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A PROGRAM PROPOSAL TO

ESTABLISH THE FEASIBILITY OF USING HIGH GRADIENT MAGNETIC SEPARATION FOR EFFECTIVE TREATMENT OF MOSTOS FROM PUERTO RICO'S RUM DISTILLERIES

PREPARED BY
U. ORTABASI
CENTER FOR ENERGY AND ENVIRONMENT RESEARCH
UNIVERSITY OF PUERTO RICO

AND

J. H. P. WATSON
DEPARTMENT OF PURE AND APPLIED PHYSICS
UNIVERSITY OF SALFORD

CENTER FOR ENERGY AND ENVIRONMENT RESEARCH
UNIVERSITY OF PUERTO RICO — U.S. DEPARTMENT OF ENERGY

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PREFACE

The relatively recent technique of High Gradient Magnetic Separation (HGMS) is proving more and more to be a powerful, rapid, efficient and economical method for removing suspended matter from water effluents of large volume with a minimum requirement for process power and space.

HGMS utilizes "state of art" technology and its applications now include:

- Mineral Processing
- Effluent and Waste-Water Treatment
- Chemical Processing
- Biochemical Processing
- Pharmaceutical Processing

Organic waste waters all around the world have been shown to be potent sources of water pollution of immense dimensions. Various organic waste waters that have been the subject of complicated environmental investigations come from the manufacture of industrial products we use every day. Some examples are distillery and brewery effluents, textile effluents, pulp and paper effluent, tannery effluents, pharmaceutical effluents.

Distillery waste water, for example, is highly charged with organic matter and its treatment before dumping has recently been subject of intense investigations.

Although no hard evidence has been presented to prove that "mostos" from rum distilleries is harmful to human health or to the ecosystems where they are discharged, environmental authorities have decided that the associated discoloring of shorelines and nearby waters and the nauseating odor of mostos make effective treatment mandatory in the shortest possible time.

Considerable work has been done on composition and treatment of distillery effluents. From the published results, however, it is apparent that none of the suggested treatment techniques has been found to resolve the problem satisfactorily.

On the basis that recent HGMS experiments at a brewery in England have produced excellent results, we believe that HGMS will prove to be a viable technique to solve mostos problems in Puerto Rico.

The purpose of this proposal is to obtain funding for a program to investigate the applicability of HGMS to the specific mostos types produced in Puerto Rico.

The proposed effort would be carried jointly out by CEER/UPR and the Department of Pure and Applied Physics of the University of Salford, near Manchester, England, a leader in the field of HGMS research and development. It includes a four month experimental program at Salford to obtain preliminary data for an HGMS Pilot Plant to treat mostos and the purchase, installation and operation of an experimental magnet at CEER/UPR for investigating local samples.

The cost of the program is estimated at $90,000 over a period of 12 months beginning June 1, 1978, and ending May 31, 1979. Progress reports will be issued at least every four months and a final report will be issued not later than June 15, 1979.

The project would constitute a valuable addition to CEER's environmental program and an excellent vehicle for the training of environmental specialists and other scientific and technical personnel.

1.0 Principles of HGMS

A high gradient, high field magnetic separator (HGMS) consists of a ferromagnetic wire wool matrix, of strand radius a, which is magnetized to the saturation field M_s by a uniform applied magnetic field H_o. Particles of radius R and magnetic volume susceptibility χ can be extracted from a fluid, of viscosity η, which carries the particles into the separator with a velocity V_o. It has been found that a quantity V_m, called the magnetic velocity, is of great importance in the determination of the performance of these separators. V_m is given by

$$V_m = \frac{2}{9}\left(\chi R^2 \frac{M_s}{a} . \frac{H_o}{\eta}\right) \qquad (1)$$

These separators have found application in the kaolin industry in the United States, in England and in Czechoslovakia. The separators have a matrix bed depth of about 20 in. with a channel diameter of 84 in. The applied magnetic field is produced by passing a DC current through water cooled copper coils, weighing about 50-60 tons, which are wound solenoidally around the matrix channel. The power required to maintain the field is between 400-600 kW. The magnetic return circuit is in the form of an iron box weighing approximately 200 tons. Although the impure kaolin particles to be extracted are only weakly magnetic and of colloidal size, it is still possible to pass about 1000 gall/min through the separator and obtain adequate beneficiation.

Although not yet in commercial practice, it has been found that organic material, coliform bacteria, viruses, suspended solids and other colored matter can be scavenged onto freshly precipitated $Fe(OH)_3$ or Fe_3O_4. This is an electric charge effect that will be described in more detail in section 2. The scavenged material can be removed by extracting the $Fe(OH)_3$ or Fe_3O_4 particles with a magnetic separator. This can be done at high velocity because of the favorable magnetic properties of the seed material. This method is cumbersome to apply in practice and suffers from the disadvantage that Fe^{3+} ions are added to the system in solution.

However, a large British chemical company has developed a scavenging material that can be used over a wide range of pH and which simply requires the addition of these particles with an in line mixer. It is this method that we propose to use in the treatment of mostos.

In section 2 we present an outline of the theory so that the main experimental data required for the pilot plant configuration and parameters will be apparent. In section 3, we outline the experimental program.

2.0 The Theory of Magnetic Separation

The equations of motion of a diamagnetic or paramagnetic particle moving with a viscous fluid in the neighborhood of a magnetized wire have been derived and solved. Thus, it is possible to show that only certain wire configurations are effective in capturing particles. Generally speaking, the velocity of the fluid can be at any angle to the axis of the wire; however, the magnetic field component perpendicular to the axis of the wire is the only component of field which is effective in the capturing process. In this section we will focus our attention on the case in which the magnetic field and the flow will be parallel to each other with both being perpendicular to the axis of the wire. (Reference 1).

From the equations of motion, it is clear the particle trajectories depend almost entirely on V_m/V_o, that is on the ratio of the magnetic velocity V_m defined by Equation (1), to the velocity V_0 of the fluid relative to the matrix. Consequently, the capture cross-section area/unit length of wire is $2R_Ca$, where R_C is termed the capture radius which depends largely on a function of V_m/V_o. A reasonable approximation for R_C when $V_m/V_O \sim 2$ is

$$R_c = 0.5\,(V_m/V_o) + k\sqrt{V_m/V_o} \tag{2}$$

Here T is the residence time given by $\epsilon_o L/V_0$ and A is a constant of such a value that when n, the number of canister volumes passed, is n = 0, then Equation (3) and Equation (4) are identical.

At this point the criteria for effluent levels that are to be used must be specified. Suppose that the final particle level concentration exited from the separator is R_L then n', must be determined, such that n' satisfies

$$\sum_{n=o}^{n=n} R(L,nT)/n' = R_L \tag{5}$$

When n' has been determined, the total process rate P can be determined by

$$P = V_o A \frac{n'}{(n' + D/T)} \tag{6}$$

Here D is the dead time of the separator, that is the total time the separator is off during the cyclical cleaning process. (Reference 4)

Seeding and Scavenging Process

In a stable colloid, the particles have surface charges which have the effect of keeping the particles apart or dispersed. Electrical potential barriers are normally greater than - 15 k_BT_0 where k_B is the Boltzmann constant and T_0 is the temperature in degrees Kelvin. If particles are introduced which have an opposite surface charge there can be a strong attractive force between the oppositely charged particles so that if the potential difference is $< 15\ k_BT_0$ coagulation occurs. It is found that at normal pH, bacteria, cells, proteins, viruses and cell debris have a negative surface charge and can be scavenged by the addition of a material with positive surface charge. As noted in Section 1 a large chemical company in England has developed a seed material which has a strong positive surface charge over a wide range of pH values. These are treated particles of Fe_3O_4 and are consequently strongly magnetic so they can be effectively removed by the separator. The important element is the volume of seed necessary to scavenge the organic material most effectively.

The proposed experimental program is based on an evaluation of the above scavenging method. The effectiveness of the seed and of organic removal will be tested using the theory laid out in this section.

3.0 Experimental Program

Microscopic Examination of Coagulation

Using phase contrast microscopy an attempt will be made to examine the interaction between the seed and the mostos. This can be done by the preparation of slides which are frozen in such a way that seed material can be placed adjacent to the mostos on a microscope slide. The slide is then warmed so that the resulting interaction can be observed when thawing occurs. This part of the program will attempt to look at mostos-seed kinetics and more particularly seed to mostos concentration ratios and also the seed to organic ratio in the coagulate so that V_m can be determined. Video recordings will be made if possible. Time spare for this part of the program is 6 man weeks.

Magnetic Separation Study

For this study it is proposed that only one matrix be used to save time. This matrix will be an ordered knitted mesh of 50 microns diameter of ferromagnetic stainless steel occupying about 5% of space. The saturation magnetization is around 1.7T.

It is also proposed that two magnetic fields, namely 1T and 2T, be used.

Based on the solids content of the mostos, various ratios of mostos solids volume to seed volume will be used ranging from 5 to 1 and 1 to 1, respectively.

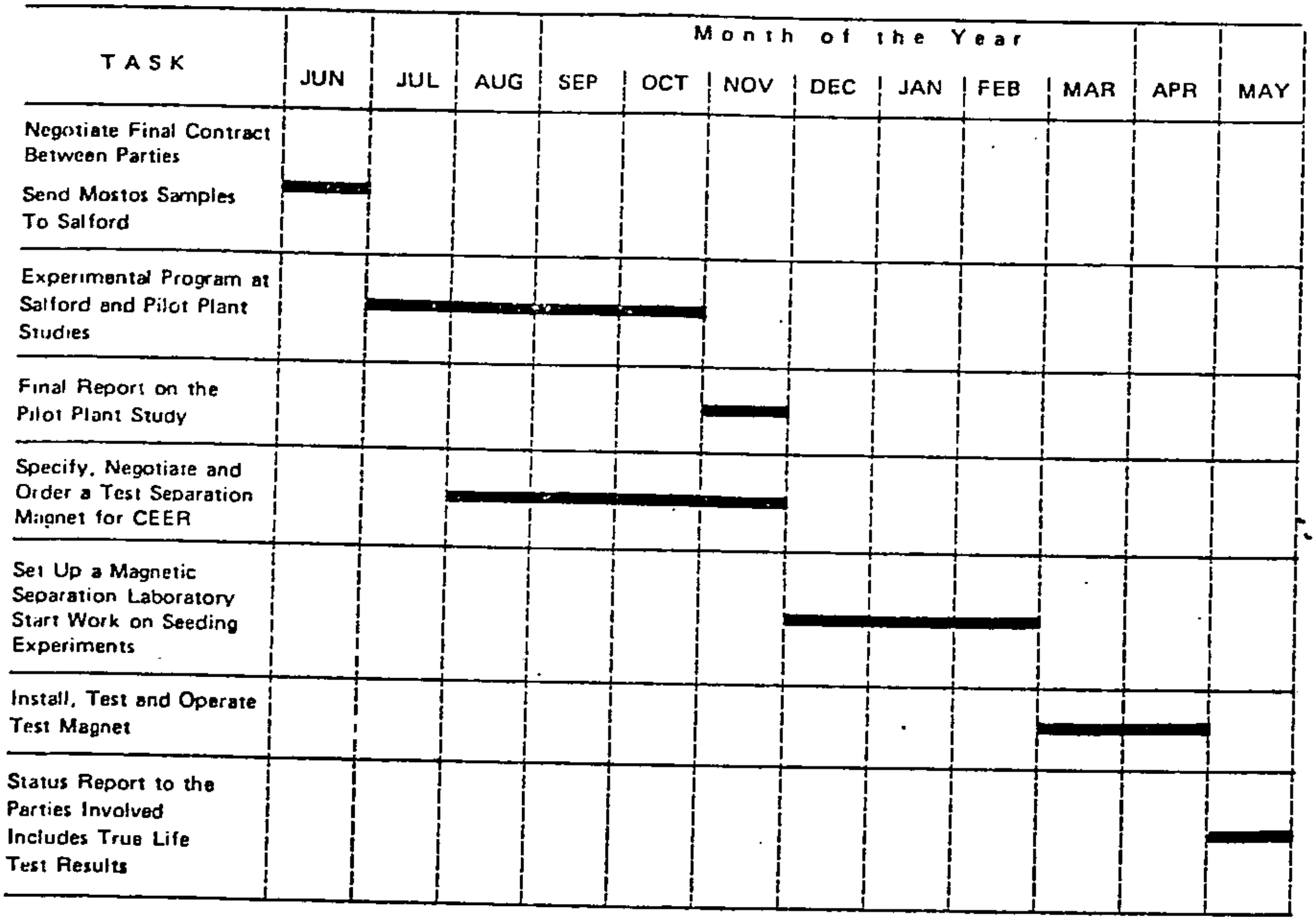
For each of the above combinations it will be necessary to do experiments at various values of V_m/V_0. In practice this will mean holding H_0 and seed dose rate constant and running at various values of V_0.

In each case, starting with a clean separator, the output will be monitored in order to determine the effluent concentration versus the number of canister volumes passed. This will allow n' the required number of canister volumes for a various effluent criterion R_L, to be determined. Also, by running the separator until it is completely ineffective, the value of N_T can be determined. The estimated time for this part of the program is 16 man weeks.

The assembly of the results and the plotting of graphs will take approximately 2 man weeks.

The total time for the experimental program at the University of Salford will be 36 man weeks to be accomplished during July - October, 1978.

MILESTONE CHART FOR MAGNETIC SEPARATION STUDIES



TASK	Month of the Year											
	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY
Negotiate Final Contract Between Parties Send Mostos Samples To Salford	■											
Experimental Program at Salford and Pilot Plant Studies		■	■	■	■							
Final Report on the Pilot Plant Study						■						
Specify, Negotiate and Order a Test Separation Magnet for CEER			■	■	■	■						
Set Up a Magnetic Separation Laboratory Start Work on Seeding Experiments							■	■	■			
Install, Test and Operate Test Magnet										■	■	
Status Report to the Parties Involved Includes True Life Test Results												■

BUDGET REQUIREMENTS FOR MAGNETIC SEPARATION PROGRAM

Direct Salaries plus Overhead	$ 42,000
Includes	
Principal Investigator (50%), 1 year	
Technician (50%), 1 year	
Consultants	
University of Salford	$ 14,000
Rose Magnetic Separation Consultant	$ 5,000
	$ 19,000
Travel	
4 man trips	$ 4,000
San Juan - Salford	
Subsistence	$ 2,000
$500/man trip	
	$ 6,000
Equipment	
Test Magnet plus Associated Equipment	$ 23,000
Subtotal Estimated Cost	$ 90,000

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(3) Private Communication.

(4) Applications of an Improvements in High Gradient Magnetic Separation, J. H. P. Watson.

SUPPLEMENTARY HGMS LITERATURE

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The Use of Paramagnetic Matrices for Magnetic Separations*

By P. W. Riley and J. H. P. Watson
English Clays Lovering Pochin & Co. Ltd., St. Austell, Cornwall

Introduction

There are various industrial processes which require the removal of micron sized ferro magnetic particles from suspensions. Typical examples are, the removal of particulate contamination from steel mill waste waters[1], ferrites formed during the removal of heavy metal ions from water[2] and ferromagnetic enzyme supports from reaction liquors[3]. All of these systems can be treated by conventional High Gradient Magnetic Separators[4] using ferromagnetic collectors. However, the cleaning of the collectors can prove difficult due to the magnetism of both collector and contaminant, leading to a loss in efficiency and ultimately to blocking of the collector.

HGM Separators have recently received considerable attention from the mineral processing industries where the problems have been to concentrate paramagnetic ores[5] or to remove paramagnetic minerals[6, 7, 8]. Cleaning the collectors in these applications is relatively easy due to the very small magnetic forces that remain between collector and concentrate once the field is reduced to zero.

This paper describes a method in which the principle of ferromagnetic collector paramagnetic particles is reversed and uses a paramagnetic collector for ferromagnetic particles to benefit from the weak interaction forces at zero fields to clean the collector efficiently. The separation performance of this configuration will obviously not be as good as the ferromagnetic collector/ferromagnetic particle case, but the loss in efficiency could be tolerated with the enhanced cleaning characteristics. In order to test the separation performance in practice a suitable system was required. At present a certain amount of interest is being shown in the use of ferromagnetic enzyme supports[3]. These supports need to be fine in order to maintain catalytic activity and must be completely separable from the reaction liquors. Work carried out at University College, London, by Munro and Dunnill[3] used nickel powder for the supports and this appeared to be an ideal system to test the paramagnetic matrix concept.

Experimental

The most likely support concentrations[9] of nickel are within the range 1-10% by volume and the reaction fluid viscosities could be as high as 1 × 10^{-1}Kg/m.sec. For this study the lower concentration (1%) was used and the viscosity was modelled by using a light mineral oil (Shell Tallus 27) which has a viscosity of 0.93 × 10^{-1}Kg/m.sec at 21°C. Two samples of nickel powder (International Nickel Company) were used. Type 255, which consisted of chains of equisized spheres, had a particle size of 2.2-3 µm equivalent Stokes Diameter (E.S.D.) and a packed bed density of 6 × 10^3 Kg/m³. Type 123 consisted of irregular aggregates of spheres, a particle size range of 3-7 µm E.S.D. and a packed bed density of 2.5 × 10^3Kg/m³.

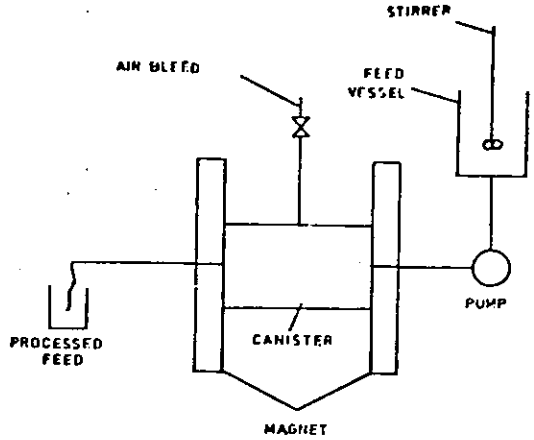

Fig. 1. Schematic layout of apparatus

Table 1. Matrix Dimensions

Ref. No.	Strand width	Gauge	Weight kg/m²	Triangular Hole size x 10²m	Voidage %
922A	3.6 x 10^{-1}m	26	0.73	0.064 x 0.034	71.9
801A	6.9 x 10^{-4}m	24	1.08	0.113 x 0.060	72.7
701A	5.8 x 10^{-1}m	24	0.98	0.237 x 0.066	79.5

The experimental arrangement is shown in Fig. 1. The canister was 0.068 m long and had a volume of 0.0654 litres. The packing consisted of discs, 0.035 m in diameter, cut from sheets of aluminium expanded metal (Expamet Industrial Products Ltd.). Details of the meshes and their packing void volumes are shown in Table 1. Flow distribution plates were placed at the ends of the canister to give a uniform flow profile through the cell. The magnet was water cooled with 0.178 m pole pieces and a 0.09 m pole gap. The poles had 0.013 m diameter holes at their axes. The peak field was 0.8 Tesla and the holes caused a minimal perturbation in the homogeneity of the overall field. Measurements were made at 0.7 Tesla by passing a known volume (0.3 or 0.5 litres) of suspension at a known volumetric flow rate through the canister in the parallel mode, that is the field and flow directions were parallel and the matrix discs were stacked perpendicular to this. At the end of each experiment 0.2 litres of clean oil were passed through the cell with the field on to remove the suspension from the feed lines and to ensure that the interstitial fluid in the canister was clean. This was collected with the processed oil. Finally, the field was switched off and 0.3 litres of clean oil were passed through the canister at a flow rate of 0.011 litres/sec to displace the collected nickel powder.

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* Patent applied for

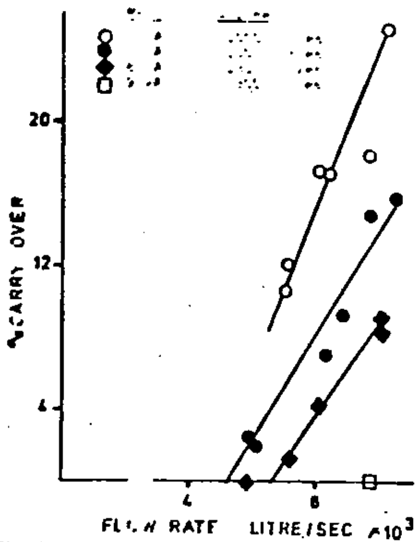

Fig. 2. Separation of type 123 nickel powder.

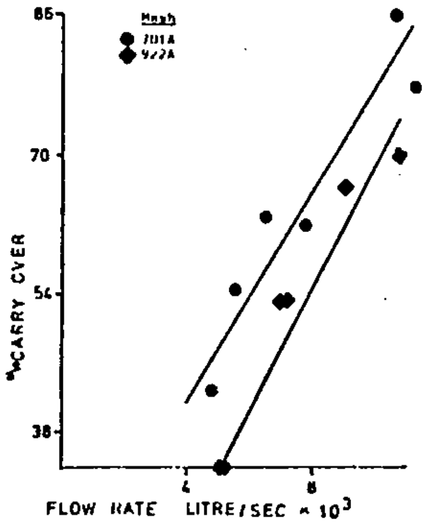

Fig. 3. Separation of type 255 nickel powder.

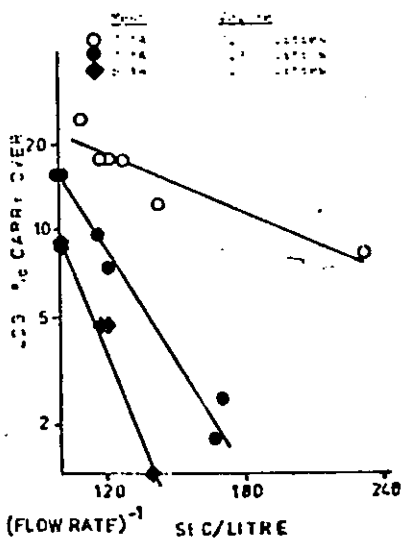

Fig. 4. Type 123 results conforming to equation 1.

Both the nickel-rich oil and the processed oil were then filtered on to weighed filter papers, washed thoroughly with trichloroethylene, dried and weighed. The results were then expressed as % carry-over of feed versus volumetric flow rate, where % carry-over is defined as the weight of nickel (in Y litres of processed oil) × 100 divided by the weight of nickel in Y litres of feed. The nickel that was carried over and the nickel concentrated within the collectors were strongly flocculated and filtered without any show through.

Results and discussion

Figs. 2 and 3 show the results obtained for the two sizes of nickel powder and the three aluminium mesh sizes at various volumetric flow rates when equal volumes of suspension are processed. Fig. 2 shows that % carry-over was found to vary linearly with flow rate once a minimum flow rate had been exceeded. The minimum flow rate can be seen to depend upon the hole size of the aluminium meshes. The finer the mesh the closer the nickel particles can approach a collection surface, and therefore, the greater the probability of capture. Also the finer the hole size for a given overall collector void volume the greater the collection surface available for capture. Other factors not investigated in this work will of course affect the minimum flow rate for carry-over. The main one being the length of the canister, for a given background magnetic field, as this will influence the size to which the flocs can grow before passing close enough to a collection surface for capture, as the minimum distance of approach for capture will be a function of agglomerate size. Increasing the length of the canister will also increase the probability of the flocs approaching close to a collection surface as well as increasing the amount of collection surface available for capture.

Fig. 3 shows the results for the finer nickel sample. Again the % carry-over varies linearly with flow rate. Comparison of Figs. 2 and 3 illustrates the importance of the packing characteristics of the particle on the separation behaviour of the system. Although there is a small difference in particle size between the two nickel samples the packing characteristics, as shown by their packed bed densities, are markedly different due to the shapes of the aggregates that make up the samples. Therefore, for any given collection volume the coarser sample can pack to a higher density than the finer sample, and because the slight difference in the particle sizes does not lead to a large difference in the volume available for collection the coarser particles are collected more efficiently under any given set of separation conditions.

Watson[10] has shown that the number of particles in a magnetic filter and the number escaping, for a monodisperse system, is determined by a quasi-linear second order partial differential equation which must be solved numerically. However, this equation can be simplified when the length of the filter $L \gg L_o$ where $L_o = 3\pi a/4R_cGF$, where a is the matrix wire radius, R_c is the capture radius of the wire[11], and G is a local function which describes the fall-off of R_c with local captured volume, and f is the fractional volume of the filter occupied by the matrix. For systems with strong interactions between particles and matrix $G = 1$ until the number of particles/unit volume trapped reaches N_T, where N_T is the number of particles/unit volume that the filter can hold when it is full, and then G 0. This means that the filter will fill up as a step function from the front. This will not strictly be true at the start of a separation where there is a strong particle/particle inter-action, as in this case, because the front will not fill up first due to the flocculating behaviour of the nickel within the filter. However, after a certain time the front will fill and then the rest of the filter will fill as a step function[12]. Once these conditions are reached the effective length of the filter L_{eff} $L - R_oV_ot/N_T$ where R_o is the number of particles/unit volume entering the filter, V_o is the fluid velocity and t is the time. If L_{eff} is used in equation 1 of reference 10 it can be shown that:

$$\log\left(\frac{N_o}{R_o}\right) = \frac{V_o}{L_oH_o}\left(n - \frac{R_o}{N_T}\right)H_o\tau \qquad (1)$$

where N_o is the number of particles leaving the filter, n is the number of canister volumes processed, H_o the background field, and τ the time taken for a particle to traverse the filter. Therefore, from run to run at fixed n or for the same run $\log(N_o/R_o)/nH_o =$ constant. As $\log(N_o/R_o)$ is equivalent to log (% carry-over) and is equivalent to the reciprocal of the volumetric flow rate for any fixed system. Graphs of log (% carry over) versus 1/(flow rate) should be linear. Figs. 4 and 5 show that log (% carry-over) varies linearly with reciprocal of the flow rate in agreement with equation 1. Similar behaviour has been observed by Oder and Price[13] with kaolin.

Conclusions

These results demonstrate the viability of using paramagnetic matrices for the filtration and separation of ferromagnetic particles. The difference in results for the two nickel powders emphasizes the fact that packing properties on the wire, which will be related to the bulk densities of the powders, plays a major part in the overall efficiency of any magnetic separation technique.

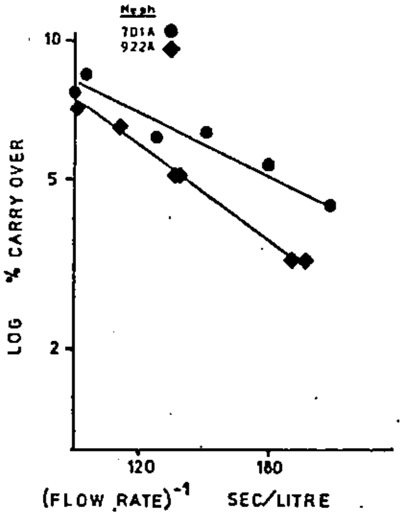

Fig. 5. Type 255 results conforming to equation 1.

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F4 Magnetic separation at high magnetic fields

J. H. P. Watson

The benefits that come from the use of superconductors in high intensity magnetic separators are first, the ability to process at high velocities without a decrease in efficiency which increases the production rate for a given system. Second, the open solenoid allows the full matrix to be changed rapidly without switching off the field, which also leads to a higher production rate. Third, the use of high fields to magnetically flocculate the particles can aid the extraction process.

Introduction

Within the last few years high-intensity magnetic separators have been developed that allow weakly paramagnetic colloidal particles to be extracted from a fluid moving through the separator. These systems were developed by the kaolin industry [1, 2], in co-operation with the Francis Bitter National Magnetic Laboratory, of Massachusetts Institute of Technology [3]. As yet the kaolin industry has the only commercial application of this technology but other large-scale applications are being considered in minerals and chemicals processing industry and in water and waste treatment [4, 5].

