}/dx) \qquad (3)$$

Thus, the net force acting on the material depends on the difference in energy when the material replaces the medium in the high magnetic field region. Magnitudes of the magnetic attractive force exerted on various materials are presented in Figure 2.

According to Equation 3, the critical parameters in magnetic separations are the magnetic susceptibilities of the materials to be separated, the magnetic field strength in the regions where partitioning occurs, the rate of change of the strength of the magnetic field between these regions, and the volume of the particles. The magnetic field gradient ($d\mathbf{H}/dx$), a measure of how rapidly the magnetic field changes with position, is important in magnetic separations. In a homogeneous magnetic field ($d\mathbf{H}/dx = 0$), a magnetically anisotropic material may align in the field, but will experience no magnetic attractive force to effect separation.

The magnetic field gradient, $d\mathbf{H}/dx$, becomes increasingly important as the volume, V, of the particles to be separated decreases. High magnetic field gradients are required to generate strong forces on small particles, and thus to produce rapid separations. The absolute strength of the magnetic field, $\mathbf{H}$, is also important, especially for paramagnetic materials, since the strength influences the magnetization of the materials. Nonetheless, the main trick in magnetic separations is to find practical methods for generating high magnetic field gradients.

Two types of magnetic separation techniques have been proposed. The first one is magnetic filtration (also called magnetic collection). Particles suspended in a medium are attracted to regions of high magnetic field associated with a magnetic collector ($(\chi_v - \chi_v^0)$ is positive in Equation 3). The relative strength of attraction depends on the magnetic susceptibility and size of the particles. The second technique is magnetic flotation. Particles suspended in a para- or ferrimagnetic medium float above regions of high magnetic field ($(\chi_v - \chi_v^0)$ is negative in Equation 3). The apparent density of the particles depends, again, on susceptibility and size. We discuss each of these techniques in turn.

Magnetic filtration

Three recent developments give magnetic separations a fresh technical interest:

- New, simple methods of generating very high magnetic field gradients have been developed.
- Efficient magnet structures and superconducting magnets capable of generating very high fields have become commercially available. These structures are relatively inexpensive.
- Technical improvements have taken place in magnetic matrix design.

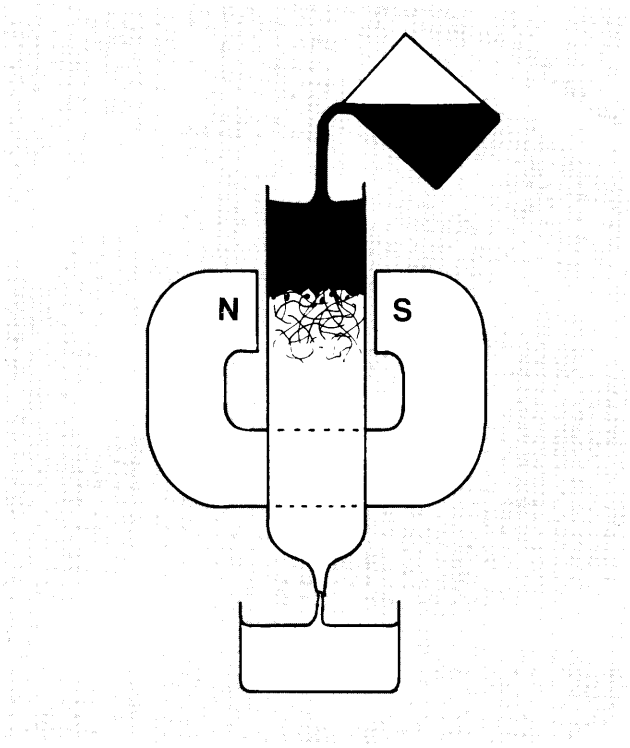

Figure 3. **Schematic design of a simple magnetic filter. A diamagnetic liquid containing a suspended ferro-, ferri-, or paramagnetic particulate solid is passed through a tube containing magnetic steel wool positioned between the poles of a magnet. The suspended solid is trapped on the steel wool**

