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ADVANCE IN MAGNETIC SEPARATION TECHOLOGY

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ABSTRACT: Most of the naturally occurring iron, titanium and chromium bearing minerals which accompany industrial minerals, such as quartz, feldspar, nepheline syenite, spodumene, andalusite, vermiculite, etc.exhibit either ferromagnetic or paramagnetic properties and can therefore be removed by means of magnetic treatment.

Magnetic separation, powered by either permanent magnets or electromagnetic coils, have been widely applied to remove iron titanium bearing minerals from industrial minerals. The removal of these impurities have significantly improved the quality of the industrial minerals processed.

The early magnetic separators used for mineral processing were exclusively resistive electromagnets using water cooled copper coils. About 9 year ago, superconducting magnets made their first entry in to this application and since that time their number and popularity has steadily increased.

Equally important İs the development of superconducting magnet systems which has brought about notable improvement with regards to process economics, ease of installation and separation flexibility which make it practical for a great number of kaolin producers to benefit from this technology.

Magnetic filtration is also greatly improved by the use of a superconducting magnetic separator.

1 INTRODUCTION

The mining and recycle industry has been using magnetic separation techniques for many years for its concentration and purification requirements. Magnetic separation exploits the force generated by a magnetic system (permanent magnet, electro-magnet, solenoid) to separate particles exhibiting different magnetic properties. In magnetic sorting operations, for the separation to succeed, this force ($F_m = {}^1/$i po Vp x V (H)^2), applied to all the particles present in a solid/fluid mixture, must be greater than all the other forces developed by the system (centrifugal, gravitational, fluid flow force).

Magnetic separation, which was supplanted by floatation processes for many decades, has made a major technological leap with the installation of a large wet method unit on mine sites. Since the early 1980s, developments in magnetic materials and expertise in cryomagnetic systems have enabled this technique to advance by the development of the following;

- High field, high gradient separators, witii copper or superconducting windings, extending the particle size limits of the treatment.
  These large-capacity separators, which have aroused intense interest among kaolin producers, are now offered in the catalogues of certain manufactures (Eriez, Carpco, Humboldt).
- Separators with permanent ceramic magnets (ferrites) or based on rare earths (iron/boron /neodymium or samarium / cobalt) whose high performance in terms of field intensity and depth have substantially improved low-intensity applications and especially dry 'high-intensity' applications.

These improvements, added to the fact that permanent magnets do not consume energy, have revived this technology in the mineral industry, chiefly in the production of industrial minerals (feldspars, wollastonite, andalousite, silica).

High critical temperature superconductors (=90 K) of the yttrium/barnium/cuprate type were developed a few years ago and significant progress has been achieved in the production of thin films, wires and blocks which display similar behavior to permanent magnets. These materials are likely to be used shortly in magnetic separators for the treatment of industrial minerals. Yet the mineral industry, which is a conventional sector, has not been the only one to benefit from this technological breakthrough. The recycling and environmental fields, particularly the purification of polluted fluids, have found an effective technique in magnetic separation, one capable of meeting their concerns.

In fact, by combining magnetic flocculation and magnetic separation, a large number of industrial effluents, containing metals in solution, can be treated by separators with superconducting coils to achieve virtually total purification, allowing the discharge of the fluid into the natural environment. This research, conducted for several years at the LEM, is also described in this article.

2 THEORETICAL BASIS OF MAGNETIC SEPARATION AND CLASSIFICATION OF SEPARATORS

2.1 Theoretical basis of magnetic separation

A magnetic separator is an instrument that alters the characteristics of the magnetic field in the treatment space. It generates a magnetic field which acts selectively on substances that display the highest aptitude to magnetization. In magnetic sorting operations • (concentration or purification), separation is achieved by applying, to all the particles present in a mixture, a magnetic force of the general expression:

$$\bar{F}_m = \frac{1}{2}\mu_0 V_p \left(\frac{\kappa_p}{1 + D\kappa_p} - \kappa_f \right) \mathrm{grad}(H^2)$$

where:

D particle demagnetization coefficient,
- V_p,Kp volume and magnetic susceptibility of substance considered,
- Kf magnetic susceptibility of fluid (air or water),

μ_0= permeabilityofft^pa«
grad'

In addition to this attractive force which acts on the magnetic particles, a combination of forces is applied to all particles, magnetic or not, acting in different directions, and of which those most frequently encountered are:

- force of gravity:

$$\bar{F}_m = \frac{4}{3}\pi(\rho_p - \rho_v)R_p^3\,\bar{g}$$

- centrifugal force:

$$\bar{F}_c = \rho_p V_p \omega^2 R$$

- dragging force by the fluid:

$$\bar{F}_f = 6\pi\eta R_p (v_f - v_p)$$

where:

- **R** radius of separation drum (or **cylinder),**
- **R_p** particle radius,
- **g** gravitational acceleration,
- **v_p and v_f** velocities of the particle and fluid,
- **ω** angle of velocity of the particle,
- **ρ_p and ρ_f** densities of the particle and fluid,
- **η** dynamic viscosity of the fluid.