High-intensity separators, in practice, consist of a ferromagnetic wire wool matrix magnetised by uniform magnetic field. The matrix is usually held in a canister into which the slurry is fed. The arrangement is shown schematically in Fig.1. The paramagnetic particles are attracted to and held on the matrix. As more particles are captured the ability of the matrix to extract particles is reduced. At any point the filter can be cleaned by first removing the magnetic field and then flushing the matrix with water.

The magnetic field used in the commercial process has been about 2 T. The purpose of this paper is to examine the advantages that are obtained when the field is increased to 5 or 6 T. This is somewhat arbitrary, but in this range of field cheap superconducting magnets of fairly large value can be reliably constructed. Also this is as high in field as experimental work has been done.

Theory of particle capture

A theory of capture of paramagnetic particles has been developed [6, 7, 8] based on the interaction between a paramagnetic particle carried by a fluid past a ferromagnetic wire magnetized to saturation by a uniform applied field as shown in Fig.2.

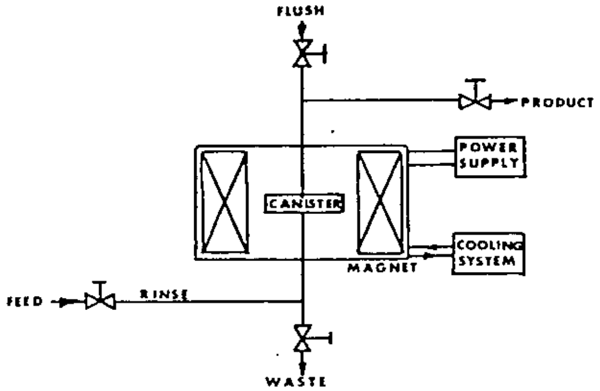
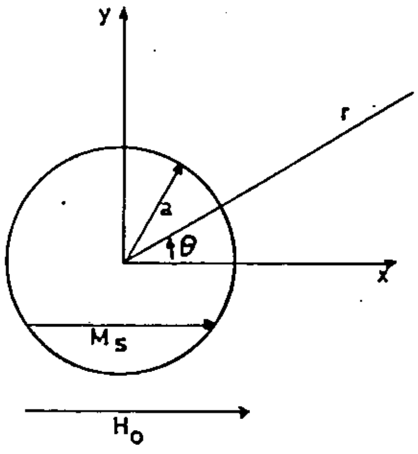


Fig.1. Feed and wash system.



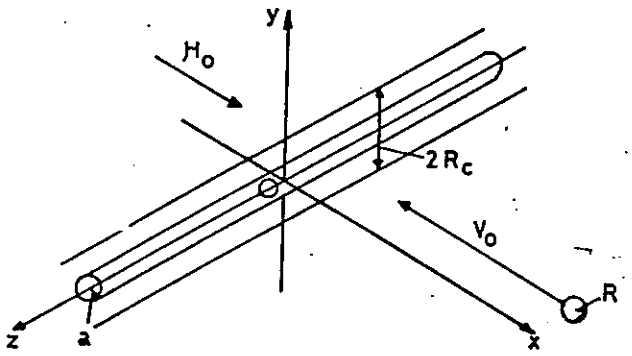


Fig.2. A paramagnetic particle carried by a fluid approaches a cylindrical ferromagnetic wire perpendicular to the wire axis. Far away from the wire the flow is parallel to the x-axis

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The author is with the Research & Development Department, ECLP & Co. Ltd, John Keay House, St Austell, Cornwall, England.

It can be shown that the equations of motion can be written in the form

$$\frac{1}{r_a}\frac{dr_a}{d\theta} = F(V_m/V_0.\ M_s/2\mu_0 H_0) \tag{1}$$

where $r_a = r/a$ where a is the radius of the ferromagnetic wire of saturation magnetization M_s. V_m is the 'magnetic velocity'.

$$V_m = \frac{2}{9}\frac{\chi R^2 M_s H_0}{\eta a} \tag{2}$$

χ is the magnetic susceptibility of the particles of radius R. H_0 is the applied magnetic field and η is the viscosity of the fluid. V_0 is the velocity of the fluid far away from the wire. V_0 is parallel to the applied field along the direction $\theta = 0$, which is supposed perpendicular to the axis of the wire.

From equation (1) it is clear that the particle orbits only depend on V_m/V_0. $M_s/2\mu_0 H_0$ and the initial position of the particle. The initial velocity is supposed equal to that of the fluid. When the applied field is greater than 2 T and when V_m/V_0 is reasonably large, then the capture cross-section of the wire depends principally upon V_m/V_0 and only weakly on $M_s/2\mu_0 H_0$. This means the capture cross-section of a clean separator depends largely on V_m/V_0 rather than V_m or V_0 separately. The performance of a clean separator at 2 T, therefore, will be the same as a separator operating at 6 T if the flow velocity V_0 is increased by a factor of 3

As the captured magnetic material builds up, the flow around the wire and consequently the capture cross-section will change. As the shape the captured material takes up is not known, the approach has been to guess a shape and calculate the capture cross-section. This has been done for cylindrical surfaces coaxial with the axis of the wire by Laborsky and Drummond [8], who find that the capture cross-section dose decreases as the volume of the captured material builds-up. They find the capture cross-section remains proportional to V_m/V_0 even in the presence of captured material so that the volume of captured material is proportional to V_m/V_0. Surfaces of ellipsoidal cross-section shown in Fig.3 have been used by the author [9], who has criticised the work of Laborsky and Drummond because of the capture condition they use and because they do not consider the stability of the captured particles. The author finds that the interception probability does not depend on the volume of the captured material, but the stability of the intercepted particles does depend on the volume of the captured material. It is shown that at the limit of stability

$$V_m/V_0 F(r_a, \theta, C_1, \lambda) = 0$$

where C_1 is the major axis of the ellipse and λ is the coefficient of friction between the particle and the surface. Although the predictions arrived at in the two cases are different in detail [8, 9] both suggest that the limiting volume of material captured is proportional to V_m/V_0. This is in agreement with work done in clay systems [10] where V_m/V_0 was varied over a factor of 20 and the variation in H_0 and V_0 being a factor of 10. It was found that the limiting volume of captured material depended linearly on V_m/V_0 with a correlation coefficient of 0.95 (30 measurements) [11]. Again this means that if the velocity of the fluid is increased proportionately with the magnetic velocity V_m, the performance of the separator remains the same which has been shown by experiment up to 5 T [10]. As the production rate is proportional to the velocity of the fluid through the filter, the production rate for a given system can be increased by a factor of three when the field is increased from 2 T to 6 T.

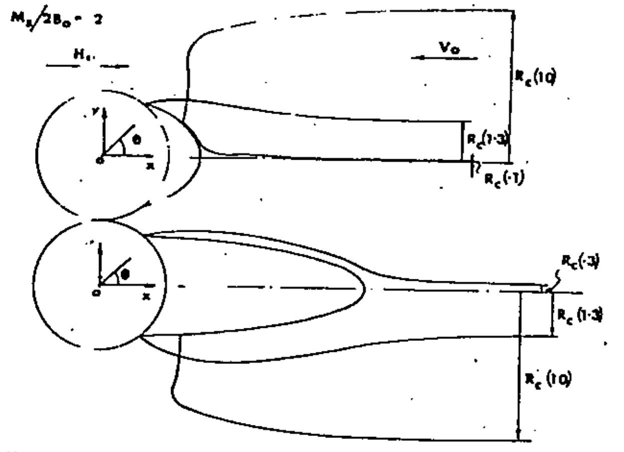

Fig.3. Particle orbits in the presence of captured material.

Magnetic flocculation

Another advantage that high field separation can have is magnetic flocculation which can considerably aid the separation process. To accomplish effective magnetic separation of a colloidal system, in practice, it is necessary for the colloid to be deflocculated. That is, the attractive London forces between the particles must be overcome by the formation of an electrical dipolar layer in the fluid around each particle which produces a net short range repulsion between them. A theory of colloid stability has been presented by Derjaguin and Landau [12] and by Verwey and Overbeek [13]. Methods of deflocculating many mineral systems have been reviewed by Vincent [14].

In a well dispersed colloid the potential barrier due to the dipolar layer is $\gg 15 k_B T$ where k_B is the Boltzmann constant. However, as this potential drops more rapidly with distance than the attractive London potential, it is often possible to develop weak attractive force between particles at a finite separation, often at a distance of 50–100 nm. If this potential well is deeper than $\sim 15 k_B T$, the colloid will slowly flocculate into this 'secondary minimum'. However, in addition to the above forces, the magnetic interparticle forces must be considered. If the particles are two equal dipoles of strength

$$\frac{\chi 4\pi R^3 B_0}{3\mu_0},$$

the interaction energy Vs, when they are separated by a distance d, is approximately $Vs = 4\chi^2\pi^2 R^6 B_0^2/(2R + d)^3\mu_0$. If d can be neglected in comparison to $2R$, and if the field B_0 is $B_0 4(2k_B T\mu_0/\pi^2\chi^2 R^3)^{1/2}$, then the paramagnetic particles in the colloid will begin to flocculate. The effect of this is to increase the effective value of V_m/V_0 and thereby increase the capture cross-section of the flocculating component. The colloid disperses as soon as the magnetic field is removed.

For kaolin particles with $\chi \sim 2 \times 10^{-4}$ of equivalent Stokes radius 1 μm, the field required for flocculation is 0.7 T; however, this produces weak flocs that can easily be broken by the shear forces in the separator. Much more stable flocs, with a much shorter time required for them to form, can be produced at high field which as pointed out above, can lead to an increase in the capture cross-section.

Calculation of the production rate

It can be shown that in the case of a clean separator [6], the number of particles/unit volume N_0 coming from N_i is given by

$$N_0/N_i \quad \exp\left(\frac{-4FR_c}{3\pi a} L \right) \tag{3}$$

where N_i is the number of particles/unit volume going into the filter, F is the volume of the matrix wire/unit volume of matrix and L is the length of the filter.

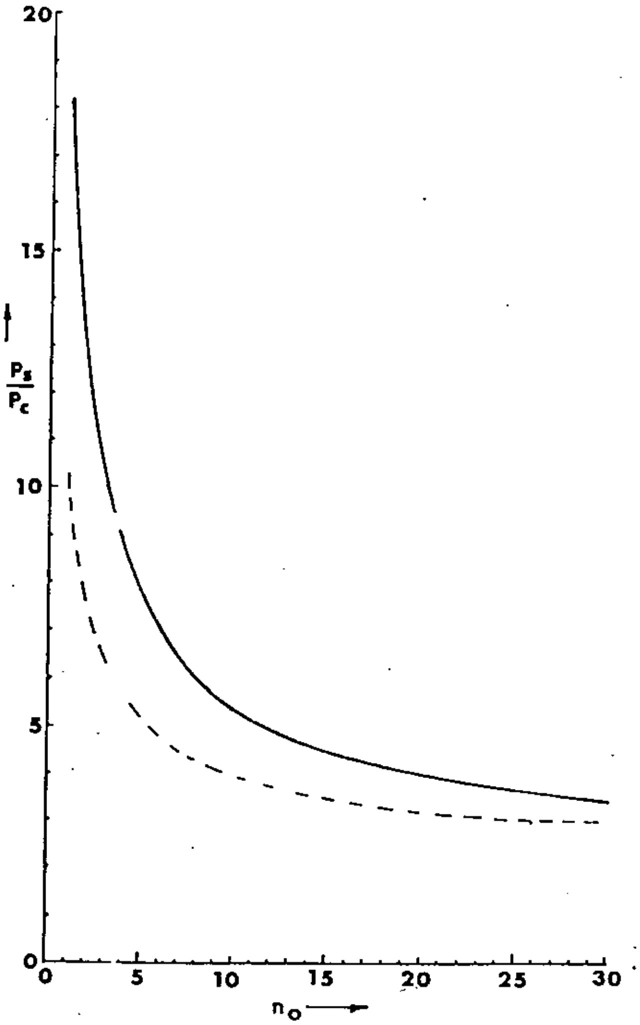

Fig.4. Ratio of processing rates for superconducting P_s *and conventional* P_c *separators of equal size versus canister volumes.*

When R_c depends on position in the filter, because of the dependence of R_c on the volume of material held by the filter, then Equation (3) no longer applies and the solution is obtained by solving a quasi-linear second order partial differential equation which must be done numerically [15]. If, however, R_c is large, and if $R_c \alpha V_m/V_0$, then the solution is approximately of the same form and can be written [16]

$$\log (N_0/N_i) = K_1(n - N_0/N_T)H_0\tau \tag{4}$$

where H_0 is the applied field and $\tau = L/V_0$ is the residence time of the fluid in the filter and n is the volume of fluid processed in units of the canister volume containing the matrix. Experimental work with American clays [17], and other materials [18], are consistent with this expression.

In practice, when n reaches some particular value, say n_0, the degree of separation reaches an unacceptable value. From Equation (4), n will remain the same if $H_0\tau$ is constant; that is, for a given separator, if V_m/V_0 remains constant which is the condition discussed previously. After this point has been reached, in normal practice, the remaining fluid is displaced from the matrix in the field H_0 with water at velocity V_0. The canister is then removed from the field and the captured material is washed out. For the case of a conventional iron bound solenoid, the field must be reduced to zero, washed out and then the field should be restored to the value H_0 before processing can be resumed. In practice this takes about 200 seconds.

For an open superconducting solenoid the canister can be easily removed from the field and at the same time a clean canister can be inserted by a magnetically balanced, reciprocating process. This allows the magnetic processing to be re-started within 10 seconds as the canister can be washed without holding up processing. This reciprocation can be continued indefinitely.

The production rate P can be written for a separator of length L of area A

$$P = V_0 A \,.\, N_0/(N_0 + 1 + D/\tau) \tag{5}$$

where N_0 is the number of canisters of fluid processed and D is the time taken to switch the field on and off and to flush the canister. In the case of the superconducting system described above, D is simply the time taken to interchange the canisters. The ratio in production rate can be evaluated for a superconducting system operating at 5 T and a conventional system operating at 2 T. By way of illustration in Fig.4, the ratio of production rates of superconductive and conventional separators is shown for various values of N_0. τ is taken to be 16 sec for 2 T. τ and V_0 are altered by a factor of 2.5 for a superconducting separator at 5 T. The dead times D are taken as 10 sec for the superconducting separator and 200 sec for the first case and 100 sec for the second case for the conventional separator. As shown in Fig.4, the production rate of the superconducting separator is many times greater than the conventional separator. The advantage is particularly great when the system is worked on a small number of canister volumes.

Conclusion

Magnetic separators using superconducting magnets have several distinct advantages over conventional magnetic separators. These advantages mainly come from the increased processing velocity the high magnetic field will allow, together with the fact that the use of open solenoids allow rapid cleaning of the separator which is particularly important when the separator must be cleaned frequently. Both of these factors lead to a higher production rate with a given system.

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THE BENEFICIATION OF CLAY USING A SUPERCONDUCTING MAGNETIC SEPARATOR

J. H. P. Watson and D. Hocking

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THE BENEFICIATION OF CLAY USING A SUPERCONDUCTING MAGNETIC SEPARATOR

J.H.P. Watson and D. Hocking*

ABSTRACT

This paper describes the reduction of the concentration of iron and potassium from a slurry of English Clay using a high intensity superconducting magnetic separator. It was found that for magnetic fields greater than about 2T, the performance of the filter depended on H_o/V_o where H_o is the applied field and V_o is the entrance velocity to the filter in agreement with theory. For fields less than 2T there is a slightly enhanced performance which is again in agreement with theory. Although in this region the theory may not be valid because particle size and shape effects become important.

I INTRODUCTION

The main purpose of magnetically processing English clays is to reduce the iron concentration and also the potassium concentration of the clay. This processing increases the commercial value of the clay. Some of these considerations have been outlined by Clark[1]. The iron in the kaolinite is in substitutional sites usually occupied by aluminium and is in the ferric state. The mica present contains iron, both in the ferrous and ferric state which substitutes for aluminium, and potassium which replaces sodium. The potassium is extracted only through its association with iron. In the absence of the iron, kaolinite is diamagnetic but the iron is present in sufficient quantity to give a paramagnetic volume susceptibility 10^{-4} (MKS).

American clays, from Georgia, have also been beneficiated by magnetic processing[2]. In this case colour bodies are removed which consist of iron stained titaniferous and micaceous minerals.

The filter used in this work was of the high-intensity type, which employs a ferromagnetic stainless-steel wool as a matrix.

It has been shown theoretically[4] that the performance of a filter of the high-intensity type depends on the ratio of the magnetic velocity V_m, to the entrance velocity V_o of the slurry to the filter. The magnetic velocity is given by

$$V_m = \frac{2}{9}\left(\frac{\chi M_s H_o R^2}{\eta\ a}\right) \qquad (1)$$

The ratio V_m/V_o consists of three parts. The first part is the matrix parameter, M_s/a where M_s is the saturation magnetization of the ferromagnetic matrix with strand diameter a. The second part is a particle parameter R^2 where χ is the susceptibility and R is the radius of the particle. If the particle properties and the matrix properties are given then V_m/V_o is directly proportional to $A = H_o/\eta V_o$ where η is the viscosity of the slurry and H_o is the applied magnetic field. A is a parameter which can be directly controlled. In Ref. 4 it was concluded theoretically that the filter performance should depend only on V_m/V_o if $M_s/2\mu_o H_o$ is small. When $\mu_o H_o = 5T$ then $M_s/2\mu_o H_o \simeq .2$, which is small enough to neglect.

II APPARATUS AND EXPERIMENTAL METHOD

The clay feed system is shown schematically in Fig. 1.

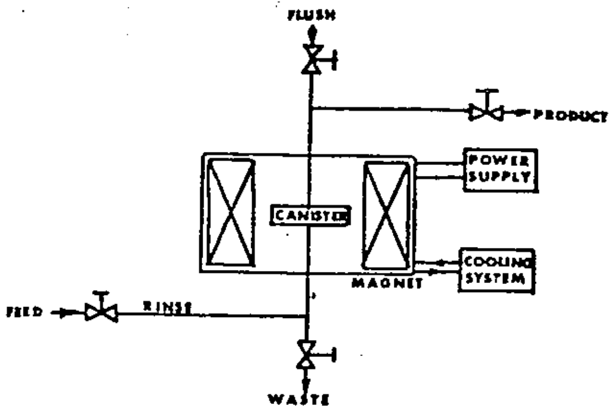

Fig. 1. Clay Feed System.

The canister contained about 5% by volume of ferromagnetic stainless steel wool with an average strand diameter 70 μm. The saturation magnetization of the matrix was 1.71T. The canister was situated in the region of maximum field parallel to the axis of the superconducting solenoid. The details of the cryostat are shown in Fig. 2 and are discussed elsewhere.[3]

The experiments consist of pumping clay upward through the canister at a constant speed in a given magnetic field. The clay was deflocculated with sodium silicate and its pH was adjusted to 8.5 by the addition of sodium hydroxide. The slurry was collected in volumes equal to the canister volume over a period of time. The canister volume was 462 cm^3 and was occupied by matrix at 5% loading. The canister volumes that came through the filter were analysed for mineral content, particle size, iron and potassium content and the amount of clay recovered.

As the filter extracts material its ability to extract further material falls. When the matrix was almost full the clay flow was replaced with water flowing at the same speed. When the clay feed had been completely displaced by water, the magnetic field was turned off and the magnetics were flushed from the canister in the opposite direction to the feed direction. The magnetics were analysed similarly to the clay passing through the filter.

In commercial practice the superconducting magnet will be operated with a double-canister system. In this system, the matrix is contained in two completely separate canisters. While one canister is filtering the other is being cleaned outside the magnetic field. Experiments with double-canister systems have now been successfully carried out.

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* English Clays Lovering Pochin & Co. Ltd.,
St. Austell, Cornwall, England PL25 4DJ.

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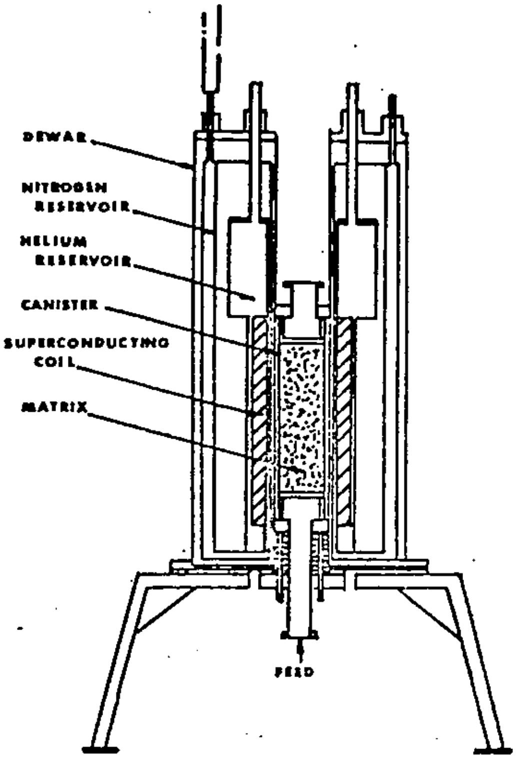

Fig. 2. Cryostat and Superconducting Magnet.

III · RESULTS AND DISCUSSION

The extraction process can be monitored by studying the material that comes through the filter as a function of time and by studying the magnetics which are held in the filter. As the product and magnetics depend upon the composition of the feed material and the ratio of the magnetic velocity to the input velocity V_m/V_o, these quantities will be dealt with first.

The composition and properties of the clay feed are shown in Table 1.

TABLE 1

PROPERTIES OF CLAY FEED

% 2 μ	6 ± 2	Kaolin	72 ± 10%
% 10 μ	53 ± 2	Mica	23 ± 20%
Brightness	76.2 ± .5	Quartz	2 ± 1
% Fe_2O_3	1.3 ± .03	Feldspar	2 ± 1
% K_2O	2.7 ± .02		

In the absence of a complete knowledge of the number of particles lying in small intervals of V_m, it is not possible to completely follow the extraction process. However, as discussed above, an extraction parameter A (= $H/_o\eta V_o$) can be introduced, where η is the viscosity. For a given clay and a given matrix configuration the use of A allows conclusions to be drawn. The filtering parameters are shown in Table 2.

TABLE 2

FILTERING PARAMETERS

A X 10^{-5}	Magnetic Field (KG)	Velocity (cm/min)	Clay/min (gram)	Clay density (gm/cm^3)
1.07	26.7	127.8	214.8	.174
1.05	35.6	173.4	291.5	.184
1.04	11.7	57.9	92.2	.184
1.03	50.0	247.7	416.4	.184
0.90	43.6	247.7	416.4	.184
0.66	43.6	337.2	566.7	.184

In order to examine the results it is convenient to introduce a quantity called the extraction efficiency. The extraction efficiency of Fe_2O_3 is defined as the difference of Fe_2O_3 in the product, expressed as a percentage of the Fe_2O_3 in the feed. A similar quantity can be defined for K_2O. It is also convenient when examining the performance to average together the material coming through the filter so an averaged extraction efficiency can be obtained for any volume that has passed through the filter.

In Fig. 3 the averaged extraction efficiency for Fe_2O_3 is plotted versus the no. of canister volumes passed.

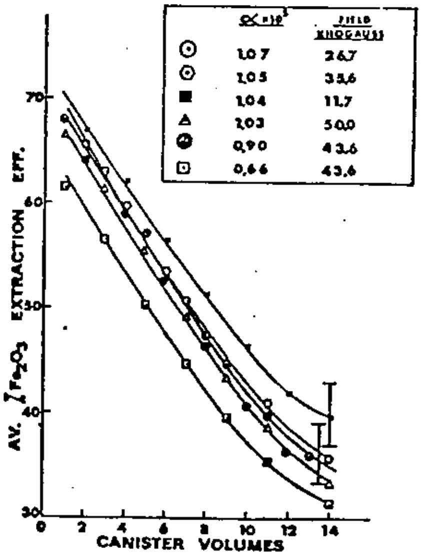

Fig. 3. Averaged Fe_2O_3 extraction efficiency plotted versus the number of canister volumes of clay processed with the extraction factor A as a parameter.

Each point on this graph represents the extraction efficiency for the material passing through the filter up to that point. As shown in Fig. 3 there is no significant difference for the extraction parameters A of 1.07 X 10^5, 1.05 X 10^5, 1.03 X 10^5 and .9 X 10^5 over 14 canisters volumes but the value for A = 0.66 X 10^5 is always significantly lower. In these results the applied field H_o and V_o vary by a factor of 2. However, for the value of A = 1.04 X 10^5 the extraction efficiency is significantly higher by about, 1 standard deviation, than for the others after about 8 canister volumes. In this case the applied field was 1.17T. It is also interesting to look at the ratio which is the ratio of the rate of capture of the .2 μm fraction compared with the rate of capture of the 10 μm fraction over the first few canister volumes. This is plotted in Fig. 4; it appears that over the first few canisters that is when the filter is fairly clean, then for A = 1.04 X 10^5 in which the applied field is 1.17T B is about 20% higher than for the other values of A near 10^5. After about 4 canister volumes the values of B are not significantly different.

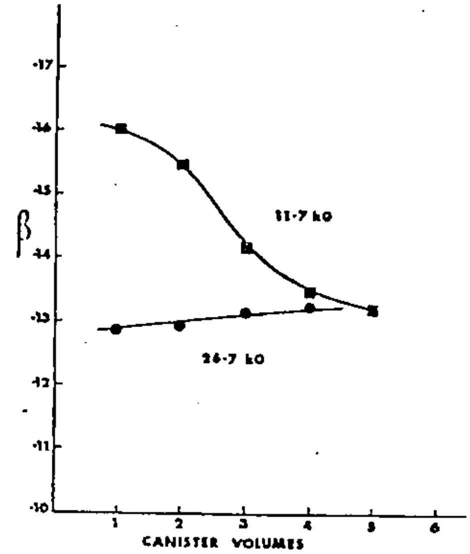

Fig. —. B, the ratio of the extraction rate of 2 μm particles to the extraction rate of 10 μm particles, plotted against canister volumes of clay processed for the applied field 11.7 kG and for 26.7 kG.

The averaged extraction efficiency of K_2O is shown in Fig. 5.

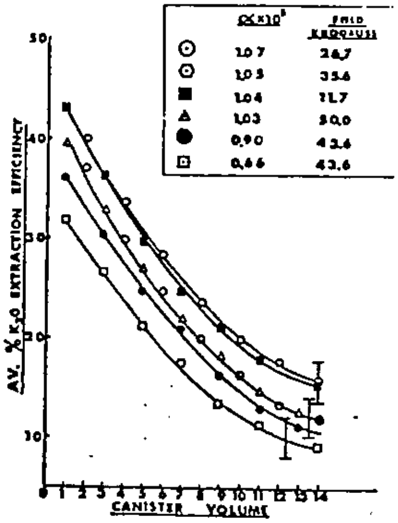

Fig. 5. Averaged K_2O extraction efficiency plotted versus the number of canister volumes of clay processed with the extraction factor A as a parameter.

Once more it appears that the extraction efficiency increases with A as does that for Fe_2O_3 shown in Fig. 3.