How is a high-gradient magnetic filter constructed? In the simplest design, magnetic stainless steel wool is packed into a tube, and this tube is placed between the poles of a magnet (Figure 3). The resulting device is an effective magnetic filter. If one passes an aqueous suspension of fine magnetite particles through the tube, the magnetite will be captured and retained by the steel wool and the water will pass through unhindered. In practice, of course, the design of a magnetic filter may be more complex. In place of the irregularly packed wool there may be regular arrays of steel pins or rods. The axis of the magnet may lie along the tube rather than perpendicular to it. There may be provisions for moving the filter bed (the steel wool) out of the high field region, or for turning off or reversing the magnetic field to release the material trapped on the filter. Nonetheless, all filters rely on the same concept. When the external magnetic field is on, particles with high magnetic susceptibilities will be collected from a flowing liquid or gas on the ferromagnetic filaments. When the field is turned off, they will be released.

How does the filter work (5)? Consider one strand of the steel wool in the magnetic field (Figure 4). The magnetic field around the filament may be considered as the sum of two components. The first component (Figure 4a) is the external magnetic field. The field is represented by the lines connecting the faces of the magnet. The more closely spaced the lines, the higher the field. The external magnetic field interacts strongly with the electrons in the (ferromagnetic)

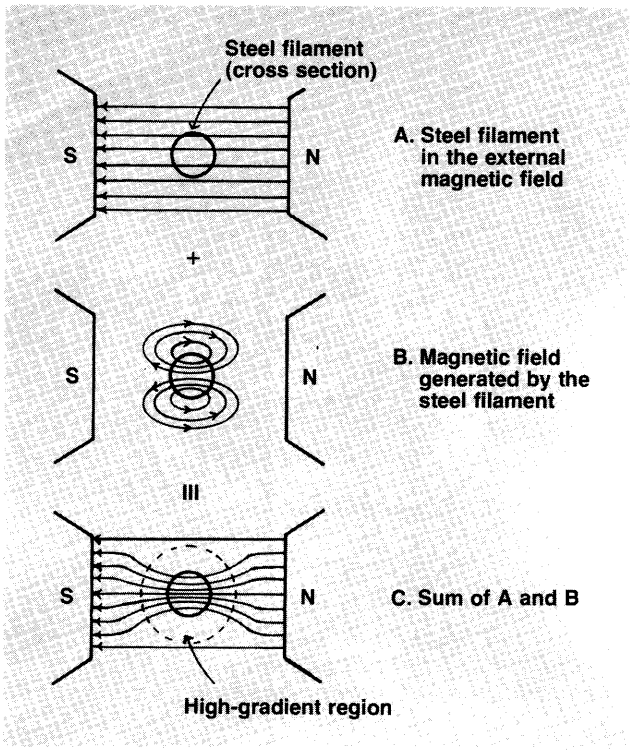

Figure 4. **The origin of the high magnetic field gradient around a steel filament is the superposition of the external field and the field induced in the steel by the external field. High gradients can be generated either by thin filaments, or by small features (ridges, surface irregularities) on larger filaments**

steel and causes their magnetic moments to line up along the field axis. Essentially, the section of the filament we are considering becomes a small magnet (Figure 4b) and generates its own local magnetic field. Addition of the external magnetic field and this local magnetic field produced by the filament gives the total magnetic field around the filament (Figure 4c).

The important feature of this analysis is that it indicates that the total magnetic field is nonuniform close to the filament—it is more intense at the sides and less intense at the top and bottom than the field far from the filament. In other words, there is a magnetic field gradient around the filament. Qualitatively, it is clear that the size of the region containing the gradient is of the same magnitude as the filament that generates it. The diameter of the matrix filaments is thus determined by the diameter of the particles to be collected. A small wire can generate a high gradient. In fact, the magnetic field gradient around a 10 μm wire may be locally 1000 Oe/μm. This high local field gradient is responsible for the action of the magnetic filter. Particles with high magnetic susceptibilities are attracted strongly by and trapped in regions of high field and field gradient.