For magnetic separation to succeed, the magnetic force must be greater than the sum of the antagonistic forces developed by the system and the interparticle forces.

2.2 Magnetic systems and classification of separators

The primary component of a magnetic separator is the magnetic field source generating the force used for separation. Three systems can be employed: permanent magnets, electro-magnets (conventional magnetic circuits), and solenoids (copper or superconducting coils).

In magnetic separation, many units are available from manufacturers, and they cannot be described without a classification. Many classification criteria can be applied: magnetic field intensity, separation medium (water or air), operating mode (extraction or deviation), magnetic field generator, etc....

The magnetic force equations show that it depends on two main factors:

- the material (or particle) for its magnetic susceptibility and volume,
- the magnetic separator, for the (J.o grad (H^2) product, i.e. the form of its magnetic field.

Magnetic separators can thus be classed in three main families (Table 1):

- **low intensity** separators (permanent magnet) with:
  Ho grad (H^2) = 2 x 10^4 to 10^6 N/m^3
- **high intensity** separators (electro-magnet or ceramic permanent magnet) with:
  Ho grad (H^2) s 2 **x** 10^7 to 4 x 10^9 N/m^3
- **high gradient and/or high field** (solenoid) separators with:
  Hograd(H^2) = 6x $10^{,0}$to $10^{,2}$N/m^3

Table 1 : Magnetic separators

unit	treatment generator	panicle size mm (I)	capacity (2) (tfh)	Uograd<H=) (N/m^1)
low intensity	permanent magnet	0.5 to 20	20 to 300(3)	$2x10^4$ lo $2x10^6$
belt separator	permanent magnet	10	60(3)	5x10*
drum separator:				
• dry method	permanent magnet	20	300(3)	$2x10^{fi}$
• wet method	permanent magnet	5	150 (3)	$2x10^s$
high intensity	pennanent magnet or electro-magnet	1 lo 5	6 to (80	$2x10^7$lo $4x10^9$
drum separator	ceramic permanent magnet	5	10	$2x10^7$
wound rotor separator	electro-magnet	3	8	2x10*
Jones separator	electro-magnet	1	180	$4x10^9$
high gradient, high field	solenoid	0.05 to 0.1	10 to 800 (4)	$6x10^{10}$to 10^{12}
conventional separator				
• batch	copper coil	0.1	too	$6xt0^n$
• continuous	copper coil	0.1	200 to 800	$6x10^{11}$
superconducting separator	superconducting coil	0.05	60 to too	$4xI0^{12}$

(t) Largest particle size in feed.

(2) Capacity given for information. It depends on many factors, including particle size distribution, percentage of magnetic product, separator size (length and diameter of rotor, for example).

(3) Capacity given per meter of useful width (t/h per m).

(4) Depending on the number of magnetic heads on the tumstite.

This classification may have some shortcomings, but, in our opinion, it is the best available for answering questions from an engineer seeking a unit designed to treat a given product characterized by its magnetic properties and particle size distribution.

Each of these families is subdivided into separators operating modes , the former normally reserved for treating coarse-grained products (particle size from a few mm to a cm), and the latter for finer-grained products (particle size less than l um).

3 MAGNETIC SEPARATORS AND THEIR DEVELOPMENT

Low-intensity units normally operate with an open magnetic field, in other words the magnetic force lines are closed in an impermeable magnetic medium, air or water. The magnetic field source generating the force used for separation consists of permanent magnets in this case. Most of these units are equipped with a ring of fixed permanent magnets inside a rotary drum.

Progress has been achieved in this area with the appearance of separators featuring ceramic permanent magnets and high peripheral speeds, designed to treat finer particle sizes or higher throughputs.

High-intensity separators feature conventional magnetic circuits (iron magnetic yoke and copper coils). They have closed magnetic fields, and develop magnetic fields ranging from 400 to 1600 kA/m for power consumption between 0.5 and 2.5 kWh per ton treated. The solid throughputs vary according to the separation method (dry or wet), and the treatment operation (concentration, purification) between 6 and 180 t/h. In this area, the most spectacular achievement occurred in the 1960s, with the appearance of extraction matrices replacing the induced rotor grooved in the air gap of the magnetic circuit.