The properties and composition of the magnetics after 14 canister volumes of clay have been fed are shown in Table 3. The particle distributions are very similar. The outstanding difference is in the % Fe_2O_3 in the magnetics. The concentration of Fe_2O_3 falls with increasing extraction parameter. This reflects the properties of the clay distribution that the iron concentration falls as the particle size decreases. The higher extraction factor allows particles with a smaller radius to be extracted which lowers the average iron concentration of the magnetics. The volume of magnetics captured is seen to increase with extraction factor, except for the case of A = 1.03 X 10^5 where it is about 10% lower than might be expected if the volume of magnetics varied as A. This may be a high velocity effect, for example, compare A = 1.04 X 10^5 and A = 1.03 X 10^5, the clay velocity differs by a factor of 4 but there is a difference of about 10% in the volume of magnetics. If the difference is due to the absolute velocity V_o of the clay then this effect is less than a second order effect. This is confirmed by more extensive work on other clays. The total amount of Fe_2O_3 extracted is in general proportional to A except for the case of A = 1.04 X 10^5 where it is about 1.5% higher than the A = 1.07 X 10^5 value. The A = 1.04 X 10^5 has a larger fraction of small particles and a % K_2O in the magnetics similar to the A = 1.07 X 10^5 case. Again this indicates that the A = 1.04 X 10^5 is extracting more small particles than might be expected from the results for A = 1.05 X 10^5 and A = 1.03 X 10^5.

TABLE 3

PROPERTIES OF THE MAGNETICS AFTER 14 CANISTER VOLUMES

A X 10^{-5}	% 10 μ	% Fe_2O_3	% K_2O	Kaolin	Mica	Vol. of Mags. Vol. of Matrix	Relative Amount of Fe_2O_3
1.07	48	2.9	4.5	63.2	36.8	2.38	.98
1.05	53	3.1	4.7	61.5	38.5	2.15	.95
1.04	50	3.1	4.5	60.6	39.4	2.25	1
1.03	50	3.2	4.8	60.6	39.4	1.94	.88
0.90	48	3.2	4.8	60.6	39.4	2.01	.91
0.66	51	3.8	5.0	58.9	41.1	1.51	.81

From these results it appears that the performance of a magnetic filter depends on the value of $H_o/\eta V_o$ and not on H_o or V_o separately. The exception to this appears when a small value of magnetic field namely 1.17T is used. Under these circumstances the extraction efficiency of Fe_2O_3 is about 1 standard deviation higher than the other cases with A within a few percent of 10^5 after about 10 canister volumes. This results in a total iron extraction 1.5% higher than the trial with A = 1.05 X 10^5. This behaviour is that predicted by the theory in Ref. 4.

CONCLUSIONS

It is found that at magnetic fields greater than about 2T the extraction of iron from a clay slurry depends only upon H_o/V_o and the volume fed and not on H_o or V_o separately. This is in agreement with the theoretical conclusions.[4] However, below 2T there is an overall increased extraction of iron and also there is an enhanced rate of capture of small particles relative to larger particles in the clean filter. This is in agreement with theory, when the effect of a large value of $M_s/2\mu_o H_o$ are included.

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Research

Seeding Principles of High Gradient Magnetic Separation

Christopher de Latour

A paper contributed to and selected by the JOURNAL, authored by Christopher de Latour of Bitter Natl. Magnet Lab., Cambridge, Mass.

This article, the second of a three-part series, examines the precipitation of Al (III), Fe(III), Cu(II) and their co-precipitates, after the addition of magnetite seed. The use of a coagulant cation produces a coagulum containing enough magnetite to permit complete removal in the HGMS device at very high filtration rates.

The discussion that follows and the data presented are based on a precise laboratory batch test program[1,2] that explored precipitation and coagulation as they affect HGMS. Therefore, Charles River water was abandoned in favor of artificial samples of distilled water with known additives. The field and flow parameters as well as the chemical concentrations used are not necessarily the optimum parameters for commercial application of HGMS.

Precipitation on a Magnetite Seed

Precipitate adsorption onto Fe_3O_4 was achieved experimentally by exceeding the solubility limit of the ion in question in the presence of the dispersed magnetite. Immediately upon addition of the ionic species to the solution, ionic hydrolysis products are formed which have a zero, positive or negative charge, depending primarily on the ion concentration, the pH, and the presence of other complexing ions. These three factors emerge early in the precipitation process and will ultimately affect the formation kinetics and the nature of the precipitate.[3-5]

The instantaneous hydrolysis species are short-lived, because the solution is oversaturated with respect to some insoluble precipitate. The hydrolysis species must change coordination groups through condensation reactions while evolving toward a stoichiometric precipitate; the rate of this process is dependent on the charge of the hydrolysis species. For example, hydrolyzed ions of the form $Fe(OH)^{+2}$ (soluble) must obtain hydroxide groups whereas the species $Fe(OH)_3$ (soluble) requires no further condensation to become a hydrated ferric hydroxide precipitate.

Ultimately, colloidal hydroxo polymers emerge which are kinetic intermediates in the precipitation. It is at this stage that the evolving precipitates can begin adsorption onto the solids present in the solution. These colloidal materials themselves have no surface charge at some unique pH value, called the zero point of charge (ZPC). Above (below) this ZPC, the colloidal species have a negative (positive) surface charge. The transition from the colloidal polymers to the visible precipitate depends strongly on the surface charge and therefore the solution pH. For values near the ZPC formation is rapid, but at other pH values surface charge repulsions retard the precipitation process.

During this evolution, the magnetite seed surface acts as an adsorption site for the precipitate, which will be removed with the seed in the magnetic separator. Figures 1, 2 and 3 show the removal by the magnetite seed of ferric hydroxide (ZPC = 7.0 to 7.2),[6] aluminum hydroxide (ZPC = 6.0 to 8.0)[6] and cupric oxide

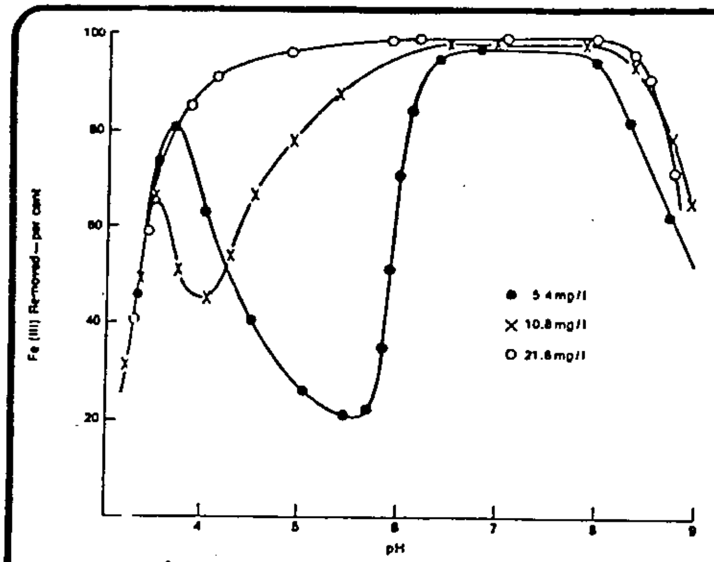

Fig. 1 Fe(III) Adsorption on 1000 mg/l Fe_3O_4 as a Function of pH
Solution agitated for 5 min before HGMS at 20 cm/s with magnetic field 10 kGauss. Fe(III) ions from ferric sulphate.

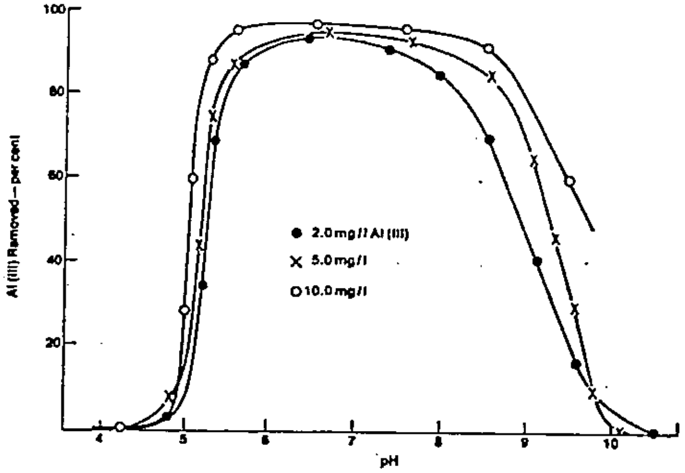

Fig. 2 Al(III) Removed With 1000 mg/l Fe_3O_4 Seed as a Function of pH
Solution agitated for 4 min before HGMS at 23 cm/s with magnetic field 8.5 kGauss. Al(III) ions from alum.

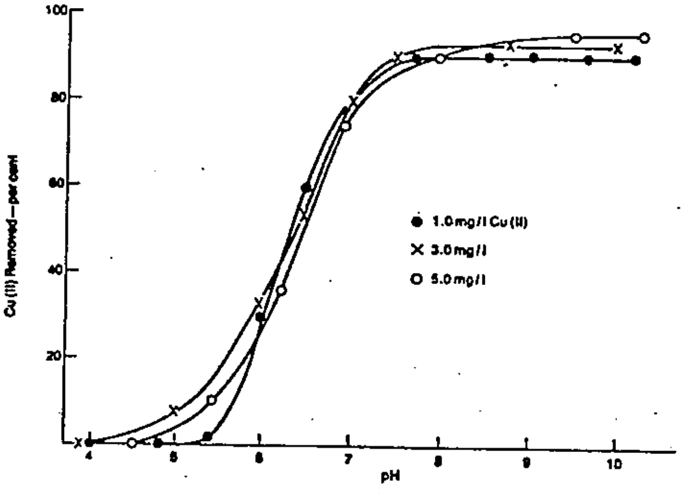

Fig. 3 Cu(II) Adsorption on 1000 mg/l Fe_3O_4 Seed as a Function of pH
HGMS at 20 cm/s with magnetic field 10 kGauss. Cu(II) ions from cupric sulphate.

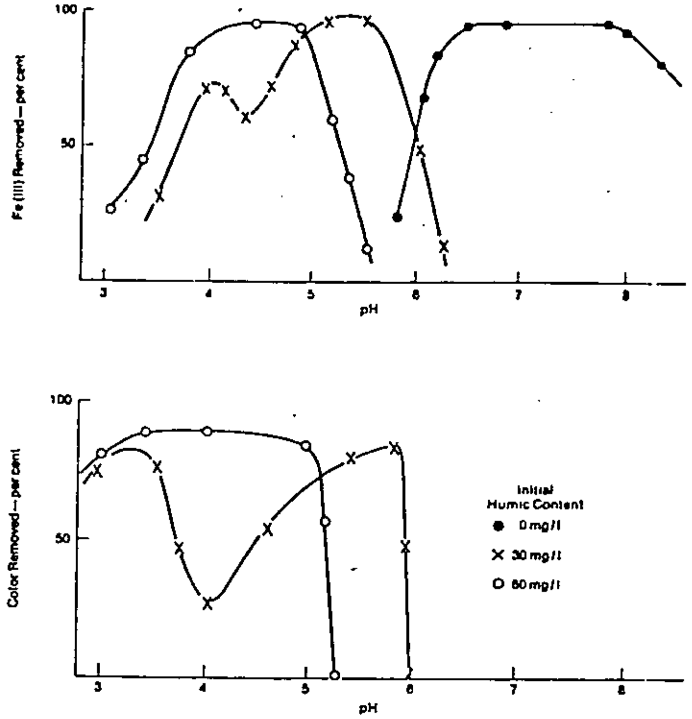

Fig. 4 Correlation Between Removal of Fe(III) and Removal of Color
Increasing content of humic substances shifts the precipitation product when the solution initially contains 5.4 mg/l Fe(III). Solution agitated for 5 min before HGMS at 20 cm/s with magnetic field 10 kGauss.

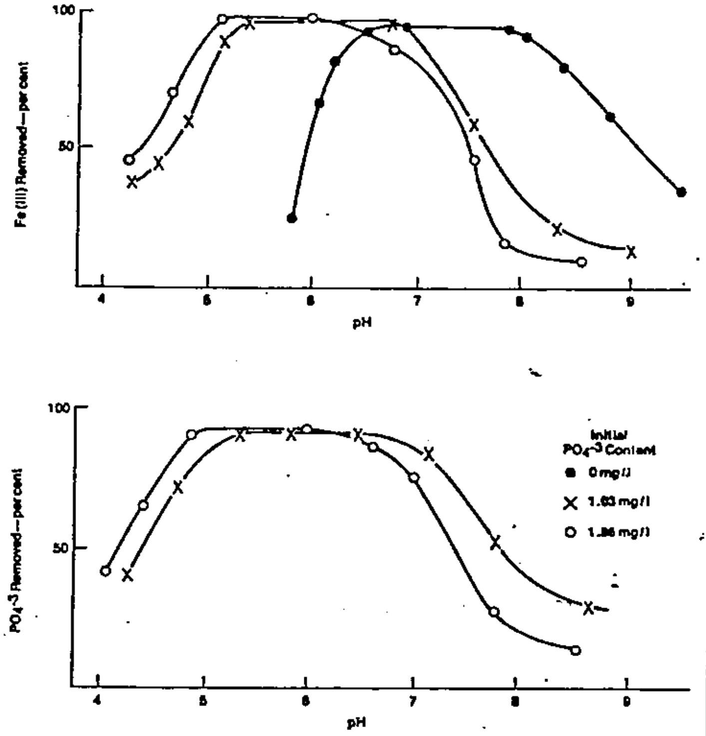

Fig. 5 Correlation Between Fe(III) and Orthophosphate Removal
Increasing orthophosphate content shifts precipitation toward a ferric phosphate species. Five-min agitation, 20 cm/s and 10kGauss were used. Orthophosphate from $Na_3PO_4 \cdot 12\ H_2O$.

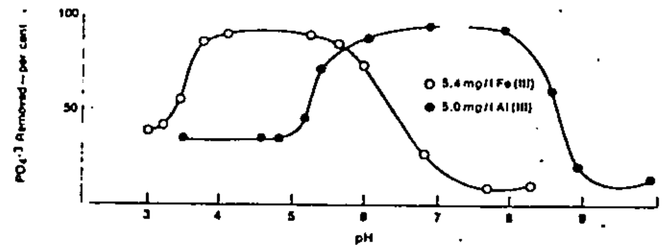

Fig. 6 Orthophosphate Removal vs pH for Two Coagulant Cations
Agitation for 5 min, flow rate of 23 cm/s, and field of 10 kGauss. Initial orthophosphate content 1.86 mg/l PO_4^{-3}.

(ZPC = 9.5.)[8] In each case, the most efficient precipitate removal occurs in a pH interval around the ZPC.

Note in Fig. 1 the strong dependence on the Fe(III) content. For 5.4 mg/l, the instantaneous hydrolysis species that dominate between a pH of 4 and 6 are of the form $Fe(OH)_n^{3-n}$, n = 4, 5 and 6; OH ions must be removed from the Fe(III) coordination positions, which retards rapid precipitation. Near a pH of 4, however, $Fe(OH)_3$ (soluble) is the dominant hydrolysis species which favors rapid formation and permits better removal, as in Fig. 1. The precipitation kinetics improve as the content of the Fe(III) ion increases; if more precipitation time is allowed, the Fe(III) removal of Fig. 1 at low cation contents will approach that of 21.6 mg/l. Aluminum cation precipitation shows less sensitivity to content and time.

These data are optimum, since the magnetite was present when the precipitation was initiated. If the seed is added while the precipitation is in progress, the aging precipitate may be less adsorptive. In the extreme, a fully formed and aged (dehydrated) precipitate will require the intervention of another chemical coagulant for attachment to the magnetite.

Co-Precipitations

The straightforward precipitation of the hydroxide or oxide of an ion is further complicated by the presence of complexing ions, which, in sufficient quantities, will force the domination of a new co-precipitation species. This makes possible the removal of dissolved species like orthophosphate or organic humic acids.[2,7]

Humic acid substances were extracted from leaf mulch to be added as a stock complexing ion.[1] In Fig. 4, the precipitation of 5.4 mg/l Fe(III) on the magnetite seed is altered with an increase in the humic content. The close correlation between Fe(III) and color removal of Fig. 4 implies that the ferric humate precipitate increasingly dominates over ferric hydroxide.

A second important co-precipitation is given in Fig. 5 when the orthophosphate ion is present as a complexing species. As the PO_4^{-3} content increases, the ferric phosphate species dominates. If the purification objective is to remove the orthophosphate species, a careful selection of the coagulant chemical used will match the precipitation span to the natural pH of the water sample. In Fig. 6, the PO_4^{-3} precipitation is achieved in two different pH intervals using Fe(III) and Al(III).

The above precipitations occurred during a 4–5 min agitation time. Without the use of the magnetite seed, such precipitations could require up to an order of magnitude more time to yield filterable solids. The magnetite seed is very clearly an excellent collector of aqueous precipitate products.

Solids Removal

The removal of suspended solids by HGMS relies on successful bonding of all the particles of the solution, including the magnetite seed material. The resultant coagulum contains sufficient

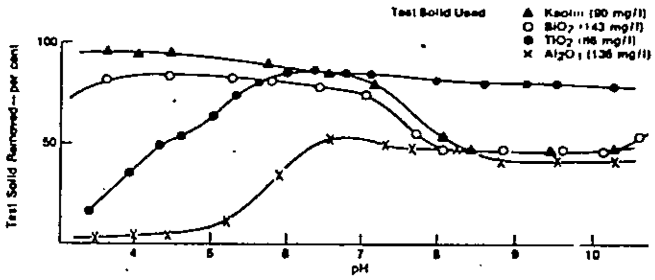

Fig. 7 Solids Removal by Fe_3O_4 Without Coagulant Cation
One mMole of $NaHCO_3$ in solution; pH adjusted with HCl or NaOH.

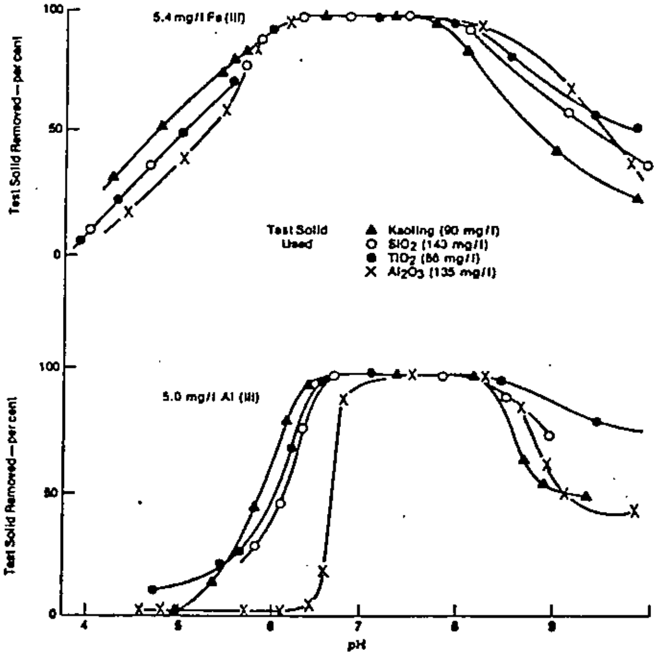

Fig. 8 Solids Removal by Fe_3O_4 With Coagulant Cation

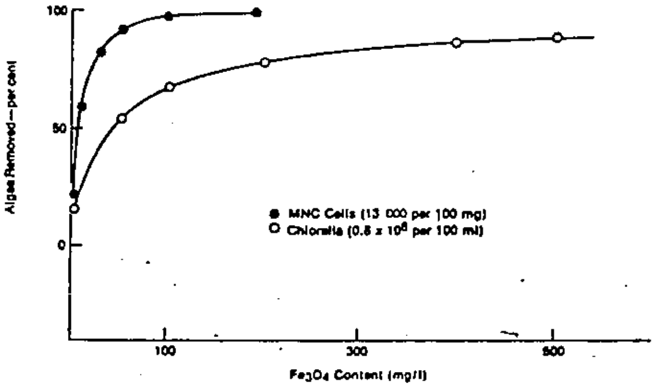

Fig. 9 Algae Removal vs Fe_3O_4—Single HGMS Treatment
Magnetite and algal cells were agitated 5 min in sea water before HGMS at 5 cm/s and 10 kGauss. A second treatment reduced the Chlorella content to less than 0.3 per cent.

Fig. 10 Floc Cluster

This photomicrograph shows a floc cluster formed by seeding sea water containing MNC and Chlorella *cells with magnetite.*

magnetite to allow rapid removal in the separator. A strong and effective bond between the magnetite and the nonmagnetic solids is crucial

Particles in aqueous solution are sensitive to surface charge interactions; flocculation into larger aggregates is achieved by a manipulation of the particle charge environment. Two methods of destabilization are discussed here:

1. The addition of a coagulant will cause a rapid formation of insoluble precipitate species that alter surface charge interactions and help to enmesh solids.
2. Double layer compression, because of an increase in the ionic content of the solution, will cause the particles in solution to agglomerate.

Solids Removal Using Coagulants. In conventional water treatment, the success of any coagulation depends primarily on the coagulant dose, the solution pH and the mixing time before separation.[5] Coagulants used today in the practice of water treatment include alum, sodium aluminate, ferric and ferrous sulfate, and a large variety of organic polyelectrolyte additives. Organic polycations are added to aid coagulation, whereas the anionic and nonionic species improve flocculation of the neutralized solids into larger aggregates. Such organic additives are generally unnecessary in HGMS unless there is a very high initial solids content or tight flocs are required to withstand very high flow rates (> 30cm/s).

To demonstrate surface charge interactions, certain micron-sized test solids were agitated for 4 min with the magnetite seed in a solution devoid of coagulant. Subsequent magnetic separation indicates the extent of the association attributed solely to surface charge interactions. The ZPC values of the materials are: Al_2O_3 9.1–9.2 pH, TiO_2 6.7 pH, SiO_2 2.5 pH; and kaolin clay, 4.6 pH.[6] The ZPC for magnetite is approximately 6.5 pH.[9]

These reported values are consistent with the trends of Fig. 7. Consider for example the interaction of SiO_2 and magnetite. Magnetite surface charge alters from positive to negative at the ZPC of 6.5, at which point the association with silica (negative surface charge above a pH of 2.5) should begin to decay. The same is observed for the kaolin-magnetite system. As another example, Al_2O_3 solids are positive until approximately 9.1 pH, and so repulsion is expected until the Fe_3O_4 goes negative near its ZPC, as observed.

When a coagulant is added to the solution, the resultant species coat the particulates and alter their surface charge characteristics. All test solids should therefore behave similarly in the presence of a coagulant. Figure 8 shows the same experiments of Fig. 7 except for the use of 5.4 mg/l Fe(III) and 5.0 mg/l Al(III). The ZPC of importance is now that of the coagulant precipitate which was discussed earlier. Fe(III) and Al(III) removal matches exactly the simultaneous solids separation in Fig. 8, so it is clearly the products of the coagulant cation that lead to enmeshment of the magnetite and the nonmagnetic solids.

Double Layer Compression. Coagulants are not always necessary for aggregation. A dispersion of colloidal or near-colloidal particles is assured if electrostatic repulsion dominates the interaction. A sufficient increase in the electrolyte content of the solution, however, will cause a severe compression of the stabilizing electric double layer around each particle; flocculation will result.[10] This mechanism is not usually important in the practice of water purification, but it is important in understanding the behavior of particulates in some natural surroundings, as for example in estuarine waters.[11] Double layer compression explains a series of experiments using HGMS for the separation of algal cells from salt water.

When magnetite is dispersed in an ocean-water sample, the high salt content removes electrostatic stabilizing factors, so aggregates rapidly form, associating the Fe_3O_4 with all the nonmagnetics present, as in Fig. 9. Concentrated stock samples of crescent-shaped *Nitschia Reversa* cells (MNC) and spherical *Chlorella* algae were used[12], and experiments with the less dense MNC exhibited better removal in the first treatment. Figure 10 is a photomicrograph showing a floc cluster that results when magnetite is used to separate a slurry of the two different cells. Flow rate during HGMS for this algal cell-removal data was 5 cm/s (75 gpm/sq ft), making HGMS a very efficient means for harvesting salt-water algal cells.

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Theory of High-Intensity Magnetic Separation

By J. H. P. Watson
Present address Department of Pure and Applied Physics, University of Salford, Salford, M5 4WT
English Clays Lovering Pochin & Co. Ltd., St. Austell, Cornwall

Introduction

The purpose of this paper is to examine the capture and retention of paramagnetic particles, of radius R and susceptibility χ, from a fluid, of viscosity η, flowing past a cylindrical ferromagnetic wire, of radius a, with a saturation magnetization M_s. The axis of the wire is assumed to be perpendicular to the flow and also perpendicular to the applied field H_o, which is sufficiently large to saturate the ferromagnetic wire. The velocity of the fluid far away from the wire has a magnitude V_o. The configuration in a plane perpendicular to the axis of the wire is shown in Fig. 1. In previous work[1] the capture cross-sector $2R_c a$ of the bare wire has been calculated. It was found that R_c depended on the parameters V_m/V_o and $M_s/2\mu_o H_o$ where V_m is the 'magnetic velocity' given by

$$V_m = \frac{2}{9}\left(\chi R^2 \frac{M_s}{a}\frac{H_o}{\eta}\right) \qquad (1)$$

Experimentally it is found that once a magnetic separator has captured an amount of material of the order of the volume of the wire matrix, then the effectiveness of the separator begins to fall[2]. The purpose of this work is to investigate the reason for this fall.

The shape that captured material adopts under the action of drag, surface and magnetic forces has not been discovered, so it remains then, to try various shapes and examine the behaviour of the capture cross-section as the volume of the captured material is increased. In this work an elliptical shape is adopted as shown in Fig. 1. The ellipse is only present on the leading side of the wire when $M_s/2\mu_o H_o < 1$. The ellipse always passes through the point $(r/a = 1, \alpha)$, α is the angle at which the normal force becomes repulsive. The volume of the ellipse is increased by increasing the major axis C_1. In this work $M_s/2B_o = 0.2$, so that $\alpha = 50.77$. Shapes different from this, based on the cylindrical surfaces in Fig. 2, have been tried by Luborsky and Drummond[3] who conclude that the capture cross-section decreased as the volume of captured material increased.

Initial calculations, using elliptical surfaces, showed that for small amounts of captured material, the capture cross-section was unchanged[4]. However, a preliminary attempt to investigate the stability of the captured particle showed that the effective cross-section of particles with small values of V_m/V_o was very low so that the net cross-section was greatly reduced[4].

More complete calculations of the capture cross-section are presented in this paper over a wide range of volumes of captured material. A probabalistic model has also been developed that allows a probability of retention to be calculated. The inclusion of these factors in the calculation of the net cross-section is vital to the understanding of the magnetic separation of a stable colloid which has a short range inter-particle repulsion due to electrical double-layers. If the particles do not form a stable colloid, either due to double-layer interactions or perhaps to magnetic flocculation[4] then in order for a particle to be captured, it is simply necessary for the particle to collide with the already captured material. This is a much less stringent condition than that for the capture of a stable colloid.

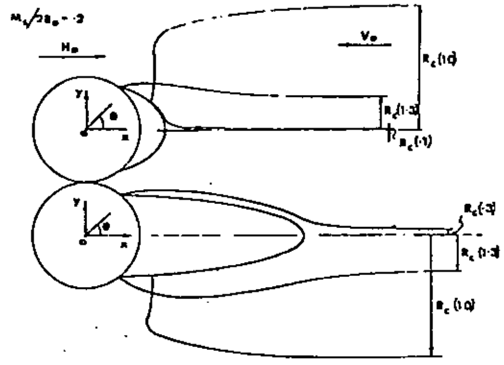

Fig. 1. Typical limiting orbits, in the presence of captured material. The capture cross-section/unit length of wire is $2aR_c$.

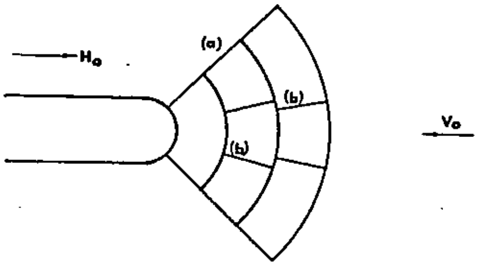

Fig. 2. Form of captured material used by Luborsky & Drummond (2).