The particles to be collected experience two major forces in competition with the magnetic force. The hydrodynamic drag, F_d, and the gravitation, F_g, on a particle can be approximated as shown in Equations 4 and 5. In these equations, d is the diameter of the particle, η is the fluid viscosity, and u is the velocity of the fluid relative to the particle.

$$F_d = 3\pi\eta du \tag{4}$$

$$F_g = mg \tag{5}$$

The efficiency of particle capture is thus related to the ratio, R (Equation 6; the magnetic force, F_m, is from Equation 3).

$$R = \frac{F_m}{F_d + F_g} \tag{6}$$

A 100-μm hematite particle ($\chi_v \simeq 10^{-4}$ emu/Oe · cm^3) experiences a magnetic force of greater than 1 dyne close to a 100-μm filament in an applied field of 20 kOe. By contrast, if the fluid velocity is 10 cm/s the drag force is only $\simeq 10^{-2}$ dyne. The gravitational force is $\simeq 10^{-5}$ dyne. In this example R $\simeq$ 100 and the hematite particle will be efficiently trapped by the filament (*6*).

Magnetic filtration has characteristics quite different from those of most other separation techniques (Table 2). It has the obvious limitation that it is only applicable to the separation of particles and then only of materials having differences in magnetic susceptibilities. Given this limitation, however, it has a number of potentially useful characteristics. When applicable, it is an efficient method for separating solids. For highly magnetic small particles, it is the most rapid filtration method known. It can be used with fine or soft particles that would clog the face of ordinary filters and with droplets of liquids dispersed in a liquid medium that would pass through ordinary filters altogether. Because the filter is often 95% void volume, the pressure drop across it can be small.

Magnetic flotation

A second technique using magnetic interactions to separate materials is based on the curious fact that a paramagnetic or ferrimagnetic liquid in a strong magnetic

Table 2. **Characteristics of high gradient magnetic filters**

Advantages

- Collect particles based on magnetic susceptibilities; allow selective separations of solids
- High filtration rates
- Applicable to small (< 1 μm) and soft particles, and to liquid droplets
- Low pressure drop across the filter

Limitations

- Limited to magnetically responsive systems (ferro-, ferri-, or paramagnetic particles in a diamagnetic liquid, or diamagnetic particles paramagnetic liquid)
- Useful only with particles; not applicable to molecules
- Magnet structure expensive
- Technical personnel may be required
- Filter size limited by magnet size
- Low filter capacity

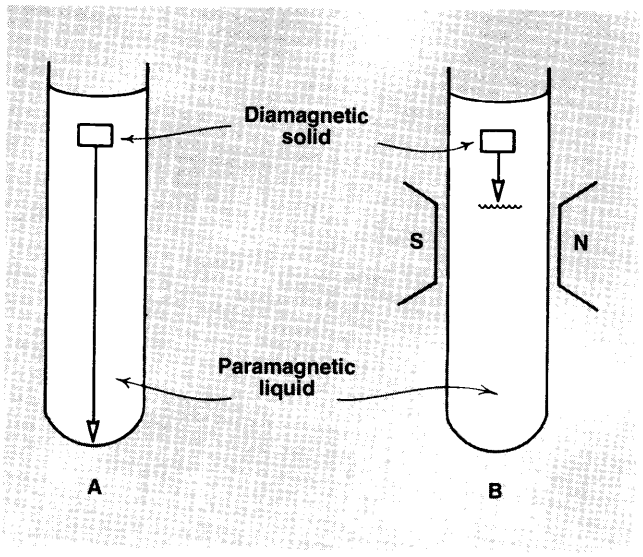

Figure 5. **A diamagnetic solid may be levitated in a less dense paramagnetic liquid in an external magnetic field**