Current wet HIMS method techniques differ from the others in that the feed is no longer distributed or under a rotor or drum. It circulate across an extraction matrix placed in an annular space (rotor disk or ring) rotating between the polar parts of a magnetic circuit with a wide or narrow air'gap.

The equipment representing the extraction matrices has different configurations according to the manufacturer: grooved plates, assembly of cylindrical or trapezial inclined bars, steel bails (Figure 1).

These separators (Figure 2) of the Jones type are marketed by KHD Humboldt Wedag, Boxmag Rapid, Eriez and Carpco, and are widely used to treat iron ores, where tiiey represent the largest installations today. The KHD Jones separator has a special feature: it uses an appropriate geared plate matrix (four teeth per inch) to treat iron ores (hematite, magnetite, martite) with large particle size (5 urn) and at high throughput (300 t/h).

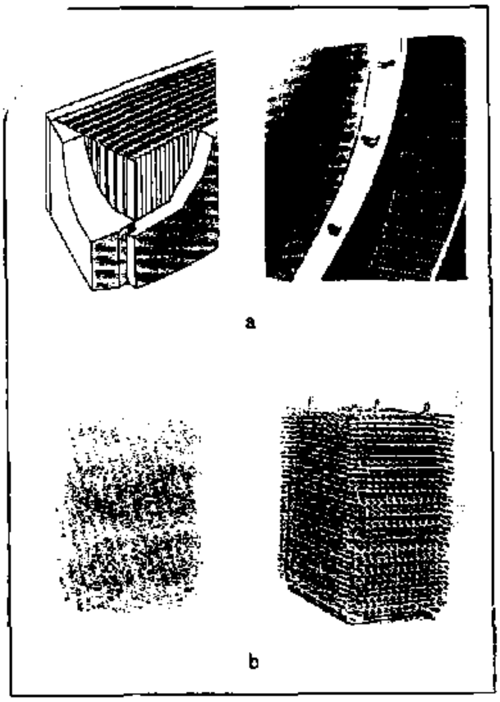


Fig 1 : WHIMS (a) and HGMS (b) matrices

Fifteen years ago, the advent of permanent magnets on the market based on rare earths (Sm/Co or Fe/Nd/B) allowed the construction of new high-intensity separators. In many fields {treatment of industrial minerals), these have supplanted the conventional units due to their substantially lower investment and operating costs.

3.1 Magnetic separators with ceramic permanent magnets

The latest developments in permanent magnet manufacturing technology have put new alloys on the market based on rare earths/cobalt, or Fe/Nd/B, exhibiting very high internal energies (BH) max and coercive fields. They can hence be used as high field generators for high-intensity magnetic separators with arrangements:

- which guarantee high field gradients necessary to generate magnetic forces on the particles to be sorted,
- which correspond to 'open fields', i.e. forces generated outside a multi-polar part avoiding the usual problems of particle circulation between the air gaps.