Theory and discussion

The capture radius, R_c, is shown in Fig. 1 and the effective capturing area/unit length of wire that the wire presents to the particle stream, $2R_c a$, is called the capture cross-section.

The components of magnetic force on the particle are assumed to act at the centre of the particle and are given by F_r in the radial direction and F_θ in the direction θ, as discussed previously ([1-3]).

$$F_r = -(6\pi\eta R)V_m((M_s/2\mu_o H_o r_a^5) + \cos 2\theta/r_a^3) \qquad (2)$$

$$F_\theta = -(6\pi\eta R)V_m \sin 2\theta/r_a^3 \qquad (3)$$

where $r_a = r/a$. Examination of Equation (2) shows that for angles $\theta > \alpha$ the radial force on the particle is repulsive. It is, therefore, assumed that the stable surface of the captured magnetic material passes through the cylinder at this angle α where

$$\alpha = \tan^{-1}((1 + (M_s/2B_o))/(1 - M_s/2B_o)) \qquad (4)$$

The particle Reynolds number $R_p \left(= \frac{V_o \rho a}{\eta}\right) < 0.1$ and for values of R_p of that order the drag force on the particle is given by $F_D = 6\pi\eta RV$ where V is the relative velocity between the fluid and the particle ρ is the fluid density.

The flow of the fluid was calculated in the inviscid approximation using a method due to Hess and Smith[5]. Bodies are not required to be slender and perturbation velocities are not required to be small. The method is numerically exact in the sense that any degree of accuracy may be obtained. The body is split into elements and at the centre of each a source is introduced. The strengths of the sources are determined by the condition that the normal component of velocity is zero. Using the symmetry of the body the number of elements can be doubled and was about 200. Under these conditions, the capture radius R_c for a circular cylinder, calculated by the Hess and Smith method, was within 1% of the value determined using the analytical expression for values of $V_m/V_o > 0.5$. For $0.5 > V_m/V_o > 0.2$ the difference was about 5%. The equations of motion become

$$a\,dr_a/dt = V_o f - V_m((M_s/2\mu_o H_o r_a^2) - \cos 2\theta)/r_a^3 \qquad (5)$$

$$a\,d\theta/dt = V_o g - V_m \sin 2\theta/r_a^3 \qquad (6)$$

The functions $f = f(r_a, \theta, C_1, \alpha)$ and $g = g(r_a, \theta, C_1, \alpha)$ are determined by the method of Hess and Smith. Equations (5) and (6) were integrated numerically using a method described previously[1]. The capture radius R_c was determined by starting the particles far away from the capturing centre and at values of $r_a \cos\theta$ that were increased progressively until a limiting value R_c $(= r_a \cos\theta_c)$ was found for which capture was obtained. Capture resulted if the path of the particle cut the surface between $\pm\,\alpha$. Typical limiting orbits are shown in Fig. 1. With these assumptions R_c was determined as a function of V_m/V_o for elliptical surfaces with various values of the major axis C_1. It was assumed that the captured particles did not alter the magnetic forces, that is the particles have the same susceptibility as the fluid. The results are presented in Fig. 3. If the particles were able to stick to the captured material, this value of R_c is appropriate. If the particles can stick to the wire independently of the magnetic forces then R_c would be slightly increased above the values given in Fig. 3, but this case will not be examined here.

We must now consider the stability of particles on the surface. The forces acting on the particle are fluid drag F_D, entirely parallel to the surface, normal and tangential components of magnetic force, $(F_m)_\perp$ and $(F_m)_\parallel$ and dissipative forces due to collisions with the surface are assumed to be friction-like, parallel to the surface and proportional to $(F_m)_\perp$. The work done/unit length of surface by the frictional force to be $\lambda(F_m)_\perp$. Then if the surface is rough on a scale 2R, the energy dissipated per collision must be $\sim 2R\lambda(F_m)_\perp$. Assuming that the binding energy of a particle in the surface is $\sim 0.6R(F_m)_\perp$, then if the surface is to remain stable under particle collisions, assuming that the particle interacts with individual particles of the captured material, then $\lambda < 0.3$. A value of $\lambda = 0.3$ is used in the numerical evaluation shown later.

As discussed above, it is expected that stable pockets will be separated by a distance approximately equal to 2R where R is the radius of the particles comprising the captured material and collisions with the surface might be expected to occur at distances separated by approximately 2R. We can assume that the surface velocity of the particle V_s is given by $((F_m)_t + F_D - \mathrm{sgn}((F_m)_t)\,\mu|(F_m)_r|)/(6\pi\eta R))$. (For the sign convention used here $F_D > 0$ but $(F_m)_t$ can be greater or less than zero). In what follows we assume that a particle collides with the surface in some element i. Normally $V_s < 0$ so that the particle moves, unless it is captured, over the surface into element i-1, then to i-2 until element 1 is reached. If the particle moves beyond this element it is not captured. The values $V_s > 0$ normally occur in the elements near 1, that is near the limit of stability. In estimating the probability of capture certain general limits can be established. The first is the limit on the value of λ, which was discussed above. The second is that if $(F_m)_t > F_D$ the particle will move against the fluid and be reduced to zero velocity at some point, so that capture should be almost certain. Thirdly, assuming $V_s < 0$, if $|V_s|$ is large the probability of capture should be reduced, in particular if $V_s > (F_m)_t/(6\pi\eta R)$ the chance of a particle falling into a pocket will be small. On this basis a probability of capture P_c was assigned/collision using linear interpolation between the limits discussed above. This interpolation scheme is shown in Fig. 4. The conditions for $P_c = 0$ and for $P_c = 1$ are both of the form $(V_m/V_o)F(r_a,\theta,C_1,\lambda) = 0$ where

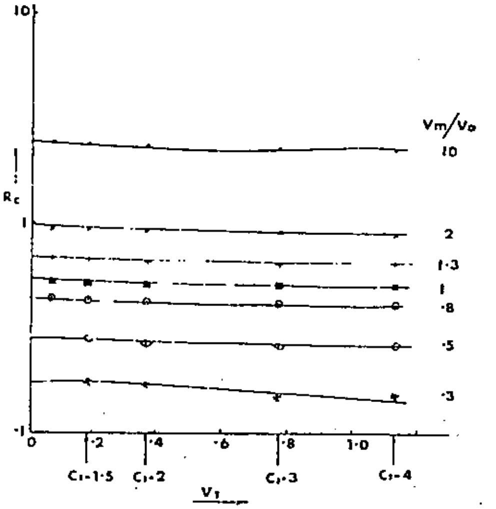

Fig 3. The capture radius R_c versus C_1 and V_T, where V_T is the volume of captured material normalized to the volume of the wire.

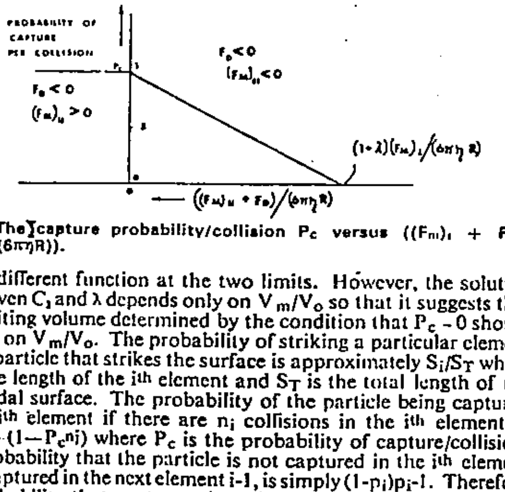

Fig. 4. The capture probability/collision P_c versus $((F_m)_t + F_D)/(6\pi\eta R))$.

F is a different function at the two limits. However, the solution for a given C_1 and λ depends only on V_m/V_o so that it suggests that the limiting volume determined by the condition that $P_c = 0$ should depend on V_m/V_o. The probability of striking a particular element i for a particle that strikes the surface is approximately S_i/S_T where S_i is the length of the ith element and S_T is the total length of the ellipsoidal surface. The probability of the particle being captured in the ith element if there are n_i collisions in the ith element is $p_i = (1-(1-P_c)^{n_i})$ where P_c is the probability of capture/collision. The probability that the particle is not captured in the ith element but is captured in the next element i-1, is simply $(1-p_i)p_{i-1}$. Therefore the probability that capture takes place in i or i-1 is $p_{i,i-1} = p_i + (1-p_i)p_{i-1}$. The probability of a particle originating in the ith element being captured in the (i-2)th element is $(1-p_{i-1})p_{i-2}$. The probability of the particle originating in the ith element and being captured in the ith, (i-1)th or the (i-2)th element is $p_{i,i-2} = p_{i,i-1} + (1-p_i)(1-p_{i-1})p_{i-2}$. Following this procedure the probability of the particle originating in the ith element and being captured somewhere between the ith and the 1st element, where the captured material joins the cylinder can be found and is $p_{i,1} = p_{i,2} + p_1 \prod_{i=2}^{l=i}(1-p_i)$.

Therefore, the total capture cross-section P into any element is

$$P = \frac{2R_c a}{S_T} \sum_{i=1}^{i=N} p_{i,1} s_i \tag{7}$$

where N is the total number of elements. Calculations were made using the value of $\lambda = 0.3$, and are shown as a function of the normalized volume of captured material in Fig. 5.

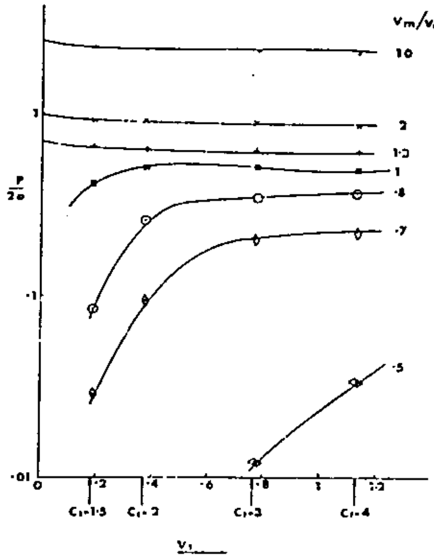

Fig. 5. The capture radius P/2a versus C_1 and the normalized volume of captured material.

As shown in Fig. 5 the effective cross-section P for values of $V_m/V_o \leq 1$ is much less than $2R_c a$ for small volumes of captured material, as the material builds up on the wire the capture cross-section P increases. This means that a filter capturing only particles with low values of V_m/V_o will be poor at first, but will improve as the filter captures more material. This kind of behaviour has been observed in monodisperse systems[4]. The improvement in the capture cross-section of the particle with small values of V_m/V_o is due to the decrease in surface velocity and to the increase of surface area as the major axis of the ellipsoid grows. It is important to realise that these calculations start with an ellipse of a given volume, determined by C_1, and capture cross-sections are calculated for particles on to the given ellipse. The consequence is that the growth mechanism of the ellipse is not considered and although particles have significant capture cross-sections for a given ellipse, the positions of capture may be such as to greatly distort the growth from uniform elliptical surfaces. To illustrate this point contours are drawn in Fig. 6 of the boundary where capture falls to zero for particular values of $V_m/V_o < 1$. The area which includes the symmetry axis is the area in which the capture is non-zero. From Fig. 6 it is apparent that an ellipse with $C_1 = 1.5$ cannot be grown uniformly with $V_m/V_o = 1$ but can almost be with $V_m/V_o = 2$ and certainly can with $V_m/V_o = 5$. $V_m/V_o = 6$ can grow an ellipse of length $C_1 = 2$ but the deposition becomes non-uniform at $C_1 = 3$. Although not shown in Fig. 6 the contour for $V_m/V_o = 10$ includes $C_1 = 4$.

In actual practice the first layer that attached to the wire might stick due to surface double-layer forces which may be attractive. In this case for particles with small values of V_m/V_o capture of the first layer may be strong, falling as the second layer is deposited.

From Fig. 3 it is clear that using elliptical surfaces there is virtually no dependence on the capture radius if the condition for capture is simply that the particle should collide with the captured material. Using this kind of capture condition and the surfaces shown in Fig. 2, Luborsky and Drummond[3] have found an appreciable dependence of R_c on the captured volume. They found

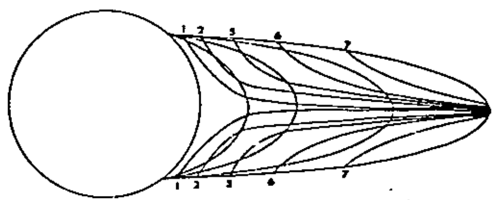

Fig. 6. Contours of limiting probability of capture onto the four ellipsoids, for various values of V_m/V_o.

that $R_c = (V_m/2V_o)(a/a_n)^2$ where $a_n = a+2R_n$ and n is the number of layers of particles. Comparing the volume of the captured material to that of a cylinder of unit length with radius of a. Then $n = 48$ then the volume of captured material is approximately equal a^2 and then R_c is reduced by a factor of 0.178, whereas for the ellipsoidal case the change is only a few percent. Some of the difference in result may be due to the fact that in the flow potential beyond the value $r = a + 2R_n$ was not investigated and it is possible that for the larger values of V_m/V_o capture behind the cylindrical surface is possible. Luborsky and Drummond did not investigate the stability of the captured particles so that it is nor possible to estimate if shapes of the kind used are to be expected to occur. Another shape shown in Fig. 2 was also tried in which layers subsequent to the first were restricted to the width 2a. This led to similar results as the first case but $R_c = (V_m/V_0)(a/a_n)^2$. This shape is much closer to the overall shape used in this work. However, the capture condition that the particles simply collide with the leading cylindrical surface is not sufficient to rule out capture onto the material behind the cylindrical surface. Luborsky and Drummond[3] used the expressions to calculate the performance of a filter separating mixtures of CuO and Al_2O_3 from the experimental results of Oberteuffer[7] Taking the first shape discussed, the theory fitted the experimental results if one assumed a certain amount of mechanical entrapment of Al_2O_3. However, another explanation is that the colloidal suspension was not fully deflocculated. This would ensure entrapment and also would make the build-up captured material much more likely to assume the shape used by Luborsky and Drummond. The analysis presented here applies where the colloid is stable.

The range of validity of the type of model has been discussed previously ([1-4]) and the same arguments apply to this work. However, the most serious other criticism of this work is the use of an inviscid fluid in the region close to the surface of the captured material. As the Reynolds number is of the order of 10 the boundary layer is ~0.3a. The actual drag on the particle is therefore overestimated. However, qualitatively, the dependence of the effective cross-section on volume of captured material should be the same as found here, as the drag on the particle will decrease with C_1 and the surface area and, therefore, the number of capture sites will increase with C_1. This means that the results obtained here should be qualitatively correct rather than quantitatively correct.

Conclusions

The calculated capture cross-section for large values of V_m/V_0 does not show a marked decrease with increased volume of captured material of elliptical shape. There is a high probability of capture over the whole surface for $V_m/V_0 > 10$ even when the volume of the captured material is of the order of the volume of the wire.

The total capture cross-section P for values of $V_m/V_0 < 1$ increases rapidly with the volume of captured material until it reached $2R_c a$. As V_m/V_0 decreases the region over which particles can be captured reduces in size and moves toward the edge of the captured material and the wire. This leads to a distortion of the growth of elliptical surface. The results indicate that if a filter is working in the range of small V_m/V_0 then the capture cross-section should increase as the capture proceeds. This work, it is suggested, applies to stable colloids where the short range forces are repulsive and this leads to a weak dependence of the capture cross-section with large volumes of captured cross-section with large volumes of captured material. If the captured material is considered as a granular solid, an examination of slip instabilities along various planes indicates that the ellipsoids become more stable as C_1 increases[8]. This suggests that the limits of growth must come through distortions from the ellipsoidal shape which increases the particle drag in the region where collection of particles occurs.

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Applications of and Improvements in High Gradient Magnetic Separation

By J. H. P. Watson
University of Salford, Dept. of Pure & Applied Physics, Salford, England

Applications of HGMS are steadily increasing and now include mineral processing, effluent and waste-water treatment, and chemical, biochemical and pharmaceutical processing. These applications are reviewed, the theory of magnetic separators is outlined, and cost reductions and processing improvements are suggested.

Anwendungen und Verbesserungen auf dem Gebiet der magnetischen Abscheidung bei starkem Gefälle

Es werden immer mehr Anwendungsformen auf diesem Gebiet entwickelt, die jetzt von der Verarbeitung von Mineralien über die Aufbereitung von Abwässern bis zur chemischen, biochemischen und pharmazeutischen Verarbeitung reichen. Disee Anwendungsgebiete werden in der betreffenden Arbeit besprochen, wobei die Theorie magnetischer Ausscheider dargelegt wird und Kostenersparnisse und Verfahrensverbesserungen angeregt werden

Applications et améliorations en séparation magnétique à forte pente

Les applications de la séparation magnétique à forte pente—HGMS—augmentent progressivement et dès maintenant comprennent le traitement des minerais, le traitement des effluents et des eaux de décharge, les procédés chimiques, biochimiques et pharmaceutiques. Ces applications sont revues, la théorie des séparateurs magnétiques est mentionée en grandes lignes; des réductions de frais ainsi que des améliorations de traitement sont suggérées.

Introduction

Magnetic separation has been in use for many years in the mineral processing industry for the removal or separation of minerals. In order to produce this separation both magnetic field and field gradient are necessary. The magnetic field has commonly been produced by electromagnets using iron in the magnetic circuit so that the field was limited to about 2T. Field gradients were usually produced by shaping or by use of secondary poles. The material was either held on to the secondary pole or deflected mechanically to achieve separation. These machines are useful when the particle size is large and the materials are strongly magnetic. It is not possible to separate colloidal systems with these separators.

Within the last few years high intensity magnetic separators (HIMS) or high gradient magnetic separators (HGMS) have been developed that allow weakly paramagnetic colloidal particles to be extracted from a fluid moving through the separator (^{1}). These systems were developed by the kaolin industry in the United States(^{2,3}) in co-operation with the Francis Bitter National Magnet Laboratory(^{1}).

High gradient magnetic separators, in practice, consist of ferromagnetic wire wool matrix occupying 5-10% of space magnetized by a uniform magnetic field so that magnetic field gradients as high as 1 kilogauss/micron can be achieved. The matrix is usually held in a canister into which the slurry is fed. As particles are captured the ability of the matrix to extract particles is reduced. At any point the filter can be cleaned by first removing the magnetic field and then flushing the matrix with water which easily removes the captured material leaving a clean matrix. When the magnetic field is restored the magnetic separation can begin again. Fig 1 shows a small high gradient magnetic separator built by International Research and Development Co. Ltd. of Newcastle-upon-Tyne and Fig. 2 shows the internal arrangement and the external plumbing for a typical HGMS system of the type in use in the kaolin industry.

As yet the kaolin industry has the only commercial application of this technology which uses electro-magnets at 2T. However, because of its ability to rapidly process colloidal systems, in comparison to other technologies, a wide range of applications in mineral processing, in water and waste treatment, chemical and biochemical engineering and in pollution control have been suggested and have been the subject of various experimental studies.

These are various ways the high gradient magnetic separators can be used.

1. When there exists a difference in magnetic susceptibility between two paramagnetic minerals they can be differentially separated even though they are of colloidal size.
2. When the particles to be collected are diamagnetic they can be separated by scavenging or coagulating them with a paramagnetic material which can then be removed with the separator.

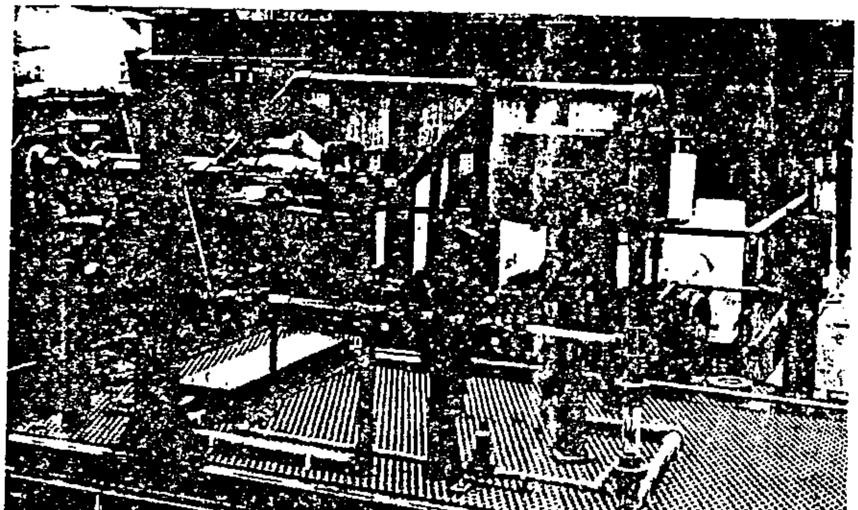

Fig. 1 A typical small HGMS system made by International Research and Development Co. Ltd., Fossway, Newcastle-upon-Tyne. [I.D. Appleton and P. Dobbing, Filtration & Separation May/June (1977)].

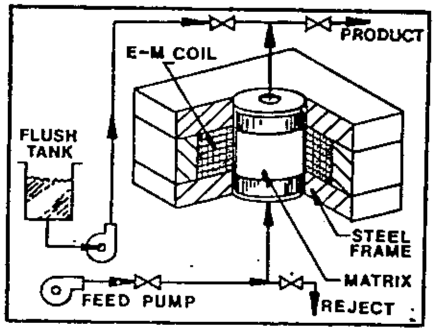

Fig. 2. A cut-away view of a conventional HGMS system together with the layout of the exterior plumbing. Supplied by courtesy of Sala Magnetics etc. (P. G. Marston, J. J. Nolan and L. M. Lontai, U.S. Patent No. 3,627,678).

3. When a dissolved species can be precipitated on to a magnetic carrier or is magnetic itself it can be removed by the separator.

The purpose of this paper is first to give a brief review of some of the applications of high gradient magnetic separation, secondly, to outline the theory of magnetic separators and third, to show how by using the theory significant improvements of the technology have been suggested.

Applications of HGMS

In the mineral processing industry, as previously mentioned, kaolin is treated using high gradient magnetic separators removing micron sized particles which contain iron. These particles lower the brightness of the kaolin and thereby make it less suitable for paper filling and paper coating(2,3). This technology can also be used for the improvement of the fired brightness of ceramic clays(4). Several large separators, with the ferromagnetic matrix contained in baskets approximately 2m in diameter, are in commercial use in the United States and in Cornwall, England. These separators operate with a field of 2T (20 kilogauss) applied parallel to the slurry flow In American clays the mineral removed is iron-stained TiO_2 particles of approximately 1 micron radius. English clays are different from American clays; the main materials extracted are kaolin particles or micaceous particles containing Fe atoms replacing some of the Al atoms in substitution which render the particles paramagnetic(4,5).

Research has been carried out by Kelland(6) at the Francis Bitter National Magnet Laboratory into the concentration and recovery of semi-taconite, a fine particle iron ore, found in Minnesota. Molybdenum has also been economically recovered from the tailings remaining from the normal extraction process(1).

An appreciable amount of research has gone into the removal of lignite and ash from solvent-refined coal. Work has also been done on crushed coal in the dry state. It is also possible to remove the organic sulphur. However, little has been done on the chemistry of the process mainly because there is a much greater proportion of lignite in North and South American coals. A conference was held on the de-sulphurisation of coal using high gradient magnetic separation at Auburn University, Georgia. U.S.A. in March 1976. The proceedings(7) were published in September 1976.

Another possibility is that in the production of magnesia from sea water some reduction of the Fe concentration can be made using HGMS. A more general look at the possibility of the beneficiation of industrial minerals by this separation method is being studied by the Department of Geology, Indiana University(8).

Appreciable scope also exists for the application of HGMS in the steel making process. One tonne of steel may require as much as 150,000 litres of water, which is contaminated in the process by dust, much of which is magnetic. Large amounts of water are used in coke production, iron making, hot forming and cold finishing which are similarly contaminated. Currently the method used to remove fine particulates is sedimentation in large clarifiers. The large volumes of water used and the low treatments rate makes necessary very large water treatment facilities which require large investment in plant and space. The use of HGMS is attractive here because of the potentially high processing rates which can be expected from the magnetic method as is shown by the work of Oberteuffer et al(9).

Another kind of application is one where a magnetic seed is used. Often, this seed would be colloidal Fe_2O_3 which is extremely cheap. The first major application is in the treatment of sewage either in the present form as currently exists with the activated sludge tanks or with other newer methods that are being considered. In the activated sludge tank, bacteria digest the nutrient and form large flocs which grow in size to a stage where they settle. The introduction of Fe_2O_3 seed into the activated sludge tank causes the bacteria to flocculate with the seed. The floc then grows on the seed and the process of separation can be enormously speeded as smaller flocs can be handled and rapidly filtered. This produces an enormous reduction in settling tank space. Finally, at the later so-called polishing stages in sewage treatment, bacteria and suspended solids can be scavenged from the water using Fe_2O_3 seed material. Water from the Charles river in Boston has been treated in this way. On the first pass sewage samples have been brought to present Charles river standards as far as coliform bacteria, turbidity, colour and suspended solids are concerned. On a subsequent pass the water is adequate for drinking as judged by the four conditions: coliform, colour, turbidity and suspended solids(10,11).

It has also been found that if a reasonable amount of suspended solids are present the addition Al^{3+} ions to the solution will remove orthophosphate ions from solution and bind them into the coagulant for removal in the separator(10). If not enough suspended solids are present, the separation is aided by the addition of a little bentonite clay. Orthophosphate ions from domestic use have been a major source of river pollution.

Water effluent containing TiO_2 particles is a major pollutant in the American Great Lakes and in the Mediterranean. However, in certain pH ranges it is possible to produce coagulation between TiO_2 and magnetite in the presence of Al^{3+} and this may lead to the removal of this problem with HGMS(12). The rapid removal of asbestos(13) and viral materials from drinking water(14) have also been reported. Much of the work on waste water treatment has been reviewed by Oder and Horst(15).

A process that removes heavy metal impurities from waste waters is a by-product of a process to make ferrite from solution by precipitation. This has been carried out by the Nippon Electric Company and in the process, Cu, Ni, Sn, Pb, Cr, Fe and Hg were reduced from the level of gms/lt down to 0.1 mg/lt. While much of the precipitation can be removed with a conventional separator, there remains about 200 mg/lt of ferrite that must be removed by HGMS(16).

Another process that has been investigated at University College, London, is the use of magnetic particles as supports in immobilised enzyme reactors(17). It is possible, using the large surface areas available on small particles, to produce fast reactions without using porous media. The advantage of solid particles is that the separation from the liquor is clean and the active surface is not fouled. The use of small particles necessitates the use of HGMS. This technique appears to have very wide possibilities, especially in biochemical engineering and in the pharmaceutical industry.

HGMS technology has been used experimentally for the separation of red cells from whole blood(18) and the recovery of respirable asbestos fibres from dust has been described by Timbrell(19) as part of a method to estimate the quantity of asbestos present(19).

In summary it appears that high intensity magnetic separation will become an important technology in the next decade, penetrating into mineral processing, effluent and waste water treatment and into chemical, biochemical and pharmaceutical processing.

Theory

A theory of capture of paramagnetic particles has been developed[20,21,22,23] based on the interaction between a paramagnetic particle carried by a fluid past a ferromagnetic wire magnetized by a uniform applied magnetic field H_o. In this analysis it was assumed that the wires composing the matrix were perpendicular to the applied field; those portions of the matrix parallel to the field create no field gradient. It was found that if a quantity V_m, called the magnetic velocity, was introduced then the equations of motion simplified and from this it was shown the particle capture cross section/unit length of matrix wire largely depended on the ratio V_m/V_o where V_o is the background velocity of the fluid. V_m the magnetic velocity is given by

$$V_m = \frac{2}{9}\,\frac{(\chi R^2 M_s H_o)}{\eta a} \qquad (1)$$

Here χ is the volume susceptibility, the particles of radius R. M_s is the saturation magnetization of the ferromagnetic wire matrix with strand radius a, η is the viscosity of the fluid and H_o is the applied magnetic field (SI units). This means that the performance of a given separator, that is the fraction 1-f of particles escaping, depends only on V_m/V_o, provided that $M_s/2B_o < .4$ where $B_o = \mu_o H_o$ and $\mu_o = 4\pi \times 10^{-7}$ h/m.