field appears to have a very high density. It will "float" dense solids (*7*). Consider the experiment sketched in Figure 5: A dense diamagnetic solid particle is suspended in a lighter paramagnetic liquid. In the absence of an applied magnetic field, the particle will simply sink under the influence of gravity. In the presence of an external field, it will sink only to some point above the region of high field and remain suspended there. Why? As the diamagnetic particle moves into the high field region, it displaces an equal volume of the paramagnetic liquid from this region. Since the paramagnetic liquid is strongly attracted to the high field region and the diamagnetic particle slightly repelled, this displacement is resisted and the downward motion of the particle stopped. Thus the paramagnetic liquid in a high field gradient seems to have a high "density"; diamagnetic solids with high densities will float on it. Using a relatively simple apparatus and a concentrated solution of aqueous Mn(II), it is easy to achieve apparent densities in the aqueous flotation medium of 5–10 g/mL. Much higher values are attainable using special apparatus or ferrimagnetic liquids (ferrimagnetic liquids, or ferrifluids, are stable magnetite colloids in water or hydrocarbons) (*8*).

In magnetic flotation (also called magnetic levitation) the apparent density of the paramagnetic flotation liquid can be varied widely without changing its chemical composition simply by changing the strength of the external magnetic field. Moreover, apparent high densities can be obtained using inexpensive components. Magnetic flotation is thus applicable to the separation of solids or liquids by density and has been used for this purpose in ore separations on a laboratory scale (*9*).

Applications

Magnetic separations have been used in the laboratory and in industry (*10*). Let us outline some of these applications in the following section.

Kaolin clay. The first large-scale industrial application of high gradient magnetic separation (HGMS) was the removal of colored impurities from kaolin clay (*11*, *12*). Beneficiated kaolin clay is a white alumino-silicate mineral used by the paper industry to enhance brightness. The mined clay is often discolored by ~1-μm particles of weakly magnetic impurities (anatase, rutile, mica, iron pyrite.)

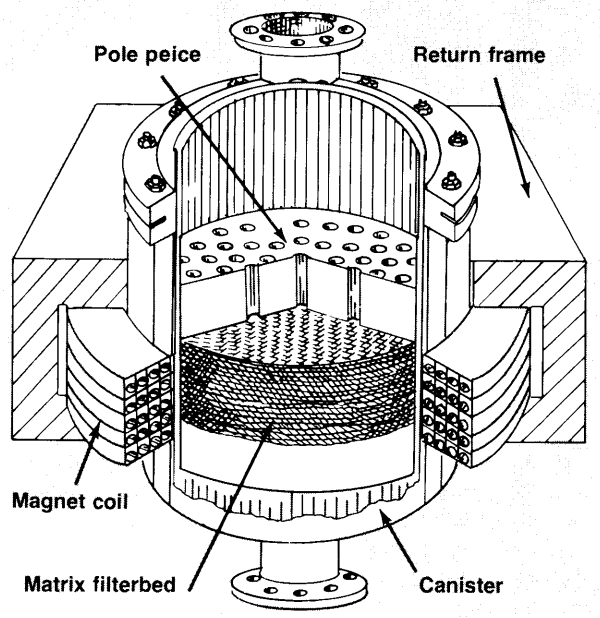

Figure 6. **Diagram of a cyclic magnetic filter (courtesy of Sala Magnetics, Inc.)**

HGMS was first used for the removal of these impurities by the J. M. Huber Co. in 1969. The separation procedure used is termed cyclic since it operates in alternate feeding and flushing modes. A cutaway diagram is shown in Figure 6. The matrix is type 430 stainless steel wool (*13*). Fluid flow is parallel to the magnetic field. This configuration is the most economical to scale up since the poles can be kept close together. The electromagnet is composed of a coil of copper wire surrounded by an iron return frame to prevent loss of magnetic flux. Since the impurities are small and only feebly magnetic, a magnetic field of 15–20 kOe is required and flow rates are low (about 0.2 cm/s). After the filter is loaded with impurities, the power to the magnet is turned off and the filter is flushed with high pressure water. The duty cycle, defined as the ratio of the feeding time to the total of feeding, flushing, and valve positioning time, is about 0.6. High gradient magnetic separators of this type with filter diameters up to 2 m are commercially available and have capacities up to 20 tons/h. The contribution of the magnetic separation step to the final cost of the kaolin clay is small. The use of HGMS has allowed the mining of clay deposits previously discarded as insufficiently pure for use. HGMS is now an established technology of great economic value in the kaolin industry.