If $M_s/2B_o > .4$ then the capture cross section for a given value of V_m/V_o increases with increasing values of $M_s/2B_o$(22,24). Over much of the range of practical interest the particle capture cross section is directly proportional to V_m/V_o. This leads to a wide range of separator behaviour given by (25)

$$\ln(1-f) - K_1(1-K_2 n)H_oT \qquad (2)$$

where K_1 and K_2 are constants, n is volume of fluid passing through the separator measured in units of the free volume of the matrix canister and T is the residence time of the fluid given by L/V_o, where L is the length of the separator.

In practice after a certain number of canister volumes have passed, say n_o, then $1-f$ will become unacceptibly large. It is then necessary to stop the separation. If the slurry being processed is valuable then it is necessary to displace the remaining canister volume of slurry from the canister, this is also done at a velocity V_o at the full applied field H_o with say n_1 canister volumes of fluid. The field is then switched off and the captured magnetics removed by flushing. The field is then restored to its full value H_o and the slurry processing continued.

The production rate P, where the material coming through the separator is the product, is given by

$$P = V_oA(1-f)\,Wn_o/(n_o+n_1+D/T) \qquad (3)$$

where A is the cross section area of the separator, W is the mass of particulate matter in the feed slurry and D is the sum of the times taken to switch the field off and on and to flush out the matrix. The quantity $n_o/(n_o + n_1 + D/T)$ is the fraction of time that material is being processed: this is often called the duty cycle.

Improving productivity, lowering costs

It is now appropriate to consider features that are desirable in a separator in order to give a low cost/processed unit.

1. High duty cycle
2. High production rate with high benefication.
3. Adequate time to clean the matrix in a low magnetic field.
4. Low power requirements.
5. Low capital cost.
6. Simple maintenance and operation.

Many of these conditions are interlinked so that in order to understand the process it is worth examining the conventional HGMS that typically operates in the clay industry using a magnetic field of 2T. For a particular matrix material and for a particular material to be processed and if the system operates at 2T, then the magnetic velocity is fixed by Equation(1) once the weight W per unit volume of material is specified, as this can affect the slurry viscosity η. Then if the product is specified by a particular value of 1-f then V_o can be chosen using Equations (2) and (3) to maximise the production rate P.

The main disadvantage with commercial HGMS systems, as they presently exist, are the large power of 400-600 kW required to maintain the magnetic field at approximately 20 kG, the large amount of iron required for the return circuit in order to avoid flux loss from the system; this leads to a high capital cost and the matrix must be cleaned at the end of each cycle, which can often lead to a very low duty cycle or an inadequate time for matrix cleaning.

As outlined above, the extraction of material by a separator depends largely on V_m/V_o and the amount of material fed to the separator. As shown above, the production rate of such a machine is roughly proportional to V_o, but the extraction of material is roughly proportional to $1/V_o$. This means that in order to get some specified level of extraction, V_m/V_o must be set at some value, say α. In order to increase the production rate, V_o must be increased and if this is to be done without lowering the extraction, V_m must be increased so that $V_m = \alpha V_o$. One way this can be done is to use the high magnetic field that superconducting magnetics can provide to increase V_m. Another way that this can be done is to allow the ferromagnetic matrix to move substantially with the fluid. The fluid moves slowly downward past the wire with a small relative velocity V_D but has a high forward speed V_f identical to that of the wire. Under these conditions the extraction is determined by V_m/V_D, but the production rate is roughly proportion to V_f which can be made large. The wire must stay in the field for a time T necessary for vertical draining through the matrix at the velocity V_D, in order to retain the captured material; consequently as the forward velocity is Vf, the total length of the system must be at least $L = V_fT$. Once out of the field, the wires can easily be washed. V_D can be made fairly small so that in order to make $V_m/V_D = a$ only a small value of $V_m = aV_D$ is needed and this can be considerably smaller than $V_m = aV_f$. The requirement of a larger value of V_m can therefore be relaxed so that a low value of applied field $B_o = u_oH_o$ can be used. In practice this field can be as low as 1 kilogauss.

These two methods are discussed in the next two sections and both have distinct advantages over the present HGMS system operating near 20 kG.

High field superconducting separator(25)

Certain metals, known as superconductors, when cooled down reach a temperature below which they have no electrical resistance. The resistance can be restored if an electric current larger than a certain value is passed through a wire of the material. The resistance can also be restored by placing the material in a magnetic field greater than a critical value. This opens up the possibility of generating a magnetic field in a solenoid of the material up to the critical field without Joule heating that normally accompanies the passage of electrical current through a resistive material. Many alloys show very high values of critical field and it is with these that many very large superconducting solenoids have been constructed and operated(25).

An experimental superconducting separator is shown in Fig. 3 and schematically in Fig 4. This superconducting separator was designed and built by Magnetic Corporation of America. The canister containing the wire wool was situated in the magnetic field of 5T (50 kG) produced by a solenoid wound from Nb-Ti wire

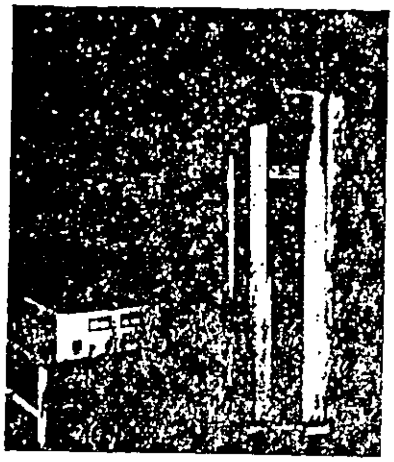

Fig. 3 Superconducting magnetic separator built by Magnetic Corporation of America. The magnetic field has a maximum value of 5T or 50 kG, and the system has a clear bore of 5 in. and a matrix length of 20 in. (Z. J. J. Stekly, IEEE Trans. Magns., MAG-11, 1594, 1975).

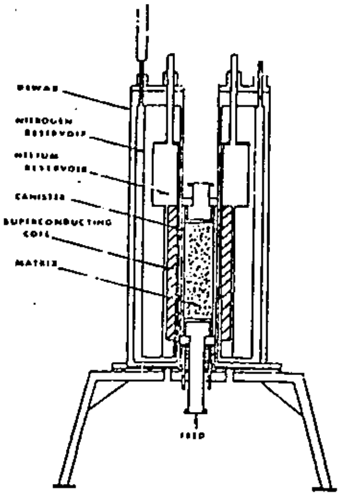

Fig. 4. Schematic of the superconducting separator shown in Fig. 3.

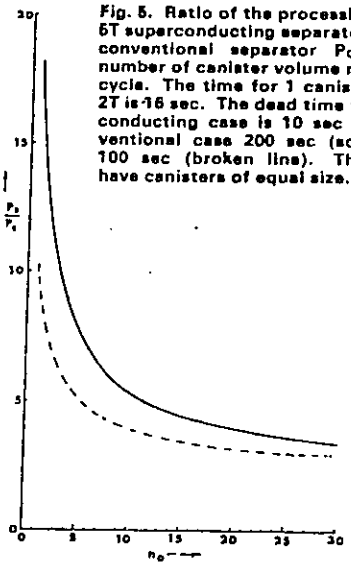

Fig. 5. Ratio of the processing rates for a 5T superconducting separator P_s and a 2T conventional separator P_c versus the number of canister volume n_0 of feed in a cycle. The time for 1 canister volume at 2T is 16 sec. The dead time for the superconducting case is 10 sec and the conventional case 200 sec (solid line) and 100 sec (broken line). The separators have canisters of equal size.

which is superconducting when held at 4.2 K the boiling temperature of liquid helium at 1 atmosphere pressure. As shown in Fig. 4 the superconducting coil is suspended inside the helium container. The helium boils off due to various heat leaks into the system and part of this gas can is used to cool the electrical leads which have a resistance. In a commercial system liquid helium would be supplied continuously by an external helium liquifier which reliquefies the gas leaving the cryostat. The inner helium container which houses the superconducting coil is surrounded by a shield cooled by liquid nitrogen at 77K although in a commercial machine this shield may also be cooled by helium gas escaping from the cryostat.

Experimental work with a superconducting separator has confirmed that the performance of a given separator depends only on V_m/V_0([4,5,25]). This means that the production rate can be increased due to the fact that V_0 can be increased in proportion to the field.

There is another important way in which the use of a superconducting solenoid with open ends can be used to increase the production rate and that is by using a double canister system. One canister is in the field processing material and when the appropriate number of canisters n_0 have been passed then the canister is pulled from the field and is replaced by a clean one. The canister can now be cleaned out of the field and as much time as the feed and rinse time can be taken. In practice the conventional HGMS system has a dead time D of between 100-200 sec whereas the canister replacement can easily be accomplished within 10 sec. These two factors lead to appreciable differences in the production rate P_s of a superconducting machine relative to the rate P_c of a conventional machine of the same matrix canister dimension.

In order to illustrate these factors the relative production rate P_s/P_c versus n_0 is shown in Fig. 5. These curves are calculated for a dead time of 10 sec for the superconducting system and of 100 and 200 sec for the conventional system. The residence time T is taken to be 16 sec for the conventional system at 2T (20 kG). The number of rinse canisters is $n_i = -1$. As shown in Fig. 5 the relative production is greater than 3 even when $n_0 = 30$.

Another important factor is the electrical power ratios; the superconducting system will need only the power required to compress the helium gas, for example a BOC TurBOCool liquefier will produce 18 litres of liquid helium for 80 kW and this amount is quite adequate for a system the same order of size as a large conventional HGMS such as operates in the clay industry. The conventional magnet requires between 400-600 kW so that the power consumption also gives the superconducting system considerable advantages.

Low magnetic field HGMS([24])

As indicated above, if the relative velocity between the matrix and the slurry V_D becomes small, then the fraction of particles extracted can be large even in a weak magnetic field, however the production rate is proportional to the absolute velocity V_F with which the slurry and the matrix move through the magnetic separator. A theoretical analysis of this system has been presented by Watson([24]). In this work as a series of canisters containing matrix and slurry passed through a magnetic field the slurry drained from the canister. It was shown that the separator performance depended on the quantity T_D/T_m where T_D is the time taken to drain the canister and Tm is a characteristic 'magnetic time' and is given by

$$T_m = 3\pi a/4FV_m \qquad (4)$$

where F is the fraction of the canister volume occupied by the matrix wires.

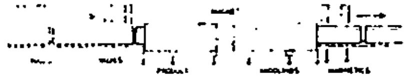

Fig. 6. Moving matrix low magnetic field separator—The canisters which are much shorter than the magnet length move into the field full of slurry. Draining takes place in magnetic field. The magnetics are removed once the canister leaves the field.

The overall configuration of this separator is shown in Fig. 6. In operation the canisters, moving with constant velocity, are first filled with slurry and water is added on top prior to the canister entering the magnetic field. Draining commences as the canister enters the field. The draining rate and the velocity V_F are adjusted so that a particular product beneficiation can be reached in the time taken to completely drain the canister of the slurry and the water, which must be done in the magnetic field. When the canister leaves the magnetic field the material formerly held magnetically can easily be washed out.

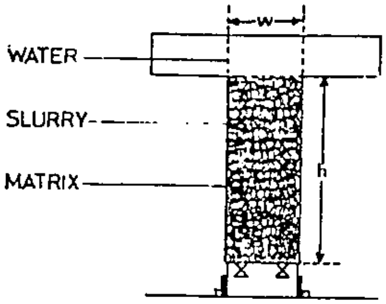

Fig. 7. Canister cross-section which is perpendicular to the direction of motion. The canister contains a matrix of ferromagnetic stainless steel wool occupying about 5%. The reservoir contains water for displacement of the non-magnetically held slurry. The canister is drained through the valves at the bottom

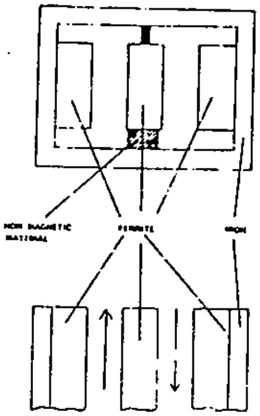

Fig. 8. Magnetic configuration of a two channel machine. If two channels are used then twice the magnetic volume can be produced with considerably less than twice the ferrite material. Considerable economies can also be made with a two channel electromagnet construction.

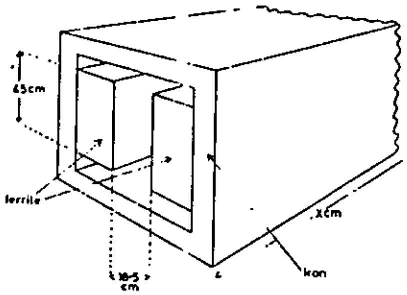

Fig. 9. Magnet configuration—The magnet shown is a permanent ferrite magnet with an iron circuit. The canister moves between the ferrite poles. A similar electromagnet can also be used.

The production rate of the system is given by P

$$P = W(1-F)wh\,V_F \qquad (5)$$

where W is the weight of clay/unit volume. 1-F is the fraction escaping, wh is the cross-sectional area of the canister shown in Fig. 7 and V_F is the forward velocity. V_F is chosen for a given magnet length L, a draining time T_D, which determines the product beneficiation, and a ratio of slurry to water volume δ, so that

$$V_F = \delta L / T_D(\delta + 1) \qquad (6)$$

The design leads to continuous operation as the canister can be returned to the start leaving ample washing time. The duty cycle is $\delta/(1+\delta)$ that is the fraction of the time spent in the magnet in which product is being processed. This is at least 0.5 and may be as high or even higher than 0.75: this is a point for more detailed study of each particular case.

The power requirements are low as the magnetic field is low and the task may be accomplished using ferrite magnets. Another important improvement is the use of two channels. as shown in Fig. 8, this leads to, for example in the case of ferrite, two channels requiring a maximum of only 50% more ferrite and may be considerably less than 50%. This technique will also lead to a small economy in the case of electromagnets. As we have seen the production rate can be high because of the large area over which slow draining takes place and the beneficiation is high because the relative velocity between the slurry and the matrix is small. The production rate can be increased in this system by either making the system longer or by making the system higher.

Capital and operating costs

Although the production rate of the system must be worked out for each particular case it is interesting to look at the capital cost and the operating power cost for the magnet shown in Fig. 9. Suppose we take h =0.45m and w=0.185m. The iron return circuit is 3 cm thick and the system is 10 metres long and operates at a magnetic field of 0.2T. Electromagnets usually have an installed cost of £1,500-£2,000 tonne which gives an upper estimate of £20,000 for the magnet system(27). Operating this maching at 0.2T with the coils at 300 Amp/cm^2 require 38 kW which allows for end correction(27). The moving bucket chain costs have not been estimated, but presumably would not cost more than the magnet. This means the capital cost is roughly an order of magnitude lower than a conventional HGMS system together with an order of magnitude lower power consumption. If permanent magnets can be used the power consumption will of course be zero.

This low magnetic field system therefore has the several advantages outlined above but also if permanent magnets can be used it is a "low technology machine" using only moving buckets, which are very well established in the mineral processing industry. This system also has the advantage that cost per unit of processed material stays low even for small tonnages, which contrasts strongly with the superconducting machine which requires a low temperature environment which makes a low tonnage machine relatively more expensive.

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Information about the Filtration Society is obtainable
from: W. G. Norris, Hon. Secretary, Filtration Society,
1 Katharine Street, Croydon, CR9 1LB, England.

Dr. Orbkins.

HIGH-GRADIENT MAGNETIC SEPARATION

Scientific American 233, 46 (1975)

A recent advance in the generation of strong magnetic fields opens the way to removing very weakly magnetic particles from mixtures. One novel application of the new process is purifying wastewater

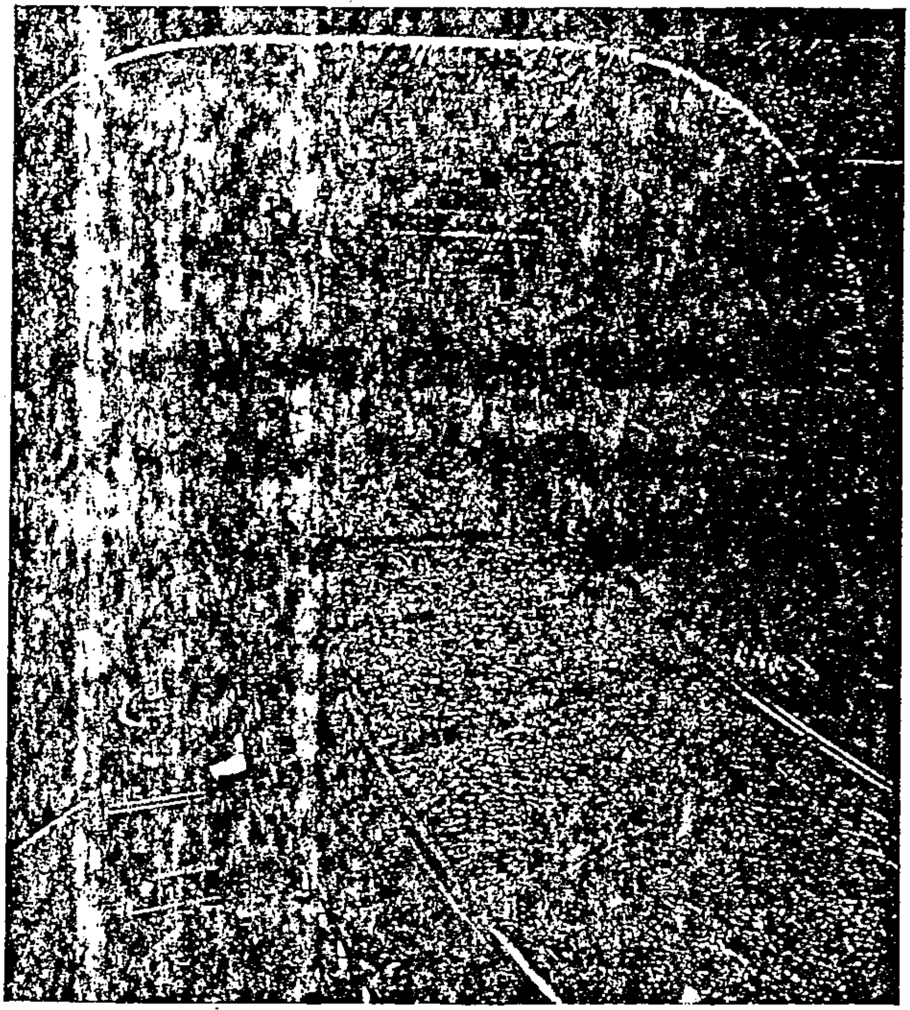
by Henry Kolm, John Oberteuffer and David Kelland

A major activity of modern industry is separating mixtures of fine particles; the desired particles are kept and the unwanted ones are discarded. Many different techniques of separation, including filtration, flotation, precipitation and magnetic separation, have proved economically practical. A recent advance in the technique of magnetic separation may prove to be revolutionary. It opens the way to dealing economically with a broad range of separation problems that have appeared unsolvable, involving fine particles that are only weakly magnetic and even some particles that are not magnetic at all. The new technique is known as high-gradient magnetic separation.

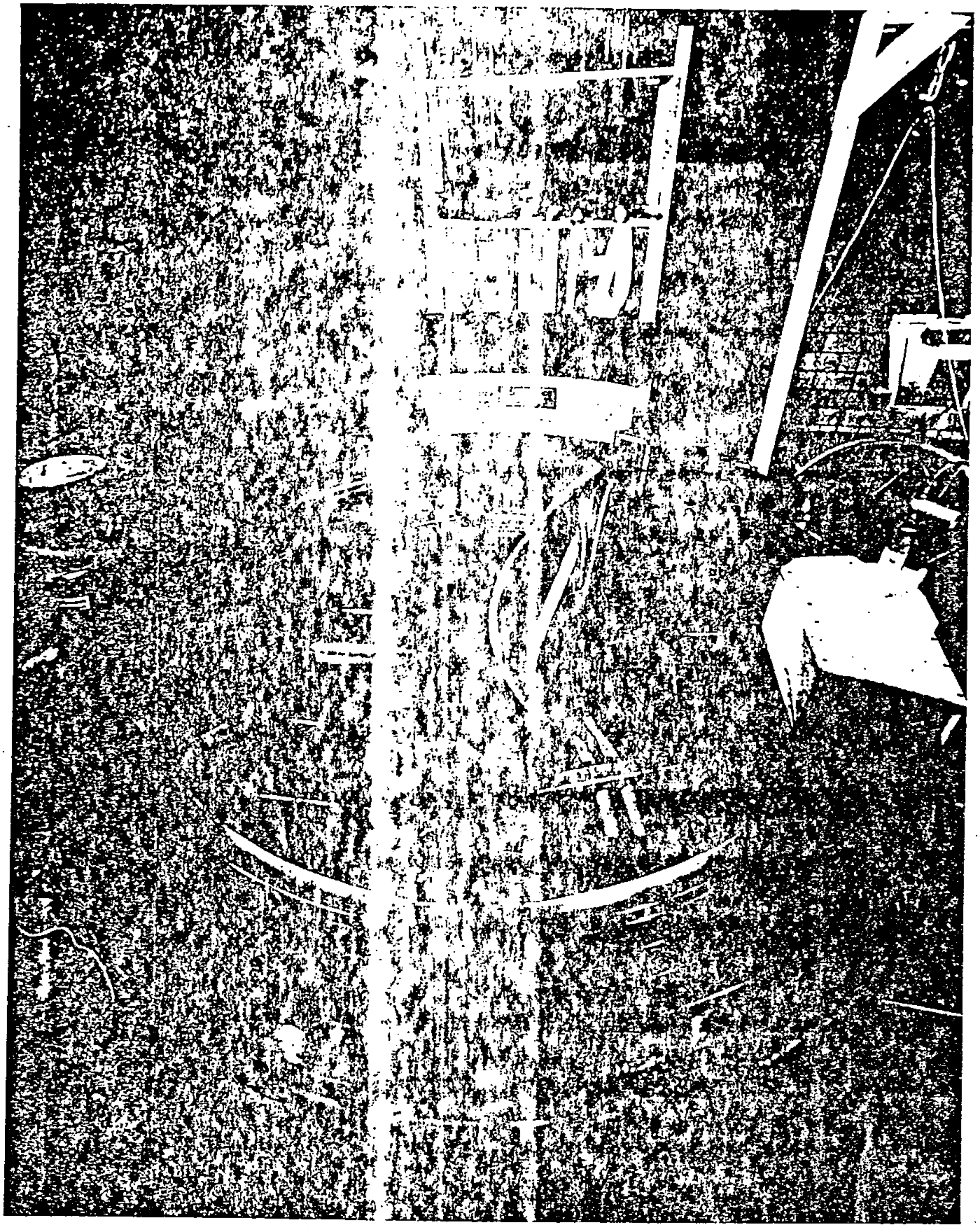
Reference to the periodic table of the elements indicates how far the high-gradient technique has advanced the art of magnetic separation. Until now magnetic separation has been confined to manipulating mixtures that contained one or more of three strongly magnetic elements: iron, nickel and cobalt. The high-gradient technique is potentially applicable to any one of a far greater number of mixtures: at a minimum those that include one or more of 56 weakly magnetic elements. Among other new possibilities is access to more than half of the world's iron resources, which consist of a weakly magnetic oxide of iron. Perhaps of even greater immediate significance is the possibility, after the appropriate "seeding" with magnetic particles, of manipulating substances that are entirely nonmagnetic, such as various pollutants in water. In brief, high-gradient magnetic separation promises advances not only in the mineral and chemical industries but also in environmental protection and water purification.

The earth is full with mixtures of finely divided matter. On a geological scale the margins of continents are constantly being enlarged by the fine solids that rivers carry to the sea. On a lesser scale a large fraction of the mineral industry is concerned with the separation of finely divided matter; indeed, the vast bulk of the earth's mineral resources remains unexploited because the materials are too finely divided to be separated economically. The chemical industry also utilizes many processes in which mixtures of finely divided solids must be purified by removing unwanted components from powders or slurries.

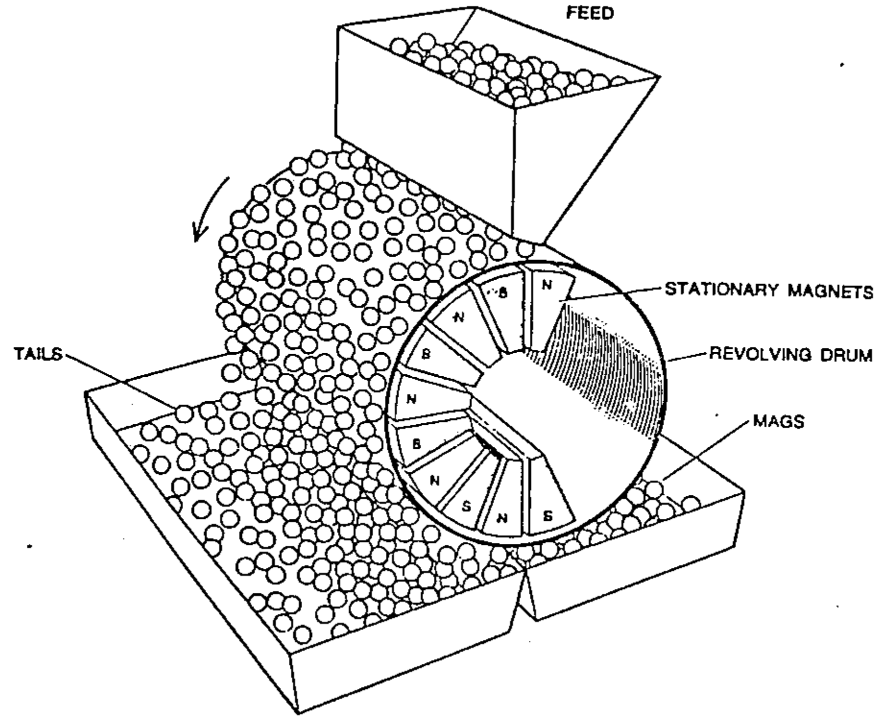
When the particles involved in these



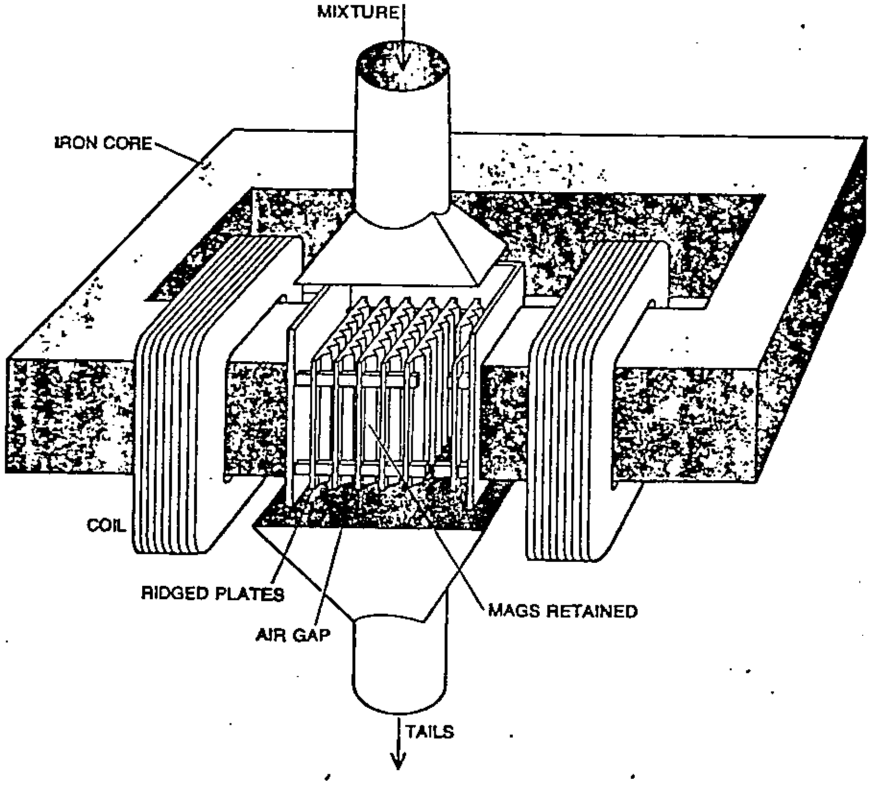
COMPARTMENTS OF STEEL WOOL are shown at the point where they enter the magnet of the Mark III carousel separator, also designed by Marston and his associates. Surrounding ring are high-performance copper coils of magnet, which are hollow for water cooling.



HIGH-GRADIENT SEPARATOR at Sala Magnetics, Inc., in Cambridge, Mass., has a six-foot ring divided into compartments filled with steel wool. The ring is rotated through the magnet structure at the top, where a finely ground slurry of iron ore is introduced. The magnetic particles stick to the magnetized steel wool and the nonmagnetic particles are flushed out. After the ring has emerged from the magnet structure, it passes through the structure at the right, where the magnetic particles are flushed out and formed into pellets that serve as a blast-furnace feed. This machine is the Mark II carousel separator, designed by Peter Marston and his associates. It can handle up to five tons of feedstock per hour. In this photograph the ring of separator is blurred because it is in operation.



CONVENTIONAL SEPARATION of magnetic and nonmagnetic particles in a mixture is exemplified by the drum separator, a device that can be applied only to strongly magnetic materials. A stationary half cylinder of magnets is fixed inside a revolving metal drum. As the mixture strikes the drum, the magnetic particles ("*Mags*") adhere and the nonmagnetic particles ("*Tails*") fall off. In this schematic drawing size of particles is greatly exaggerated.



HIGH-GRADIENT SEPARATION is applicable to mixtures containing weakly magnetic particles. Shown here is the first practical separator of this kind: George Jones's salient-pole-plate separator, designed early in the 1960's. The ridges on each plate in the stack of plates within the air gap act effectively to trap fine particles of weakly magnetic materials in a mixture. Jones machine is used to divide low-grade iron ores into hematite and waste.

processes are very small (with a diameter of a tenth of a micrometer or less), they fall within the domain of the colloids. A colloid is a state of matter quite distinct from the solid, liquid and gaseous states. Particles of colloidal dimensions will not settle when they are suspended in a liquid. The electrostatic surface charge on each individual particle keeps the particles from coalescing into larger aggregates. At the same time the thermal energy of each small particle more than counterbalances the particle's gravitational potential energy, or tendency to settle.

The reverse of the colloidal state is the mechanism that builds river deltas and makes continental margins grow. Contact with the ions in seawater neutralizes the surface charge of the suspended particles, promoting the process of aggregation. Once enlarged by aggregation the particles yield to gravity and sink. In dealing with matter consisting of particles of a size lying within or near the boundaries of the colloidal domain, high-gradient magnetic separation has advantages over other separation techniques.

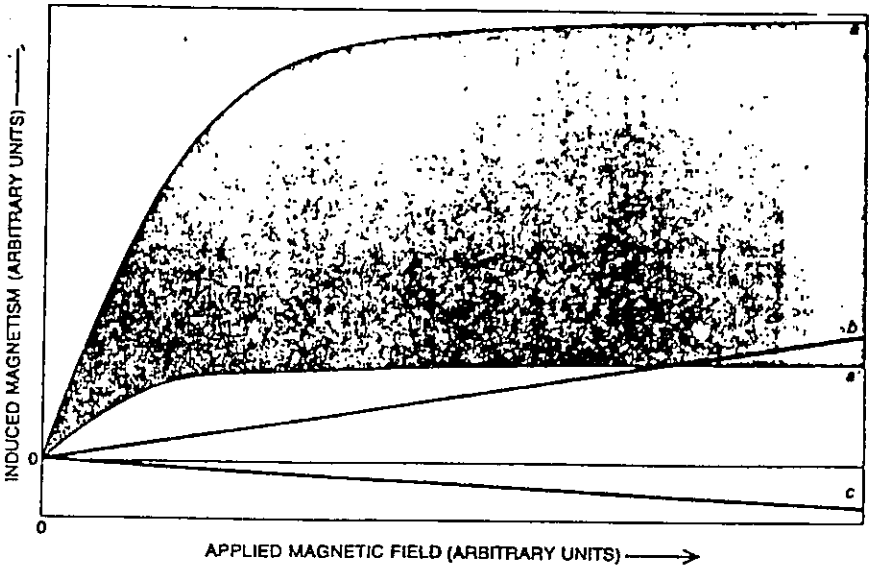
The physical phenomena governing magnetic separation fall under two headings. How do various substances behave when they are exposed to a magnetic field? How are the magnetic forces exerted? On the first heading, consider a graph that plots the response of various classes of substances to increasingly strong magnetization. Such a graph displays three different kinds of magnetic behavior [*see top illustration on opposite page*]. Strongly magnetic materials, members of the ferromagnetic group, are easily magnetized by a relatively weak magnetic field, and so the slope of their magnetization curve is steep at the beginning. (That is why a bar magnet, which does not have a very strong magnetic field, can attract ferromagnetic materials.) As the strength of the magnetic field increases, all the individual domains—regions with paired north and south magnetic poles—in a ferromagnetic material become aligned; magnetization "saturates" the material. Thereafter the slope of the curve remains relatively flat regardless of any further increase in the strength of the magnetic field. The saturation level, that is, the field strength beyond which no further magnetization takes place, depends on the iron content of the material. For example, pure iron is saturated at a magnetization of some 220 electromagnetic units per cubic centimeter in an applied field of several hundred gauss.

Weakly magnetic materials, members of the paramagnetic group, are far less susceptible to an applied magnetic field than ferromagnetic materials. At low field strengths their magnetization curve on the graph remains well below the ferromagnetic curve and its slope is much shallower. A paramagnetic material, however, rarely becomes saturated, and so its degree of magnetization continues to increase as the applied field gets stronger. This means that even though a bar magnet will not attract a paramagnetic material, such materials may become more highly magnetized in a sufficiently strong field than dilute ferromagnetic materials.

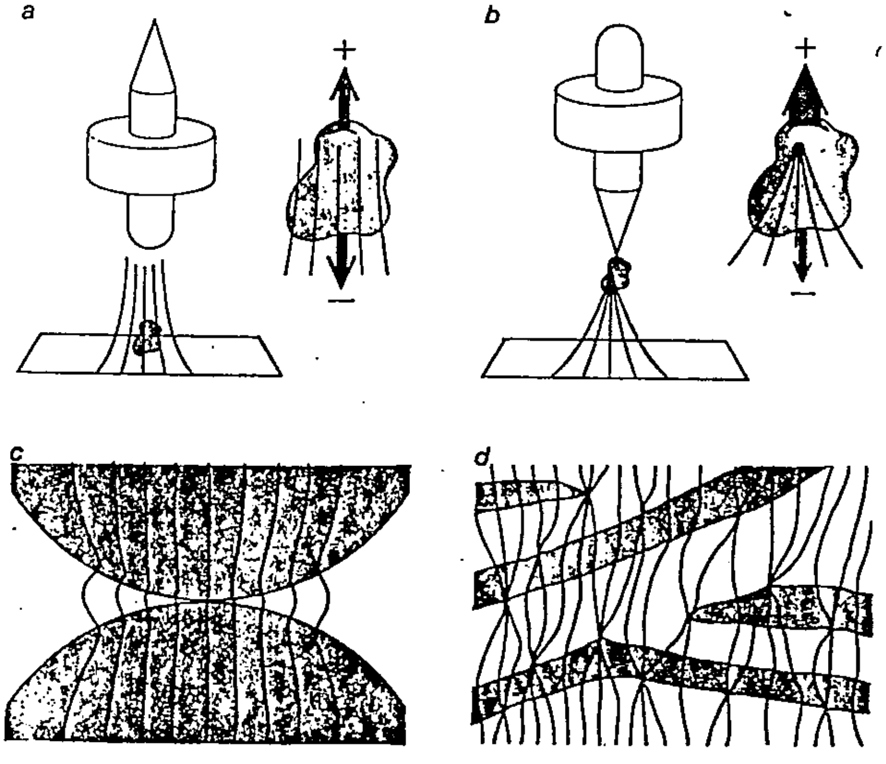
A third type of behavior in a magnetic field is displayed by materials that become magnetized in a direction opposite to that of the applied field. These are diamagnetic materials, and their curve on the graph is shallow and negative. For the purposes of this discussion diamagnetism is a small effect with no practical importance.

On the second heading—how magnetic forces are exerted on materials in an applied field—it is useful to think of each magnetized particle as acting temporarily as if it were itself a small bar magnet, with a north pole at one end and a south pole at the other. In magnetically "hard" materials the parallel alignment of the dipoles is in fact not temporary but permanent, and a magnet made of such a material is called a permanent magnet. The alignment in magnetically "soft" materials is impermanent; it is induced only while a magnetic field is applied, and it becomes random when the field is absent.

When a uniform magnetic field is applied to a magnetized particle, the forces acting on the two poles of the particle will be equal and opposite. The forces therefore cancel each other, and the resulting net force is zero. Only if the applied field differs in intensity at the two extremities of the particle will a net magnetic force act on the particle. This is to say that the applied field must have a gradient, a spatial variation that is appreciable in terms of the dimensions of the magnetized particle. Anyone who has tried to remove iron filings from a horseshoe magnet is familiar with this effect. The lines of force extending from the poles of the magnet diverge in such a way that the density of the magnetic flux (the intensity of the field) increases with nearness to either pole and the maximum spatial variation in the flux is at the sharp edges of the pole. It is the higher gradient of the magnetic field at the sharp edges that makes the iron



THREE RESPONSES are evident when the magnetization of a material is plotted as a function of the applied magnetic field. Ferromagnetic materials (*a*) show an immediate steep curve; some respond more strongly than others (*colored area*) but all eventually "saturate," as the flattening curves show. Paramagnetic materials (*b*) show a much shallower response, but they rarely saturate; in a strong field their magnetization can exceed that of a weakly ferromagnetic material. Diamagnetic materials (*c*) are of no industrial importance. On exposure to a field such a material shows a slight but opposite magnetization.



MAGNETIC-FIELD GRADIENT is needed if an appreciable force is to be exerted on a fine particle. Flux lines (*color*) around the blunt pole of a magnet (*a*) are essentially uniform with respect to the particle below the pole; the magnetic forces acting on the two poles of the particle (*enlarged at right*), being equal and opposite, cancel out. Flux lines around the sharp pole (*b*) are divergent with respect to the particle; the resulting high gradient exerts a strong force on the particle (*enlarged at right*). Stacked iron balls (*c*) represent one extreme in making a high-gradient matrix. They conduct the flux well (*color*), but their field is almost uniform. Steel wool (*d*) represents the other extreme. As the pinched flux lines show, gradients are high, but steel wool, being mostly void, is very hard to magnetize.

filings preferentially collect there. In short, the net force exerted on a magnetized particle by a magnetic field is proportional to three quantities: the intensity of the magnetization the field has induced in the particle, the volume of the particle and the gradient of the field, that is, the difference between the intensity of the field at one end of the particle and the intensity at the other.

With these basic facts in mind many experimenters have attempted to apply improved techniques of magnetic separation to two kinds of mixture that are particularly hard to deal with. These are mixtures containing particles that are strongly magnetic but very small and mixtures containing weakly magnetic particles of any size. The improved separators were generally built around a scaled-up version of a horseshoe magnet: an iron yoke, or frame, provided a strong magnetic flux across the air gap between the two poles of a permanent magnet. The passage of an electric current through a pair of copper coils surrounding the yoke further increased the strength of the magnet. The mixture that was to be separated into its magnetic and nonmagnetic components was fed through a filter placed in the air gap. The principle was simple: the filter would complete the magnetic circuit and, being strongly magnetized itself, would selectively entrap any magnetic particles in the mixture while letting the nonmagnetic particles flow through. The practical problem the experimenters faced was that the two functions the filter structure was supposed to serve are incompatible.

On the one hand, a filter structure must be a good conductor of magnetic flux; this is necessary not only to close the gap in the magnetic circuit but also to keep the flux lines from straying out of the gap. On the other hand, in order to provide both an adequate surface area for the entrapment of magnetic particles and a high-gradient local magnetic field, the conducting filter material must present a combination of many sharp edges and abundant void spaces.

In an attempt to overcome these incompatibilities experimenters made filter matrixes out of stacked iron balls, iron mesh, steel wool and even carpet tacks. The stacked balls represent one extreme: they furnish a good flux path but a low field gradient. Steel wool represents the opposite extreme: when it is magnetized to saturation, it has a large number of points with high field gradients and it has ample surface area, but it is very difficult to magnetize to saturation. The reason steel wool resists magnetization is that however tightly it is compressed it remains a spongy material that is 90 percent empty space. It is only slightly magnetized when inserted into the air gap of a conventional magnetic circuit. If the experimenter turns to alternative ways of applying a more powerful magnetic field to steel wool, he encounters a second difficulty that arises from the geometry of the stuff. The steel ingot from which steel wool is made would be relatively easy to magnetize because its long axis can be made parallel to the direction of the applied field, but in the steel wool the long axes of a large number of the filaments are inevitably perpendicular to the direction of the applied field. The applied field required to magnetize the randomly oriented mass of filaments is more than 10 times stronger than the field that will saturate the ingot from which the filaments were made.

Two experimenters have attempted to solve the filter-matrix dilemma. As early as the 1940's the inventor Samuel Frantz recognized both the advantages of steel wool and similar matrixes and the difficulty of magnetizing them in the air gap of a conventional magnetic circuit. Frantz began by eliminating the magnet's iron yoke and inserting a canister, filled with the matrix of his choice, in the hole through the center of the coil previously occupied by one leg of the yoke. The coil now operated as an electromagnet of the solenoid type.

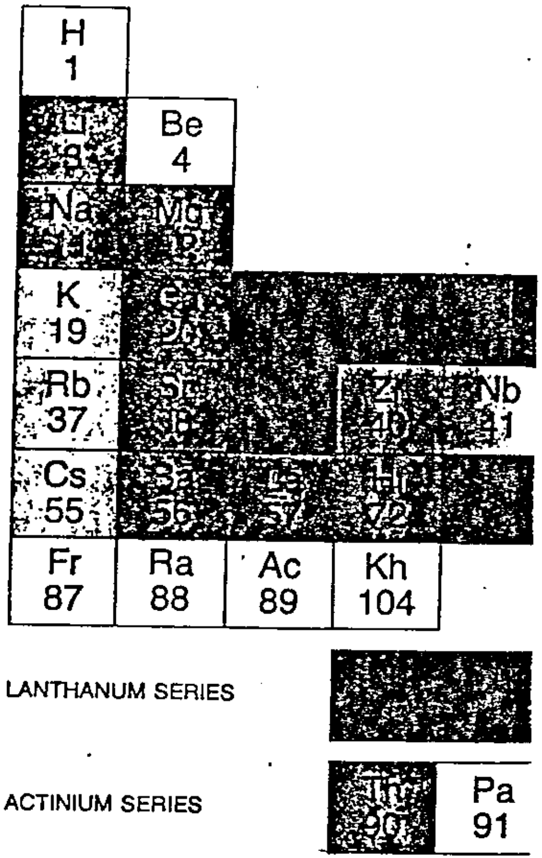
Now, if a solenoid is to generate a reasonably uniform field, it must be longer than it is wide. Unfortunately for Frantz, this is an unfavorable shape for separation purposes. If the matrix is to work efficiently, it must be shorter than it is wide.

Frantz also found that the strength of his magnetic field was limited almost entirely to what the solenoid itself could provide. Adding iron poles to the ends of the coil did not strengthen the field appreciably, nor did surrounding it with an iron sleeve. The Frantz Ferrofilter, incorporating a relatively coarse matrix, is an effective separator of some strongly magnetic particles. It could not, however, economically achieve the field intensities needed to magnetically saturate steel wool or to magnetize weakly magnetic materials. When it was equipped with a steel-wool matrix, it was suitable only for laboratory-scale work.

In the early 1960's George Jones, a British engineer, worked out a compromise between the two extremes of stacked balls and steel wool. Jones preserved the yoke-and-electromagnet structure and completed the magnetic circuit by placing a different kind of matrix in the air gap of the magnet. His matrix consisted of a stack of steel plates, flat on one face but with many parallel sharp ridges on the other. The plates were held out of contact with one another by means of nonmagnetic spacers at each corner. The use of spacers that differed slightly in thickness enabled Jones to make fine adjustments in the width of the air gaps between adjacent plates.

When the stacked plates are magnetized, the field gradients in the vicinity of the sharp ridges are high because the flux lines passing through each ridge diverge widely toward the flat back of the adjacent plate. By adjusting the air gap between the plates, Jones was able to balance the degree of gradient against the degree of flux conduction to achieve optimum conditions for each mixture he undertook to separate.

The Jones separator leaves something to be desired. For example, a dispropor-



PERIODIC TABLE of the elements is marked to indicate which elements are ferromagnetic (*gray*) and which have paramagnetic properties (*shades of color*). Only three elements are ferromagnetic: iron, cobalt and nickel. Compounds that include tionately large volume of steel is needed to magnetize a relatively small matrix. Furthermore, the geometry of the ridged plates is such that they can present field gradients only about 1 percent as high as saturated steel wool does. The Jones machines were nonetheless the first high-gradient separators to achieve commercial success. They are effective separators of paramagnetic materials as long as the particles in the mixture are not too small.

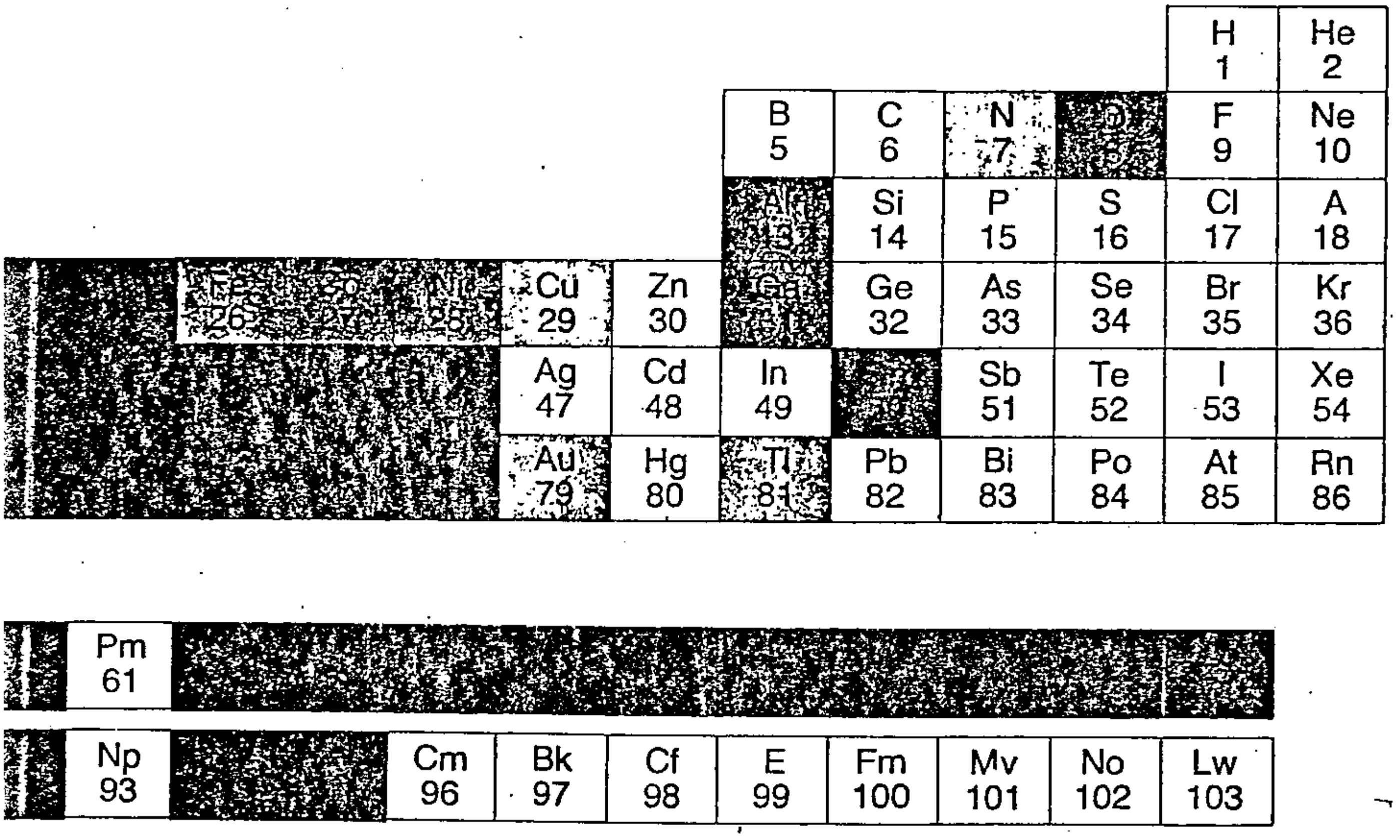
In the mid-1960's we became involved in these matters when our laboratory, the Francis Bitter National Magnet Laboratory at the Massachusetts Institute of Technology, was asked to assist in solving a practical problem in magnetic separation. Today the available supply of kaolin, the white clay used as a coating for paper, usually contains certain micrometer-size impurities. The principal impurity, titanium dioxide, is accompanied by particles of iron oxide that tend to discolor the finished product. As it happens, kaolin is very weakly paramagnetic. The impurities are more strongly paramagnetic, although they are only a ten-thousandth as magnetic as iron. Thus it was possible to separate them from the kaolin magnetically, although at that time no device existed that could do so on an industrial scale.

Some years earlier we had investigated very intense magnetic fields and had become aware of the very high gradients that could be attained with magnetically saturated steel wool and similar matrixes. Approaching the kaolin problem with this background, we soon found that saturated steel wool would almost totally remove the impurity particles. There remained the practical problem of building a magnet that could saturate a large volume of steel wool. The magnet also had to meet two other specifications: its cost of construction had to be acceptably low and so did its consumption of power.

All three specifications were met by Peter Marston and his associates, a group in Cambridge, Mass., specializing in the design and construction of complex magnets for both scientific and industrial purposes. (The Marston group is now associated with a Swedish manufacturer of mineral-processing equipment, Sala.) Like Frantz, Marston based his design on a solenoid surrounding an empty space where a matrix could be placed. Unlike Frantz's solenoid, however, Marston's incorporated an iron pole structure and was wider than it was long. The solenoid coil was also surrounded by an iron shell that facilitated the return of flux.

The practical impact of Marston's innovation has been considerable: his magnets can generate uniform fields of up to 20,000 gauss in large empty spaces. The throughput rate of some of the high-gradient separators incorporating his magnets is 60 tons of kaolin clay per hour. Moreover, compared with conventional separators, Marston's iron-bound solenoids require only a tenth of the capital investment and consume only a tenth of the power.

Kaolin purification is an example of separatory processes where a small un-



one or more of the three elements may be strongly or weakly ferromagnetic or may only be paramagnetic. Fifty-five elements have paramagnetic properties. Of these, 32 (*dark color*) form compounds that are paramagnetic. Another 16 elements (*lighter color*) are paramagnetic in pure form, but the compounds that incorporate them are diamagnetic. The remaining seven elements (*lightest color*) become paramagnetic when one or more are present in a compound, although two of them, nitrogen (*N*) and copper (*Cu*), are slightly diamagnetic in pure form. Of the 46 remaining elements, all but 16 have diamagnetic properties. Since the paramagnetic compounds greatly outnumber the ferromagnetic compounds, high-gradient magnetic separation has many potential applications.

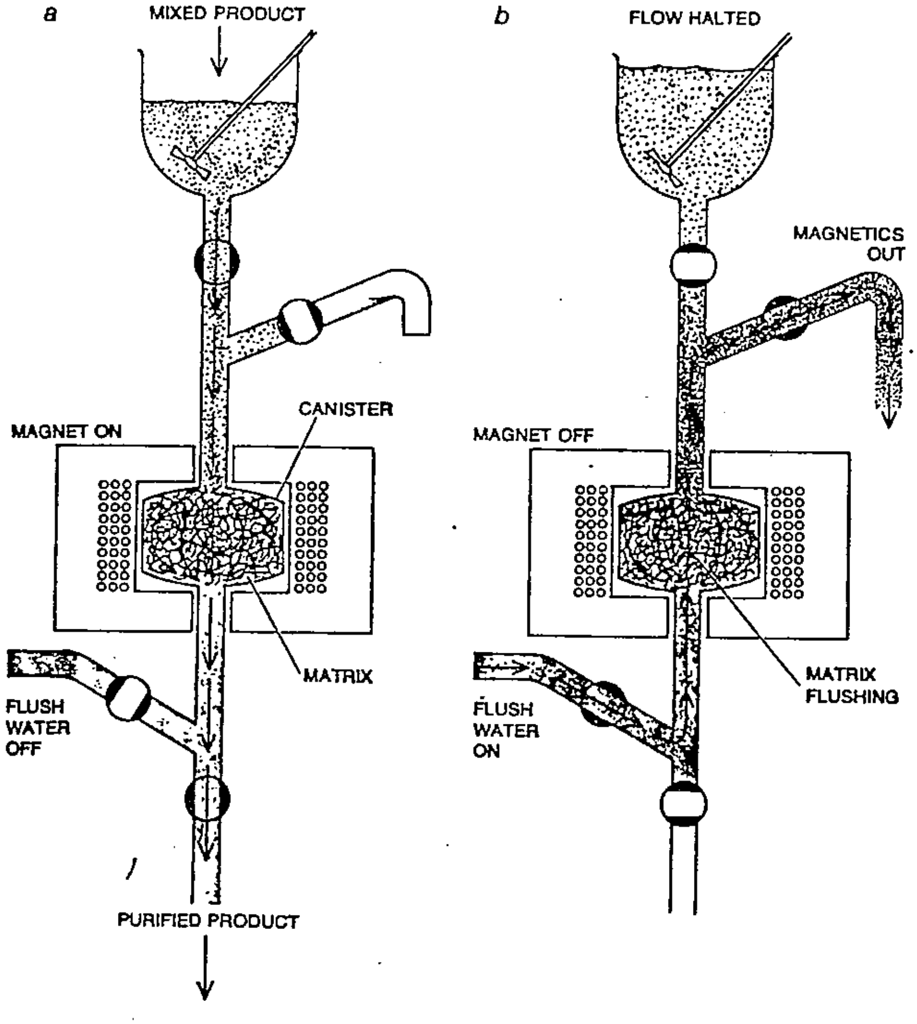
wanted magnetic fraction is removed from the mixture fed into the separator. Other examples of such processes are the purification of certain pigments and glass sands. There are numerous potential applications of high-gradient separation where the small magnetic fraction is the desired one. A case in point is the material discarded in the extraction of molybdenum and tungsten by nonmagnetic methods such as the removal of sulfides from the ores by flotation. The tailings that are discarded after flotation still contain appreciable amounts of these metals in the form of oxides that are paramagnetic. It is estimated that magnetic methods could extract from the tailings an average of about a cup of molybdenum or tungsten oxide per barrel of material processed.