Stack gases. The stack gases from several industrial processes, primarily in the iron, steel, and ferroalloy industries, contain large quantities of magnetic particulates. Pilot plant work has demonstrated that these magnetic pollutants are efficiently removed by dry, high gradient magnetic separation of the stack gases from basic oxygen furnaces and sintering plants in the steel industry. Capital costs and power requirements are competitive with current methods used to control these pollutants (*14*).

Fly ash from power plants burning bituminous coal contains about 22% alumina and 18% iron oxides. Electric utilities in the U.S. currently produce over 50 million tons of fly ash per year. About 15% of this ash is used in structural applications while the remainder constitutes a serious disposal problem. Magnetic filtration is effective in isolating about 15% by weight of the fly ash as a magnetic fraction. This fraction can replace commercial magnetite in certain applications, as, for example, in heavy-medium materials used for coal beneficiation. Roy et al. have estimated that resale of the magnetic fraction might allow American utilities to recover a significant fraction of the cost of stack gas cleaning, and to decrease the volume of unwanted material (*15*).

Water purification. The ability to remove small amounts of highly magnetic impurities rapidly from large volumes of water makes high gradient magnetic separation a possible solution for several water purification problems. Nearly 50 electromagnetic filters have been installed in thermal power and steam generation systems to remove ferromagnetic impurities arising from corrosion of pipes and machinery (*16*). Precipitated iron from coal mine drainage has been removed by HGMS (*17*). The technique has also been applied to the purification of various types of waste from steel mills (*18*, *19*). and is more effective and economical than other filtration methods in certain circumstances. For example, a cyclic high gradient magnetic filter has been in full scale operation at Kawasaki Steel Corporation in Japan since 1977. The filter removes fine particles suspended in condenser-cooling scrubber water discharged from a vacuum degassing process. The 3 kOe magnetic filter has a diameter of 2.1 m and operates with a flow velocity of 7.5 cm/s. Using this filter, the concentration of suspended solids is reduced from 100 mg/L to less than 20 mg/L at the flow rate of 900 m^3/h (*20*).

Dissolved or suspended diamagnetic impurities can sometimes be removed from wastewater by first seeding with colloidal magnetite and a flocculating electrolyte such as Al(III) (*21*). This indirect HGMS effectively removes suspended solids (including microorganisms) from municipal sewage. The technique has also been applied to eutrophic natural water from which 99% of algae and most orthophosphates were successfully removed (*22*). Dissolved orthophosphates are removed most efficiently by adding clay prior to the addition of magnetite and Al(III). Recently, advances have been made in the removal of hydrocarbons (including polychlorinated biphenyls) and weakly magnetic solids from an aqueous phase (*23*).

Beneficiation. Most iron ores are composed of magnetite and hematite, and are ferri- or paramagnetic (*24*). HGMS is being used as a beneficiation method to separate magnetite and hematite from unwanted diamagnetic silicates and alumina and phosphorous-containing materials (*25*). Although initial capital costs may be greater for HGMS than for other beneficiation methods, lower processing costs and reduced water treatment problems make the magnetic method competitive over the long term (*26*). Ore beneficiation is particularly important in the U.S. because the higher grade ores (over 50% iron) have been depleted. Unoxidized taconite containing only 25% iron is the largest domestic source (*25*).