There is, of course, a substantial economic difference between magnetic purification and magnetic recovery. With kaolin the investment in extraction yields barrels of the final product in the same length of time it takes to get a few cups of molybdenum or tungsten oxide. Many applications of oxide extraction so far lack the economic incentive that accompanies shortages and will have to await the time when today's tailings have become tomorrow's ores.

The most important long-term application of high-gradient separation to minerals may prove to be the beneficiation of low-grade iron ores, an area where conventional magnetic separation is already playing a leading role. The reason is that reserves of low-grade taconite ore include far more of the weakly magnetic iron mineral hematite than of the strongly magnetic mineral magnetite. For example, in the Mesabi Range of Minnesota, the nation's chief source of iron, the ores with an iron content of 65 percent or better (the only ores that can go directly into the blast furnace) were exhausted more than a decade ago. The place of the high-grade ores was then taken by taconite ores containing iron in the form of finely disseminated magnetite. The ores are pulverized and subjected to conventional magnetic separation. The concentrate is then formed into hard pellets, making it suitable for feeding into the blast furnace. The iron content of much of the Mesabi taconite and of most of the world's low-grade ores, however, is in the form of hematite rather than magnetite. High-gradient magnetic separation ought to do for hematitic ores what conventional magnetic separation and pelletization have done for magnetite. The new process may even do so economically before the world's supply of magnetite is exhausted; its feasibility has been demonstrated in pilot-plant tests supported by the division of the National Science Foundation concerned with research applied to national needs (RANN).

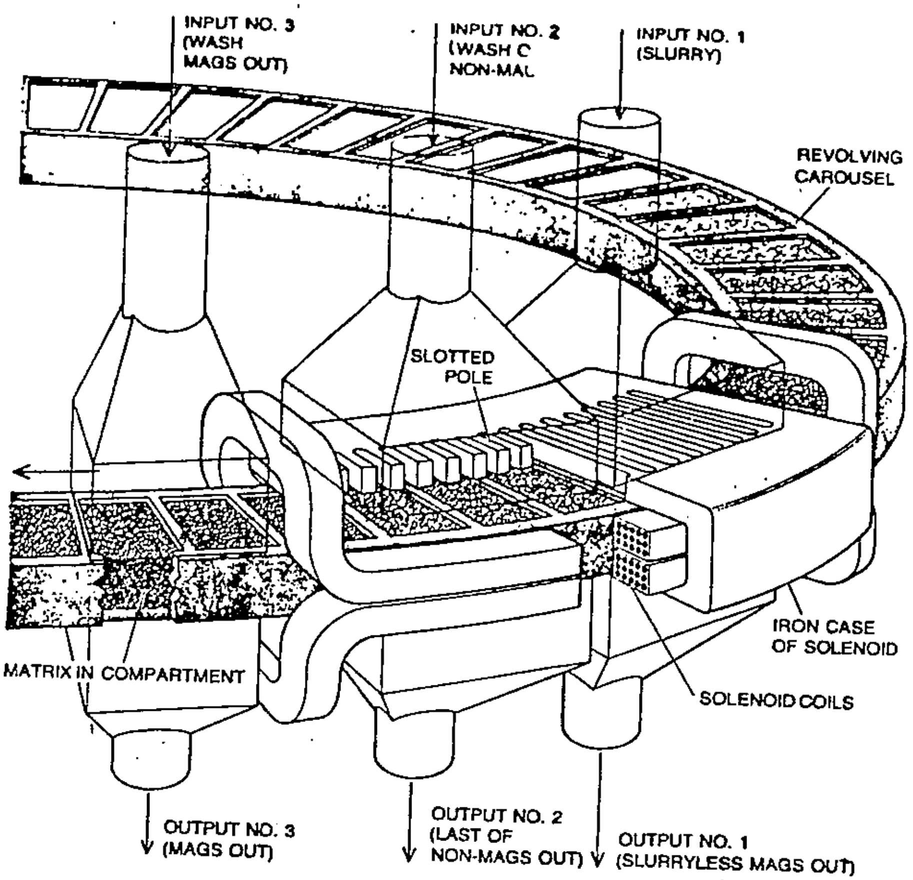
Another potential application of high-gradient separation is in the desulfurization of coal. Much of the sulfur in coal is in the form of the mineral pyrite. Pure pyrite is very weakly magnetic, but it usually contains a certain amount of pyrrhotite, a rather more magnetic sulfide of iron. We have found that when pulverized coal (the form in which coal is fed to most steam-turbine electric-power plants) is passed through a high-gradient apparatus, the pyritic sulfur in the mixture can be economically removed. Emanuel Maxwell of our laboratory and his colleague Sergio C. Trindade conducted these studies. Application of the technique to the removal of sulfur from liquefied coal products is now under investigation. Achieving a practical process for this purpose will require a much higher degree of technical sophistication than was needed for the purification of kaolin.

A key potential application of high-gradient separation lies in the purification of water. Water is best purified by percolation through the ground or evaporation into the air, but the demands of modern communities have long since outstripped the capacity of these natural cycles. The primary criteria for urban water supplies have been that the incoming water be reasonably sterile and the outgoing water be something less than poisonous. The principal means of



BATCH SEPARATION utilizes a canister filled with a magnetic matrix and surrounded by a solenoid electromagnet enclosed in iron. A slurry of the materials to be separated flows through the strongly magnetized high-gradient matrix, where the paramagnetic particles in the slurry are retained (*a*). At intervals the feed is halted and the electromagnet is turned off so that the particles can be flushed out (*b*). Such a system can process 50 tons per hour and is equally suited to removing small amounts of magnetic impurities from materials such as kaolin clay, glass sands and pigments or to collecting small amounts of such metals as molybdenum and tungsten from low-grade ores or materials discarded by older processes.

achieving sterility has been chlorination, a process with a potential for toxic and carcinogenic by-products that is only now being recognized.



CONTINUOUS SEPARATION utilizes a rotating ring divided into compartments filled with magnetic matrix. Such a system is embodied in the separators shown in the photographs on pages 46 and 47. As each compartment enters an elongated solenoid (*right*) a slurry is fed into it through slots in the magnet. While the compartment is still within the magnet it is washed (*center*) to rid the matrix of nonmagnetic particles that might be adhering to it. As compartments leave magnet (*left*) a second wash removes magnetic particles.

In fact, no form of water purification currently in use is acceptable in the long run. Most effluent treatments do little to diminish the eutrophic degradation of rivers and lakes into which the nutrient-laden wastewaters are discharged. Neither do most treatments prevent the cumulative loading of groundwater and other reservoirs with nutrients, particulate matter and heavy metals. A current example is the contamination of the water supply of Duluth and surrounding Lake Superior communities by the discharge of asbestos fibers into the lake. No conventional filtration methods will remove these carcinogenic particles.

Since high-gradient separation is an efficient means of collecting fine particles, it can be applied to water purification in a variety of ways. For example, the particulate contaminants that are present in steel-mill process water and wastewater are paramagnetic. Other contaminants can be made to associate themselves with magnetic particles seeded in the water; such associations can be brought about by surface adsorption, mechanical entrapment, coagulation or coprecipitation. For example, it has long been known that coliform bacteria, one of the commonest contaminants, tend to adhere to the surface of fine particles of iron oxide. Soon after Marston developed his ironbound solenoid he seeded water samples from the Charles River Basin in Boston with small amounts of iron oxide and subjected the samples to high-gradient separation at the remarkable rate of 150 gallons per minute per square foot of the magnetic matrix's surface. The Charles River drains parts of Suffolk, Norfolk and Middlesex counties, receiving a broad spectrum of effluents in the process, but it does not discharge directly into the sea. It is kept at an artificially high level by a dam near its mouth, and so it is virtually stagnant and has been heavily polluted with coliform bacteria and other contaminants for years. Marston found that a single high-velocity pass through the separator purified water from the river almost to the standards of drinking water. The treatment not only removed most of the coliform bacteria but also reduced the turbidity and the color of the water and lowered the number of suspended solid particles.

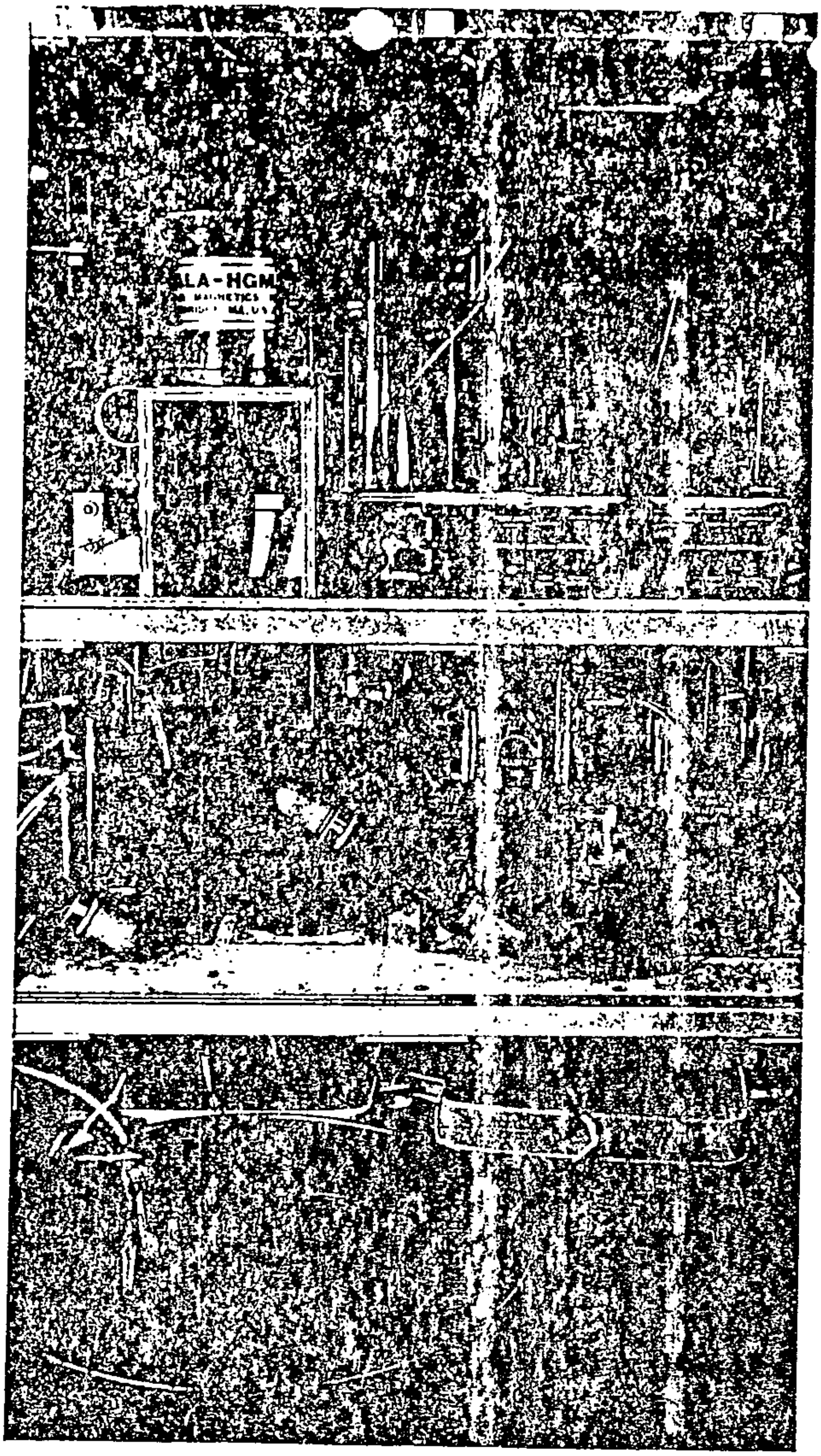
Christopher DeLatour, a graduate student working in our laboratory, followed up Marston's test with a series of separation experiments conducted in collaboration with the Metropolitan District Commission of Boston, the agency responsible for sewage and water treatment. DeLatour found that the process was almost as effective in purifying effluent from Boston's Deer Island sewage plant as it was in purifying river water. His results were sufficiently encouraging for the commission to order a full-scale engineering feasibility study to determine whether or not a high-gradient separator mounted on a barge could economically restore the waters of the Charles River Basin to recreational standards of purity. The conclusion of the study was affirmative. Swimming in the Charles may one day be a pleasure instead of a risky venture by an occasional rash teenager.

The removal of dissolved nutrients in wastewater, notably phosphate and nitrate, is mandatory if the lakes and streams that receive waste discharge are to escape eutrophication. In conventional water recycling the process that removes nutrients, referred to as tertiary treatment, requires filtration and chemical treatment that are elaborate and costly. It is therefore of particular interest that in preliminary tests DeLatour has been able to reduce the phosphate content of Charles River water and Deer Island effluent significantly by seeding the samples with bentonite clay, magnetite and aluminum sulfate. With these additives acting as coagulating agents, the nonmagnetic phosphate was trapped as the water passed through the high-gradient separator.

Probably the most dangerous contaminants of water are viruses. Their ability to pass through the finest filters is definitive, so that they not only are not removed by conventional water-recycling methods but also are not detected. The possibility of infection by, say, the hepatitis virus prevents the utilization of waste nutrients for growing food. It is therefore encouraging that Ralph Mitchell of Harvard University and Theodore G. Metcalf of the University of New Hampshire have found that certain viruses can be scavenged by iron oxide and other magnetic seeding materials and removed from water by the high-gradient separation process. Preliminary tests on a laboratory scale also show that asbestos particles of the kind and size entering Lake Superior as an industrial effluent can be removed from water by high-gradient separation. The development of a practical large-scale system for this purpose, however, would call for a substantial engineering effort.

Could the magnetic-separation method be applied to water recycling on a nationwide scale? Preliminary estimates indicate that its costs are competitive with conventional treatment systems and its space requirements (an important consideration in many urban areas) are substantially smaller. For very large systems, designed to treat billions of gallons per day, the energy requirement would be a serious limiting factor. Here superconducting magnets are likely to be used. In superconducting magnets the temperature of the coil is reduced to a few degrees above absolute zero; the coil becomes superconducting and current flows through it without resistance (and heating). One of the world's largest superconducting magnets, the ironbound solenoid used in a bubble chamber at the Argonne National Laboratory, generates a 20,000-gauss field at an energy cost no greater than that of illuminating the room where the magnet is housed. To generate an equivalent field with an ordinary copper solenoid would require about 12 megawatts, which is roughly the amount of power that is consumed by a small city.

The Argonne superconducting magnet was built at a cost of about $3 million. If a magnet of similar size, generating a less intense field, were equipped with a steel-wool matrix, it could purify more than 100 million gallons of water per day at an extremely modest cost in energy. (For purposes of comparison, the five boroughs of New York City produce about 1.4 billion gallons of raw effluent per day.) For the present, economic factors and the level of the industrial commitment to magnetic separation favor the continued use of ordinary copper-coil magnets for any high-gradient system. High-gradient separation may, however, become the first major practical application of superconductivity. Such a development would make it possible to close the water cycle, to decontaminate lakes and rivers and to exploit many of the earth's currently unrecoverable minerals.



WATER IS PURIFIED in this laboratory high-gradient system at Sala Magnetics. The high-gradient magnetic separator itself is the small cylinder at the upper left labeled SALA-HGMS. At the bottom is a tank filled with dirty river water. Water drawn from it passes through a series of vessels, some of which are visible on the middle shelf. In them the pH is adjusted, alum is added as a coagulant and finally a polyelectrolyte and finely divided iron oxide are added. Most impurities adhere to the particles of iron oxide and are removed in the magnetic separator. The output of the process is the clear water in the vessel to the right of the separator. Overall the system removes coliform bacteria, viruses, suspended solids and some dissolved nutrients. It substantially reduces turbidity, color and odor. In one pass the coliform bacteria count is reduced from 16,000 per 100 milliliters to less than five.

84: 79379w **Removal of iron from spent metal surface treatment solutions.** Kaneko, Kyozo **Japan. Kokai** 75,121,193 (Cl. C01G, C25F), 22 Sep 1975, Appl. 74 27,215, 11 Mar 1974; 2 pp. Fe ions in spent solns. contg. H_3PO_4 [7664-38-2], CrO_3 [1333-82-0], and H_2SO_4 [7664-93-9] for Fe surface treatment is treated by electrolysis and crystalized as $FeSO_4$; the cryst. $FeSO_4$ [7720-7[illegible]] is removed from the soln. which is recycled. Thus, a dild. spent soln. contg. H_3PO_4, H_2SO_4, and CrO_3 used for *18-Cr steel* [56457-65-9] surface treatment was concd., the concd. soln. was placed in the cathode chamber which was sepd. from the anode by an ion-permeable, acid resistant membrane; and 8% H_2SO_4 was added to the anode chamber. The electrolysis was performed at a cathode current of 8 A/dm² and cathode c.d. 4A/100 ml. The treated cathode soln. was allowed to stand at 0-20° for 72 hr. Filtration of the soln. yielded 12.9 g of crude crystals contg. 1.6 g $FeSO_4$. The filtrate was recycled.

84: 79380q **Production of ion-exchange adsorbents from waste liquid glass sludge.** Saraki, Naomi; Tejo, Yutaka (Shionogi and Co., Ltd.) **Japan. Kokai** 75,122,466 (Cl. B01D) 26 Sep 1975, Appl. 74 29,316, 13 Mar 1974; 9 pp. Materials having a high adsorbancy and ion-exchange capacity are produced from sludge formed during refining of liq. glass, $Na_2Al_2O_4$ and optionally $Na_2Si_4O_9$. Thus, H_2O 10 and 10*N* NaOH 10 ml were added to 60 g of sludge (solids 32.8%, SiO_2 14.48 g) from a liq. glass-refining process. The mixt. was heated at 30° and to this was added 31 ml of a soln. contg. 59 g $Na_2Al_2O_4$ [12598-12-8] (Al_2O_3 20, Na_2O 19%) with stirring. The mixt. was heated at 28° for 17 hr and at 100° for 4 hr. The mixt. was filtered; the filter cake was washed until the pH of the filtrate was 10-11 and dried. The product $(1.05)Na_2O \cdot Al_2O_3 \cdot (3.43)SiO_2 \cdot XH_2O$ [1344-00-9] had an NH_4^+-exchange capacity of 377.8 mequiv./100 g. When the product was activated by being heated at 400° for 2 hr, its NH_4^+-exchange capacity was 355 mequiv./100 g.

84: 79381r **Treatment of colored waste waters.** Kawamata, Tadanao; Tsuchiya, Hiroya (Jec Enterprise Co., Ltd.) **Japan. Kokai** 75,124,879 (Cl. B01D, C02C), 01 Oct 1975, Appl. 74 31,938, 20 Mar 1974; 3 pp. Waste waters contg. colored materials from textile dyeing plants are treated with a soln. contg. galactomannan and(or) gluconogalactomannan and >1 of $CaCl_2$, $FeCl_2$, $FeCl_3$, $Al_2(SO_4)_3$, $FeSO_4$, or $Fe_2(SO_4)_3$ to ppt. the colored material with the polysaccharide compn. Thus, to 1000 l. of waste water (colored materials 5000 ppm) was added to 43 kg of glue contg. $Al_2(SO_4)_3$ [10043-01-3] 11.2, *galactomannan* [11078-30-1] 28%, in water. The mixt. was stirred and filtered to obtain colorless water.

84: 79382s **Magnetic treatment of waste waters containing heavy metals.** Kondo, Goro **Japan. Kokai** 75,127,450 (Cl. C02C), 07 Oct 1975, Appl. 74 32,832, 23 Mar 1974; 3 pp. A heavy metal-contg. waste water is mixed with a powd. magnetic compd.; the suspension is stirred, the pH adjusted to neutral-acidic, and, if necessary, a high-mol.-wt. flocculent is added to ppt. metals with the magnetic compd.; the ppt. is removed by magnetic treatment. Thus, a waste water contg. 100 ppm Cr^{6+} was adjusted to pH 4-5 and magnetic FeO [1345-25-1] powder (300 mesh) 10 and a high-mol.-wt. flocculent 10 ppm were added. The mixt. was adjusted to pH 8.5 with NaOH. The mixt. was treated by a separater equipped with a magnetic drum which collected the magnetic floc. The floc was added to 6*N* H_2SO_4 and the mixt. was stirred in an alternating magnetic field (1000 G) to solubilize $Cr(OH)_3$ and to demagnetize FeO powder which was recovered and recycled.

84: 79383t **Purification of waste waters from the leather industry.** Pleshakov, V. D.; Chernyshev, V. N. (Ordzhonikidze, S., Polytechnic Institute, Novocherkassk) **U.S.S.R.** 487,024 (Cl. C02c), 05 Oct 1975, Appl. 1,845,856, 09 Nov 1972. From *Otkrytiya, Izobret., Prom. Obraztsy, Tovarnye Znaki* 1975, 52(37), 76. Waste waters from the leather industry are purified by alkalization by lime with sepn. of the resulting ppt. by pressure flotation. To remove proteins, Cr, and suspended substances the waste water was acidified initially to pH 4-5, the resulting ppt. was sepd., and then the water was alkalized to pH 7.5-8.0.

84: 79384u **Treatment of wastes containing mixture of plastics and ebonite.** Saito, Kozo; Izumi, Sumio (Mitsui Mining and Smelting Co., Ltd.) **Japan. Kokai** 75,126,077 (Cl. C08J, B29C, B01J), 03 Oct 1975, Appl. 74 33,303, 25 Mar 1974; 3 pp. Waste mixts. of polystyrene plastics and ebonite are recovered from waste water by flotation. Thus, 300 g of *ABS* [9003-56-9] resins 50 and ebonite 50 wt.% was placed in a tank contg. 8000 ml H_2O. After introducing bubbles into the water for 7 min, 148.5 g ABS resins with 99.7% purity were floated and sepd. from 151.5 g ebonite with purity of 98.4%.

84: 79385v **Recovery of alkali in waste liquors from manufacturing of paper pulps.** Nagasawa, Takeo; Morita, Munetaka (Nihon Kami Parupu Kenkyusho) **Japan. Kokai** 75,125,902 (Cl. D21C), 06 Oct 1975, Appl. 74 33,464, 27 Mar [illegible] Waste liquors from paper pulp manuf. are treated smelt consisting of mostly NaCl and Na_2CO_3; addn. of water to make an aq. soln. of the smelt; addn. of CaO to the soln. to convert Na_2CO_3 to NaOH and filtration to remove by-product $CaCO_3$; concn. of the filtrate to ppt. NaCl, centrifugation, and filtration to recover NaCl; concn. of the filtrate to ppt. the remaining NaCl and Na_2CO_3 and filtration to recover NaOH soln. and NaCl and Na_2CO_3. The alkali salts or soln. thus recovered are recycled in the pulp manufg. processes. Thus, 1 kg smelt contg. NaCl 270 and Na_2CO_3 730 g, obtained from combustion of wood pulping waste is dissolved in an aq. soln. contg. NaCl 450 and Na_2CO_3 117 g and the final vol. was adjusted to contain 1.25 g Na^+/100 ml H_2O. To the above mixt. was added an amt. equal to the equiv. amt. of CaO (with respect to the equiv. amt. of Na_2CO_3) and the mixt. was reacted at 85-7° for 1 hr and filtered to remove the remaining CaO and $CaCO_3$ formed. The filtrate was concd. at 60° under reduced pressure to form a slurry contg. 6% NaCl. The slurry was centrifuged and filtered to obtain 240 g NaCl. The filtrate was further concd. at 110° to obtain a ppt. contg. NaCl 450 and Na_2CO_3 117 g and a filtrate contg. 50% NaOH; the recovered ppt. is recycled in the next treatment of smelt and the NaOH soln. is recycled in the pulp manufg. process.

84: 79386w **Regeneration of active C after waste water treatment.** Okamoto, Hiroshige; Watanabe, Shiro; Higashino, Fusamitsu (Asahi Chemical Industry Co., Ltd.) **Japan. Kokai** 75,128,695 (Cl. C01B, B01D, C02C), 09 Oct 1975, Appl. 74 34,608, 29 Mar 1974; 3 pp. After waste water treatment active C [7440-44-0] is regenerated by 1st mixing with 10-60 wt.% (with resp. to active C) of Ni oxides and then reacting with NaClO soln. This treatment is rapid and effective regeneration of active C without high heat. Thus, after treatment of a waste water contg. 5000 ppm Na alkylbenzene sulfonate (I) [98-11-3] the active C was mixed with 35 wt.% of Ni_2O_3 [1314-06-3] or NiO_2 [12035-36-8] and treated with NaOCl [7681-52-9] (2%) soln. for 15 min. The adsorption capacity and methylene blue decolorizing efficiency of the regenerated active C was similar to fresh active C, compared with a redn. to <1 and ~13%, resp., for regeneration without treatment of Ni oxides.

84: 79387x **Treatment of waste waters containing suspended solids.** Shintani, Takashi; Shimizu, Akihiko (Toyo Soda Mfg. Co., Ltd.) **Japan. Kokai** 75,128,689 (Cl. B01D, C02BC), 09 Oct 1975, Appl. 74 34,650, 29 Mar 1974; 6 pp. Suspended solids in waste waters are flocculated with chloroprene latex and (or) chloroprene copolymer latex contg. ≥1 kind of cationic surfactants. These latexes rapidly flocculate the suspended solids and form large flocs, which can be easily removed by filtration. Thus, 500 ml waste water discharged from a pulp plant was treated with 0.5 ml of a chloroprene latex prepd. by polymg. chloroprene 100, water 95, *n*-dodecylmercaptan 0.10, $NaHSO_3$ 0.02 and the acetate salt of polyoxyethylenated *N*-(tallow alkyl) propylene diamine 4.5 parts at 40°. The transparency (detd. at 550 mμ) of the resulting supernatant 5 min after the treatment was 88% and the sedimentation rate and final vol. of the flocs were 3.0 cm/min and 13.0 ml, resp. In contrast, the transparency was 20.5% and the floc sedimentation rate and vol. were <1 cm/min and 8.8 ml, resp., in the absence of chloroprene latex.

84: 79388y **Treatment of waste waters from a dye-processing plant.** Tanaka, Kiichi (Nittan Co., Ltd.) **Japan. Kokai** 75,132,757 (Cl. C02C), 21 Oct 1975, Appl. 74 39,501, 09 Apr 1974; 3 pp. Waste waters obtained during dye processing are treated with nitrohumic acids and then the pH is adjusted to 2-7 to flocculate the pollutants. Optionally, a mixt. of nitrohumic acid with either multivalent metal salts, org. bases, or both is used instead of nitrohumic acid. This method effectively removes pollutants such as dyes, pastes, surfactants, fibrous wastes, and other dye-processing chems. Thus, 1 l. turbid, reddish brown waste water (pH 7.9, transparency 2 cm, and BOD 230, COD 75, and suspended solids 55 ppm) contg. surfactants, disperse dyes, and reactive dyes was rotated at 50 rpm and mixed 1st with nitrohumic acid in ammonia soln. and then with aq. $ZnCl_2$ [7646-85-7] soln. The final concn. of nitrohumic acid and $ZnCl_2$ in the mixt. was 100 and 80 ppm, resp. When the pH of the mixt. was adjusted to 5.8, flocs formed rapidly. After sepg. the flocs by filtration, a filtrate with pH 5.8, transparency 25 cm, and BOD 25, COD 27, and suspended solids 7 ppm was obtained.