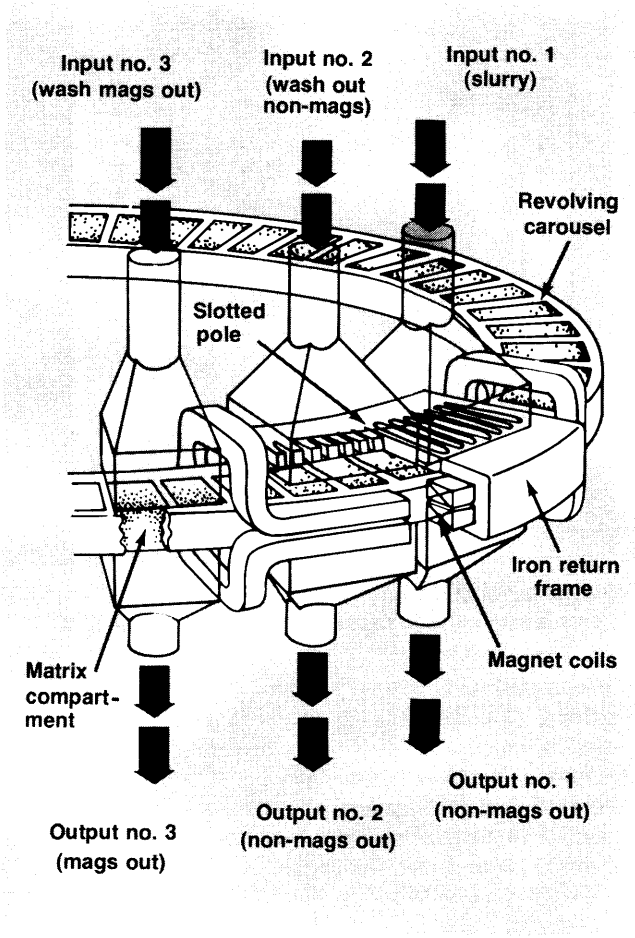

Figure 7. **Diagram of a continuous separator (courtesy of Sala Magnetics, Inc). The feed enters at the input station 1 and the magnetic material is trapped in the matrix compartments. The matrix ring rotates and nonmagnetic material is washed from the matrix. The ring continues to rotate and the magnetic material is washed from the matrix as it leaves the magnet station. Continuous separators with multiple magnet stations are commercially available**

Beneficiation of iron ore requires a continuous separator since the ore slurry contains a high percentage of magnetic materials and large quantities of ore must be processed. A continuous high gradient magnetic separator (Figure 7) comprises a rotating ring that contains the ferromagnetic matrix. The feed enters the ring at the magnet station, an iron-bound solenoid modified in shape to allow passage of the matrix ring. The nonmagnetic particles are collected below the magnet station while the magnetic particles are flushed from the matrix to the right of the magnet. Continuous separators with matrix widths of up to 150 cm, multiple magnet stations, magnetic fields from 3–15 kOe, and capacities up to 300 tons/h are commercially available.

Desulfurization of coal. With renewed interest in coal as a utility fuel and increased concern about air quality, methods to desulfurize coal prior to combustion are being studied. Although 30–50% of the sulfur in Interior Basin and

Appalachian coals is organic, most of the remaining sulfur occurs in the form of pyrite (FeS) (*27*). The weakly paramagnetic pyrite grains (*28*), once liberated from the bulk by grinding the coal, can be removed by HGMS. If most of the pyrite is removed, the sulfur content of the coal may be sufficiently low to bypass costly gas scrubbing.

To improve the efficiency of removal of pyrite sulfur, it has been suggested that this pyrite be converted to ferrimagnetic pyrrhotite (*29, 30*), Fe_7S_8, by reaction with gaseous $Fe(CO)_5$ at 200 °C (*31*). This pretreatment may be omitted if the coal is fed to the separator in a dry air stream. The advantage of performing the separation in air is that the fluid drag forces acting on the particles are greatly reduced. By dropping the coal through the matrix at a low velocity, the pyrite and a significant portion of the other paramagnetic impurities are captured. Particles of less than 10-μm diameter may have to be removed prior to HGMS if the moisture content of the coal is too high. As with the HGMS treatment of iron ore, fine coal is cleaned of pyrite and ash using a continuous separator.

Magnetic supports in chemistry. Inert materials are often used to support catalysts. Several magnetically responsive heterogeneous catalysts have been prepared, used as catalysts, and recovered by HGMS (*32, 33*) (e.g., reduced palladium chloride on a catalyst support of magnetite deposited on carbon).