84: 79389z **Removal of heavy metals from waste water.** Sano, Masakatsu; Sugano, Izuru; Okuda, Taneaki (Nippon Electric Co., Ltd.) **Japan. Kokai** 75,133,654 (Cl. C02C), 23 Oct 1975, Appl. 74 41,351, 10 Apr 1974; 2 pp. A waste water contg. heavy metals is adjusted to pH <2 and to this is added >4 times as much of a mixt. contg. Fe^{2+} and Fe^{3+} (1:1-2) as the total heavy metals contained and >1 equiv. alkali per total acids in the waste water to form ferrite crystals; the heavy metals are adsorbed onto or captured in the lattice of the ferrite crystals and pptd. with the crystals. Thus, $FeCl_2$ [7758-94-3] 0.21 and $FeCl_3$ [7705-08-0] 0.28 mole/l. were added to 1 l. of waste water

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Feed Systems for Solenoidal High-Gradient Magnetic Separators

J.H.P. Watson*

University of Salford, Department of Pure
and Applied Physics,
Salford M5 4WT, U.K.

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Introduction

High gradient magnetic separators consist of a ferromagnetic wool matrix situated in a uniform background magnetic field. Magnetic particles can be extracted onto the matrix from a fluid carrying them through the matrix. These magnetic separators have found commercial application in the clay industry [1]. Usually, these separators are in the form of iron-bound solenoids[2]. The fluid passes through the pole cap and into a canister containing the matrix. The fluid passes through the canister in a direction parallel to the applied magnetic field. In this type of separator, the power consumption is reduced by reducing L, the length of the solenoid. An increase in A, the cross-sectional area of the solenoid, does not affect the power consumption as strongly as an increase in the length and has the advantage that the volume of material processed in proportional to A. Consequently, iron-bound solenoids, used for magnetic separation have the solenoidal diameter greater than the length. The production rate P of such a system is given by

$$P = pV_o fAN_o/(N_o+N_1+ D/T) \qquad (1)$$

where p is the mass of solids/unit volume of slurry, 1 - f is the fraction of the solids entering the separator retained on the matrix, V_o is the velocity of fluid entering the matrix. The matrix occupies a volume $1 - \varepsilon_o$ of the space in the canister, as the fluid velocity through the matrix is V_o/ε_o and for a canister length L, the residence time of the fluid in the canister, T, is $T = \varepsilon_o L/V_o$. The free volume in the canister $\varepsilon_o LA$, called the canister volume, is a convenient unit in which to express the volume of slurry entering the separator; in equation (1), N_o is the number canister volumes processed before cleaning the matrix becomes necessary. N_1 is the number of canister volumes of water, if any, used to displace the slurry from the canister, at the same velocity V_o, prior to switching off the magnetic field. D is the dead time, that is the time taken to switch off the magnetic field, clean the matrix and restore the field to the value at which the process can be restarted.

If T>>D, the production rate P becomes $P \propto N_o/(N_1+N_o)$, that is P is largely independent of T. In these circumstances, p, N_1, N_o and f being governed by the details of the process, P can be increased by increasing A, provided $D/T >> N_o+N_1$. As suggested above, this consideration has led to the design of iron-bound solenoids, with the diameter greater than the length. On the other hand, if $D/T >> N_o+N_1$ $P = N_o LA/D$, then the production rate can be increased by increasing L or A.

Now consider the case of superconducting magnetic separators operating at 5T. The performance of separator at 5T will be the same as a separator operating at lower field if the velocity V_o and the applied field H_o are increased in the same ratio[3]. This increased velocity reduces the residence time T appreciably and the point where D/T becomes large can only be off-set by a reduction of D. It is proposed that this be done by alternately using two separate canister systems in conjunction with a superconducting solenoid[4], so that one is in the magnet processing slurry while the second canister system is, being cleaned, out of the field. D becomes approximately equal to the time taken to shift the canisters [4].

In order to increase the production rate of the superconducting separator the length can be increased until an optimum processing cost/ processed volume is reached. There is an optimum because the cost roughly scales with the length but the production rate finally becomes independent of length when $N_o+N_1>>D/T$. The production can also be increased by increasing the cross-sectional area, unfortunately this is a much more costly approach than an increased lenth.

There is then a need to have feed systems for a superconducting solenoids where the production rate increases with the length.

In this paper a radial feed system with this property will be examined. As shown in Fig.2, the slurry is fed down a perforated tube centered along the axis of the solenoid. The slurry flows radially outwards, through the holes in the tube, and into the region containing the matrix. After passing through the matrix radially, the slurry returns, flowing parallel to the solenoidal axis, in an outer cylindrical annulus.

In the next section the differential equations describing the behaviour of particles in a radial system will be examined and various approximate solutions will be considered. In the final section, the axial feed and the radial feed systems will be compared.

II Theory

The development of the theory of separator performance will closely parallel that for the axial feed system discussed previously[5].

In Fig.3 a sector of the cross-section through a radial canister system is shown. The slurry is fed in the matrix at radius r_1 and leaves at radius r_2. $N(r,t)$ is defined as the number of particles per unit volume of the separator that are present as captured particles at radius r at time t. $R(r,t)$ is the number of particles per unit volume of the slurry. The number of suspended particles per unit volume of the separator is $\varepsilon R(r,t)$ where ε is the porosity of the separator.

$$\varepsilon = \varepsilon_o - \beta N v \tag{2}$$

ε_o is the porosity of the clean bed and if the particles have volume v and a packing factor β, the volume occupied by N particles is $\beta N v$. For high gradient separators the porosity is so high that $\beta N v$ can be neglected.

If entrance velocity at radius r_1 is V_1 and at radius r the superficial velocity $V(r)$ is given by,

$$V(r) = \varepsilon_o V_1 r_1 / r \tag{3}$$

By considering the particle and fluid balance, at radius r, at time t in an element of thickness dr, it can be shown, if diffusion is neglected,

$$\beta\, \partial N(r,t)/\partial t + \varepsilon_o\, \partial R(r,t)/\partial t + \varepsilon_o\, V(r)\, \partial R(r,t)/\partial r = 0 \tag{4}$$

This equation has been derived previously by Ives and Horner . If τ is kept constant, an element of the suspension can be followed through the separator. On changing variables equation (3) becomes,

$$\beta\, (\partial N(r,\tau)/\partial \tau)_r + \varepsilon_o\, V(r)\, (\partial R(r,\tau)/\partial r)_\tau = 0 \tag{5}$$

The rate of capture of particles is also equal to the product of the total capture cross-section presented to the slurry per unit volume of matrix and the flux of particles. In deriving this equation in the axial case, it is assumed that 2/3 of the matrix wire is in the 'longitudinal' configuration[8]; that is, field and flow parallel and perpendicular to the axis of the wire. This means the a single value of R_c, the capture radius can be used.

The radial feed system is more complex, as 1/3 of the matrix is in the 'transverse' configuration[7]. Both of these configurations can be represented by a capture radius, which behave physically in the same way, so the cross-sections can be added. Watson has shown the capture radius for the longitudinal and the transverse configurations are almost identical[9]. The axial cross-section is somewhat lower than the transverse configuration[8]. In this work, the capture radius R_c is taken to be the average of the capture radii from the two configurations. The kinetic equation can be written as

$$\beta\ (\partial N(r,\tau)/\partial\tau)_r = 4\beta\varepsilon_o(1-\varepsilon_o)R_cR(r,\tau)\ V(r)/3\pi a \qquad (6)$$

R_c can be written, for the case of high energetic field, appropriate to the use of superconductors, as

$$R_c = CV_mG/V(r) \qquad (7)$$

where C is a constant, $V_m = 2\chi R^2M_sH_o/9\eta a$ appropriate to particles of radius R and susceptibility χ, wires of radius a and saturation magnetization M_s, with a slurry viscosity η and an applied magnetic field H_o. G is a parameter with values ranging between 0 and 1 because of the dependence of G on the volume of captured material per unit volume of the separator[5]. That is, when $N(r,\tau) = N_T$, G = 0 and when $N(r,\tau) = 0$, G = 1. If V_m is written, $V_m = OH_o/\eta$, then from equation (5), (6) and (7) we get,

$O = \frac{2\chi R^2 M_s}{9a}$

$$(\partial R(r,\tau)/\partial r)_\tau = -\ 4\beta(1-\varepsilon_o)O\ (H_o/\eta V(r))\ GR(r,\tau)/3\pi a \qquad (8)$$

For the clean separator G = 1, so equation (8) can be integrated and gives, between r_2 and r_1,

$$\ln\ (R(r_2,\tau)/R_o) = -\ (4\beta(1-\varepsilon_o)O/3\pi a)\ \overline{A}\ (r_2-r_1) \qquad (9)$$

where R_o is the slurry concentration at the entrance to the separator and where

$$\overline{A} = \left(\int_{r_1}^{r^2} (H_o/\eta V(r))\ dr\right)/(r_2-r_1) \qquad (10)$$

Equation (9) has exactly the same mathematical form as in the axial case[5], except that $1/V(r)$ has been averaged between r_1 and r_2 and r_2-r_1 replaces the length of the separator L. Introducing the residence time T and using equations (3) and (10)

$$T = \varepsilon_o\ (r^2_2 - r_1^2)/r_1V_1 \qquad (11)$$

$\overline{A} = H_oT\ (r_2-r_1)$, equation (9) becomes

$$\ln\ (R(r_2,\tau)/R_o) = -\ (4\beta O/3\pi a)(1-\varepsilon_o)H_oT \qquad (12)$$

This type of relationship has been observed in the case of axial separators[10].

In the strong-coupling limit, it is assumed that

$(4\beta O/3\pi a)(1-\varepsilon_o)H_oT >> 1$ which often arises when $V_m >> V_o$.

The captured material can be regarded as having a sharp interface. On the front side of the interface it is assumed that the filter has captured the maximum number of particles N_T and on the exit side of the interface no particles have been captured. This model has been discussed previously[5] in connection with the conventional feed system.

In calculating the position the interface it is assumed that $= A^{\gamma}$, so that $N_T(r) = N_1(r/r_1)^{\gamma}$. The number of particles entering the separator in time t is $2\pi r_1 V_1 R_o t$. Assuming that the position the interface is at r_o at filter time τ then number particles which have entered and been captured is

$$2\ r_1 V_1\ R_o(t - (r_o^{\ 2} - r_1^{\ 2})\varepsilon_o L)\ /2r_1 V_1)$$

The number of captured particles can also be written

$$\frac{N_1}{r_1^{\ \gamma}} \int_{r_1}^{r_o} 2\pi r^{\gamma+1}\ kr = (2\pi N_1/r_1^{\ \gamma})(r_o^{\ \gamma+2} - r_1^{\ \gamma+2})/\gamma+2)$$

If the number of particles in suspension is neglected in comparison with the number captured that is if $R_o << N_T$ then at time τ

$$R(1c)(r_o/r_1)^{\gamma+2} = N_1/r_1,\ 1 + (\gamma+2)\ (V_1(R_o/N_1 r_1)\ )k \qquad (13)$$

This equation must be solved simultaneously with equation (12) but with T replaced by T_s

$$T_s = \varepsilon_o\ (r_2^{\ 2} - r_o^{\ 2})/r_1 V_1 \qquad (14)$$

If $(\gamma+2)(V_1/r_1)(R_o/N_1)t << 1$ equation (13) can be approximated by

$$r_o = r_1 + V_1\ (R_o/N_1)\tau \qquad (15)$$

With equations (12) and (14) this gives

$$\ln\ \ (R(r_2,\tau)/R.) = -\ (4\beta(1-\varepsilon_o)D/3\pi a)H_o T(1-\varepsilon_o\ n\ R_o/N_1) \qquad (16)$$

Here n is the number of canister volumes slurry which have left the canister. This equation is identical in form to the conventional feed system[5].

III Comparison between the conventional and the radial system.

If $(\gamma+2)(V_1/r_1)(R_o/N_1)t << 1$ the approximation which leads to equation (15) can not be made and equation (13) and (14) must be solved simultaneously. However it can be argued that for an axial system and a radial system, which have equal performance when the separator is clean, then the separator having the largest particle storage capacity will perform better as the separator starts to collect material. If the separator parameters are the same then the conventional and the radial systems will have equal performance provided that $H_o T$ is the same in both cases. This condition can be written

$$A = H_o L/V_o \eta = H_o(r_2^{\ 2} - r_1^{\ 2})/2r_1 V_1 \eta\ \ = \bar{A}(r_2 - r_1) \qquad (17)$$

If the slurry flow rates are considered for the conventional system F_c and for the radical system F_r. it can be shown that

$$F_c/F_r = \bar{A}\ (r_2 - r_1)/AL + r_1 V_o/LV_1 \qquad (18)$$

If the quality of equation (17) is satisfied, then $F_c/F_r>1$. That is, if the initial performance is the same, the flow rate to the conventional system is higher, although the difference is small if $LV_1 >> r_1V_o$.

The relative holding oapacity of the two systems can be determined if it assumed the $N_T \propto A(r)^\gamma$. If the total capacities for the conventional and radial systems are N_c and N_r respectively, then

$$N_c/N_R = (r_1/L)^\gamma \ (\gamma+2)(S^2+1)(S^2-1)^\gamma \ (AL)^\gamma/2^{\gamma+1}(S^{\gamma+2}-1)(\bar{A}(r_2-r_1)^\gamma \tag{19}$$

where $S = r_2/r_1$. Experimentally[11] it has been shown that $\gamma = 1/2$ and for the two systems to have the same initial performance equation (17) must be satisfied. Also, when the two systems are to have equal capacity then $N_c/N_r = 1$. Under these conditions, equation (19) gives the results shown in Table I.

Table I Parameters at equal capacity

r_2/r_1	L/r_1
2	2.70
3	2.94
4	3.53
5	4.20

From Table I, if $r_2/r_1 = 2$, $N_1> N_c$ if $L/r_1> 2.7$. If the L/r_1 ratio is increased, the storage capacity of the radial canister becomes relatively better for the condition where the initial performances are identical. However, the flow rate through the conventional system is higher, but the difference decreases as L/r_1 becomes larger.

In the case of English clays the conditions are different those described above and very much more favourable for the radial system.

It has been found that if the brightness gain is considered at equal numbers of canister volume then the gain depends on the value of A. The condition for equal performance is simply that[3]

$$A = \bar{A} \tag{20}$$

Putting this condition into equation (19) gives

$$N_c/N_R = (5/4\sqrt{2})(S^2+1)\sqrt{S+1}\ /(S^{5/2}-1) \tag{21}$$

with $N_c/N_R = 1$ then $S = 5.74$ which mean if $r_2/r_1 >5.74$ $N_R>N_c$ and independent of the length. Also when $\bar{A} = A$ then $V_o \approx V_1$ so equation (18) shows $F_c/F_R \approx r_2/L$. This means the radial canister has a much greater throughput than the conventional canister if $L >>r_2$.

Fig. Captions

Fig.1 Conventional Feed system $H_o \| V_o$

Fig.2 Radial Feed system $r_3^2 = r_1^2 + r_2^2$. Field is applied parallel to the axis.

Fig.3 Section through radial canister. Matrix is between r_1 and r_2.

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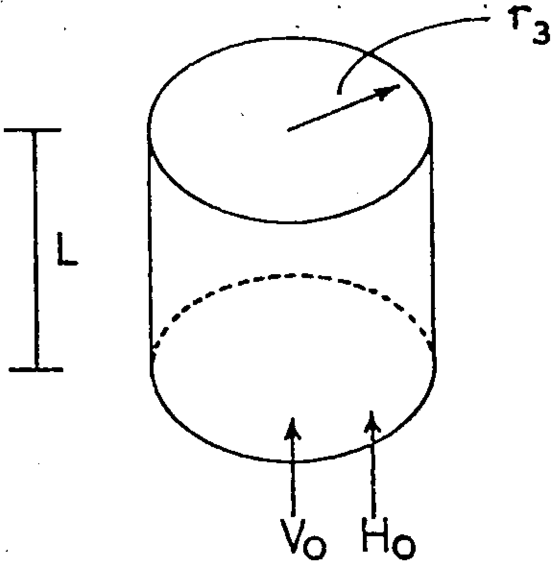

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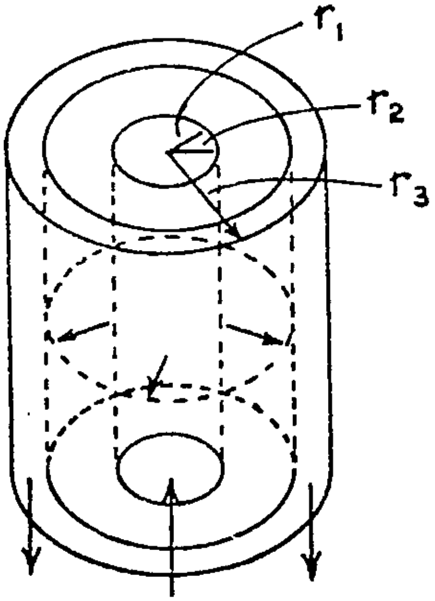

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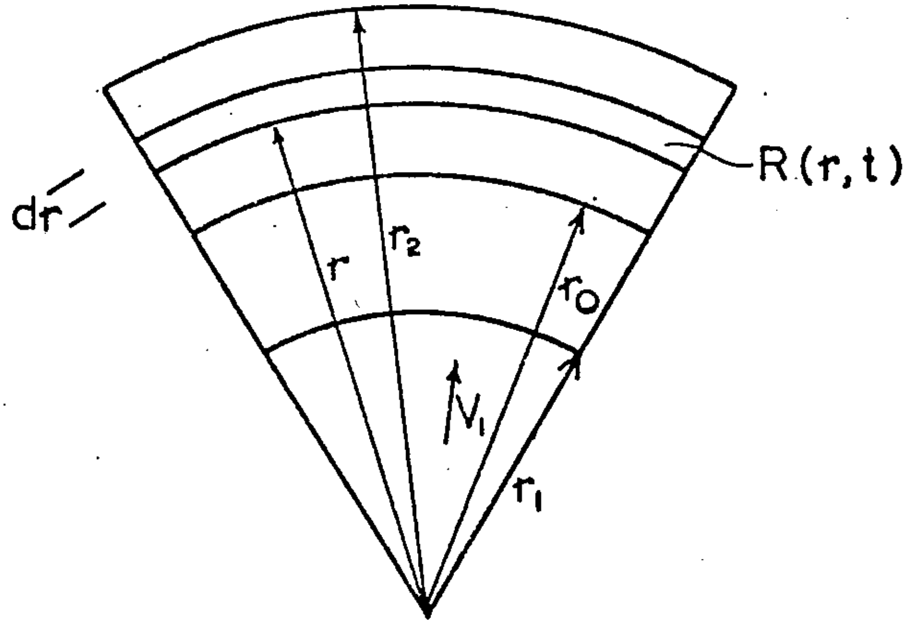

R(r, t)
dr
r
r2
ro
N1
r1

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IMPROVEMENTS OF A LOW-FIELD, HIGH-INTENSITY MATRIX SEPARATOR **

J. H. P. WATSON *
DEPARTMENT OF PURE AND APPLIED PHYSICS
UNIVERSITY OF SALFORD
SALFORD M5 4WT, U.K.

** Brit. Pat. App. Nos. 36476/77 and 46291/77

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1. INTRODUCTION

A high gradient, low field magnetic separator has been described and analysed previously [1]. This machine consisted of a series of containers, holding a ferromagnetic wire wool matrix, which moved through a low magnetic field and from which a slurry was slowly drained. The containers were filled before they entered the field. In this process, paramagnetic particles can be captured from the slurry and held on the ferromagnetic matrix, the relative velocity, between the slurry and the matrix being low. The particles are released when the containers leave the field. It was shown that the fraction of particles extracted depended on the ratio of the canister draining time T_D to the 'characteristic magnetic time T_m'.

$$T_m = 3\pi a/4FCV_m \qquad (1)$$

where a is the radius of the ferromagnetic matrix wire of magnetization M. F is the fraction of space occupied by the matrix wire and V_m the 'magnetic velocity [2] given by:-

$$V_m = \frac{2}{9}\,\frac{\chi R^2 M H_o}{\eta a} \qquad (2)$$

χ is the susceptibility of the paramagnetic particles of radius R, H_o is the applied magnetic field. It was also assumed in the analysis that R_o the capture radius 2 depends linearly on Vm/V so that:-

$$R_o = CV_m/V \qquad (3)$$

V is the velocity the fluid would have far away from a single wire and, for the case of the canister described here, it is the actual velocity of the slurry surface as draining proceeds.

C is a parameter which depends on $k = M/2\mu_o H_o$. In practice for fields greater than 2T, C is practically independant of applied field, but below 1T, the increase in R_o with $M/2\mu_o H_o$ increases the efficiency of separators [3].

SUMMARY

A high-intensity magnetic separator, which employs a ferromagnetic wire matrix in a low magnetic field, has been described and analysed, previously. In this paper, the improvement in performance with the reduction in magnetic field is shown to be limited to the field H_L where k ($= M/2\mu H_L$) becomes equal to unity, M being the magnetization of the matrix strands. However, it is shown that it is possible to obtain further improvements in performance, at magnetic fields lower than this limit, by the use of an hysteretic matrix. This involves first magnetizing the matrix in a high field before reducing the field to a low operating value, which may even be zero. The captured material is removed after the matrix is demagnetized.

However, the largest value of k that can normally be obtained with the soft ferromagnetic stainless steel is $k = 1$, due to the large demagnetizing factor of wires of circular or almost circular cross-section magnetized perpendicular to their axis. This factor limits the maximum efficiency of the moving matrix separator to approximately the field at which the matrix becomes saturated. It is the purpose of this paper to investigate, in more detail, the behaviour of R_o at low magnetic field and to suggest, that the use of materials with high coercive force can move the maximum efficiency of the moving matrix separator to very much lower applied fields.

The next section discusses the behaviour of the particle–wire interaction at fields much less than the field required to saturate the matrix. The introduction wire with a high coercive force is considered and then an attempt to evaluate the performance of likely materials is made. In the final section, the structure of machines which use this technique is considered.

2. THEORY

A theory of capture of paramagnetic particles has been developed [1,2, 4, 5, 6] based on the interaction between a paramagnetic particle carried by a fluid past a ferromagnetic wire magnetized by a uniform applied magnetic field H_o. By studying the equations of motion, the particle trajectories striking the wire can be found, which allows the capture cross-section $2R_c a$/unit length of the wire to be determined. The capture radius R_c was found to depend on k and on V_m/V_o. Cowan et al.[7] have found that, provided $V_m/V_o < \sqrt{2}$ R_c can be written,

$$R_c = (1/2)(V_o/V_o + k\sqrt{V_o/V_o}) \tag{4}$$

As shown in Equation (4), when $V_m/V_o < 1$ and V_m/V_o decreases in value, the term $k\sqrt{V_m/V_o}$ becomes the dominant term, especially when k is large. For example, when $V_m/V_o = .1$ and $k = 1$, the second term is a factor of 3 greater than the first. In the magnetic processing of clay, the values of V_m/V_o are usually much less than .1 In the following simple analysis therefore, equation (4) is approximated by:-

$$R_c = (k/2)\sqrt{V_m/V_o} \tag{5}$$

When a cylinder, of circular cross-section, is magnetized by an applied field H_o, then the actual internal field H_i is appreciably different from the applied field H_o, due to the presence of a large de-magnetizing field, so that

$$H_i = H_o - M/2\mu_o \tag{6}$$

where M is the magnetization of the cylinder. If the wire has a permaability $\mu >> 1$, then the magnetization M is given by

$$M = \chi\mu Ho\ (1 + \chi/2) \doteq 2\mu_o H_o \tag{7}$$

where $\chi = \mu - 1$. At low field H_o, the magnetization is therefore determined by the reciprocal of the de-magnetizing factor, and k has the value $k = 1$.

If the material is hysteretic, with a coercive field H_c, the magnetization on the de-magnetizing part of the cycle, M is $M = 0$ at $H = H$, so that at low applied field:-

$$M \neq 2\mu_o \; (H_o + H_c) \qquad (8)$$

and

$$k = 1 + H_c/H_o \qquad (9)$$

Also, the magnetic velocity V_m can be written

$$V_m = \frac{4}{9} \frac{\chi R^2}{\eta a} \mu_o \; k \; H_o^2 \qquad (10)$$

and

$$R_c = Ak^{3/2} \; H_o/V_o^{\;1/2} \qquad (11)$$

where

$$A = (1/9) \; \chi R^2 \mu_o/\eta a)^{1/2} = \text{constant}$$

An examination of equation (11) reveals a way in which the operation of the low field system can be done. The quantity V_o/H_o^2 is a measure, for a given value of R_c, of the volume of material processed per unit power cost. This is because the volume of material processed/sec is proportional to V_o and the power cost is proportional to H_o^2. From equation (11) we have,

$$\frac{R_c^{\;2} V_o}{H_o^{\;2}} = Ak^3 \qquad (12)$$

If H_o is reduced, but V_o/H_o^2 is kept constant, then, in the absence of hysteresis, k and consequently R_c, slowly increase with decreasing field, until k reaches the maximum value of k = 1. Beyond this point, there is no increase in R_c produced by lowering value of H_o at constant power/unit volume of processed material. This point is determined by the details of the magnetization curve and by the size of de-magnetizing factor and is less than, but approximately equal to, $M_s/3\mu_o$ where M_s is the saturation magnetization.

In contrast if the de-magnetization branch of the curve is considered, then k increases with decreasing H_o, as shown by Equation (9). If the power/processed unit volume is held constant, while H_o is decreased, then R_c increases as $k^{3/2}$ and consequently, at constant power/processed unit volume, the performance of the separator can be appreciably increased as E_o is reduced. For example, if $H_o = H_c$, and if we compare the magnetization branch with the de-magnetization branch, then the values of k are 1 and 2 respectively. From Equation (12), we see that R_c^2 is increased by a factor of 8 on the de-magnetization branch relative to the magnetization branch. It seems likely therefore, that the field H_o can be reduced so that permanent magnets can be used to supply H_o, and perhaps H_o can even be reduced to zero.

It is interesting to consider the properties desired in a matrix for operation in a separator. As we have seen, the most important requirement is a large coercivity H_o. The second most magnetic important property is a large permeability near the operating field Ho, this ensures that the magnetization has the maximum value allowed by the de-magnetizing factor.

The third factor is mechanical one, the material must be ductile so that the matrix can be formed into wires or sheets. A list containing suitable alloys is given in Table 1.

Table 1 - Alloys suitable for low field separation.

Name	Composition *	Coercivity	Prep.	Heat Treat.	Mech. Preps.
Vicalloy 2	52Co 14V	510	)Cold)Roll,)draw,)machine)punch)	D,B600 Q1070,B700	)))Ductile)))
Cunife 1 (Magnetoflex)	20Ni60Cu	590			
Cunico 1	21Ni29Co50Cu	700			

* Fe to 100%

If the separator is operated at 0.2T, and if hysteresis is used, then for Vicalloy 2, Cunife 1 and Cunico 1, the values of k are 1.25, 1.3 and 1.35, respectively. If the processing is done without using hysteresis then k = 1; if hysteresis is used, then from Equation (12), if R_o and H_o are held constant, then the processing velocity can be increased by a factor of k^3. These factors are 2, 2.2 and 2.5 for the three alloys, respectively. This leads directly to a change in the power cost per unit volume which varies inversely with k^3 namely, 0.5, 0.45 and 0.4, respectively.

3. Magnetic Separators

In order to take advantage of the low power cost/unit volume processed, it is necessary to use a hysteretic matrix material. In the moving matrix system 1, the following procedure may be adopted. The canister, which is one of a large number, containing an hysteretic matrix is filled with slurry. The container is moved into a high magnetic field region and slow draining of the slurry commenced. The container then moves between the poles of a low field magnet in which most of the draining is done. The low magnetic field may in some cases be reduced to zero. When draining is completed, the canister passes into a section where the matrix is de-magnetized by an alternating magnetic field of decreasing magnitude. The retained particles can then be washed from the matrix. This machine consists of a chain of containers, consequently the operation is continuous.

It should be pointed out that an hysteretic matrix can be used with any magnetic separator; however, in many cases, the gain in processing velocity or performance, resulting from the increase in k, may be so small that it does not warrant the extra complication.