The preparation and use of magnetically responsive supports for immobilized enzymes and bioaffinity adsorbents have been reviewed (*34*). Enzymes immobilized on magnetic supports (*35–39*) are easily retained in fluidized bed reactors and recovered from batch reactors by taking advantage of their magnetic properties. Similar results have been demonstrated for whole yeast cells immobilized on magnetic supports (*40*) that have been used for alcohol fermentation. Covalent attachment of affinity ligands to magnetic supports (*41, 42*) results in the preparation of magnetic affinity matrices useful for isolating specific enzymes directly from liquors containing suspended solids. Magnetic supports labeled with antibodies, lectins, or antigens have been used to separate cells based on their differences in surface receptors (*43, 44, 45*). An example of this type of cell separation is the specific separation of neuroblastoma cells containing ganglioside Gml in their membranes, using cholerogen-modified magnetic microspheres. (*45*).

Considerable attention has been paid to the use of magnetic supports in enzyme–immunoassay (*46*) and radioimmunoassay procedures (*47–50*). Use of magnetic supports allows facile magnetic stirring of the preparations, eliminating the need for vertical rotation of tubes during incubation. These materials permit facile separation of antibody-bound and free fractions, eliminating the need for multiple centrifugations and washes. Two approaches have been used. In one, the free antigen is nonspecifically adsorbed on charcoal or ion-exchange resin incorporated into magnetic supports. The second approach uses antibodies or specific binding proteins covalently incorporated into magnetically responsive particles. Magnetic immunoassay procedures have been described for digoxin, thyroxine, triiodothyronine uptake, vitamin B_{12}, and human placental lactogen.

Polymer particles containing magnetite have also been used as filter aids (*51*). These particles agglomerate, forming tortuous channels in a filter bed; they offer little resistance to the flow of water but effectively remove suspended matter. The filter aid is easily fluidized and recovered by sedimentation and magnetic methods.

Can magnetic separation be applied in chemistry?

In principle, magnetic techniques may be applied in any instance in which one is concerned with manipulating (separating, containing, mixing) two or more bulk phases, at least one of which is ferro-, ferri-, or paramagnetic. Most applications to date have involved separations of materials that are naturally magnetic (boiler scale, ores, paramagnetic impurities). More applications await those who are willing to design some part of their system to meet the requirements of magnetic separation technology. The following list includes ideas that have been demonstrated (albeit sometimes only on a laboratory scale), or that seem obvious areas for demonstration:

- removal of used catalyst-derived impurities from products. Many catalyst systems are strongly paramagnetic; some (Raney Ni, Fischer–Tropsch catalysts) are ferro- or ferrimagnetic
- design of catalyst supports to facilitate separation; magnetically responsive catalysts could either be metal- or enzyme-based
- operation of magnetic fluidized bed or magnetically stabilized reactors (*37, 39, 52*)
- separation of adsorbents (carbon, affinity resins for biochemical separations)
- separation of isotopes. The chemical fate of a radical pair generated in a magnetic field can depend on the nuclear spin of the atoms bearing the lone electron. This effect is enhanced when the reaction occurs within a micelle (*53*)
- magnetic orientation of crystals. This technique has been used to facilitate the examination of solid-state dynamics by NMR (*54*) and to examine magnetic anisotropies (*55*)
- polymerization in a magnetic field. In a magnetic field, polymerization may produce oriented polymers (*56*)
- separation of red blood cells from solution (*57*). Red blood cells infected by malarial parasites contain oxidized heme products and are more paramagnetic than uninfected cells. Magnetic separation has been used to concentrate infected cells (*58*)

- manipulation of magnetically responsive microspheres in vivo (*58, 59*)
- thermomagnetic surgery: Hysteresis heating of ferromagnetic particles within tumors causes necrosis of the cancer cells (*60*)
- separation of materials with different affinities for paramagnetic ions (*61*)
- separation of nickel hydroxide electrodes from zinc electrodes. Recovery of nickel from used batteries will reduce the cost of zinc/nickel hydroxide batteries (*62*).

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