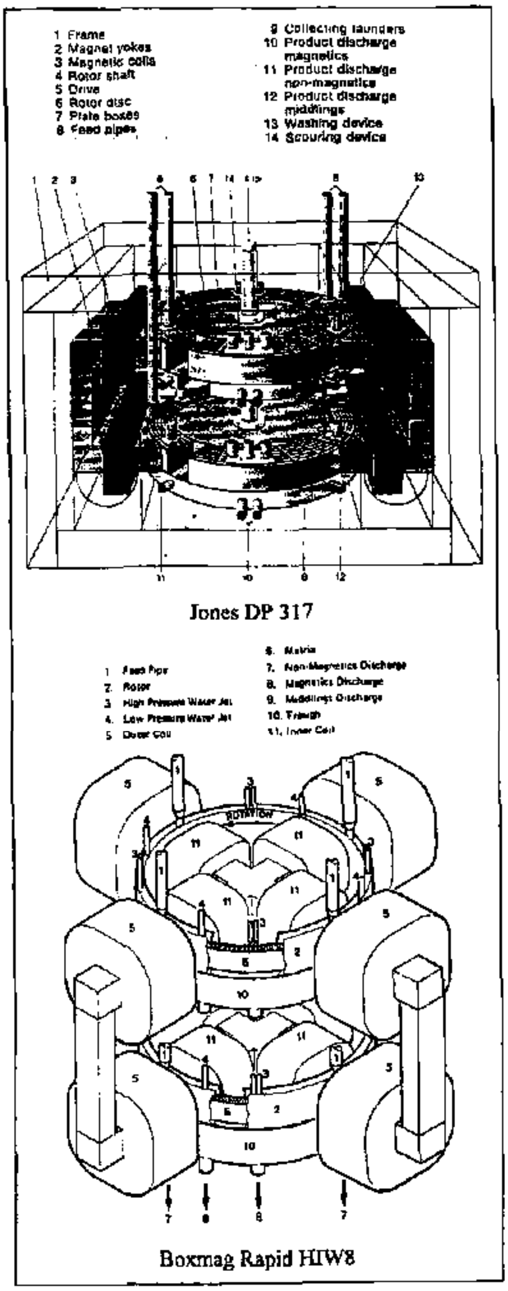
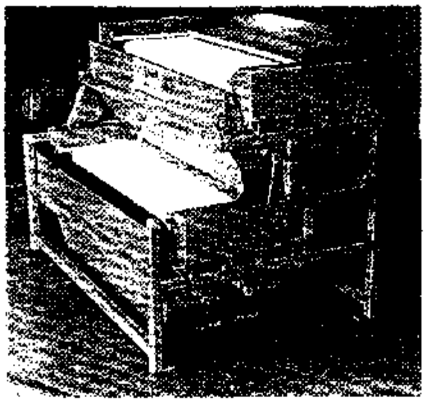


Fig 2: WHIMS separator

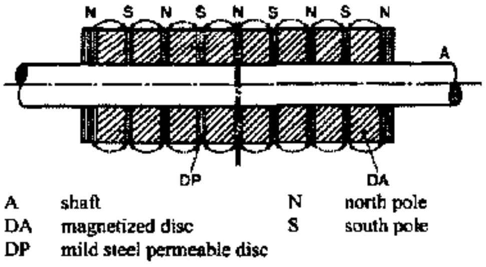
At the present time, the separators proposed by the different manufacturers, essentially for the upgrading of mineral raw materials, are designed with multi-polar and cylindrical heads. It correspond to the assembly of magnetized discs combined alternatively in order to loop the field lines in very tight geometries and thereby guarantee high gradients.

Other types of equipment include:

- *Permroll* built by Ore Sorters International (OSI),
- *Rollmag* built by Raoul Lenoir (France) (Figure 3),
- *Magnarolt* built by Boxmag Rapid (United Kingdom),
- *Roll* built by Eriez (USA),
- *High Force* built by Inprosys, marketed by Denver Sala,
- *Rollap* built by Fives Cail Babcock (France),
- *Pernios* built by KHD Humboldt Wedag.



Rollmag separator



Magnetic pulley

Fig 3: Rollmag permanent magnets separator

Most of these units correspond to technologies in which the polar head operates as a belt pulley for feeding the product to be treated. Some manufacturers also design their separators so that the cylindrical polar head directly receives the free-falling feed on its surface on one of its generating lines (e.g. the *Pernios* separator). In .all cases, the open field design allows the treatment of large particles (over 10 urn) and irregular particle shapes (chips, fiat or elongated particles etc).

These separators mainly have industrial applications in the purification of various materials and minerals such as feldspars (elimination of mica in Norway and France), andalousites (South Africa), and diamond (South Africa), but also increasingly in metal recycling and the purification of foundry sands.

In economic terms, these systems also offer the advantage of:

- requiring smaller investments than conventional electro-magnetic separators (about 50% per ton treated),
- exhibiting very low power consumption, limited to solids transport and rotation of the polar part (low maintenance and treatment cost),
- normally permitting direct treatment of a product not previously treated by low-intensity magnetic separation, with the ferromagnetic particles being detached by devices provided for overall magnetic materials,
- lighter units (ten times lighter) with smaller floor occupancy (50%) than wound rotor separators.

The main constraints and limitations are essentially due to:

- the maximum intensity of the fields which is reached today by iron/neodymium magnets (= 1600 kA/m): since these are the most sensitive to heat, their magnetization deteriorates rapidly at temperatures around 100°C (many treatments are applied at a furnace exit),
- the thin dimension of the useful field, imposed by the need for high gradients which considerably influences the magnetic force applied to large and variably shaped particles,
- separation conditions which can only be controlled by the drum or belt speed,
- the possibility of pollution of products separated by ultrafines adhering to the belt by electrostatic effect, or the inability or difficulty to treat fine products (deterioration of separation Below ? 30 to 40 urn).

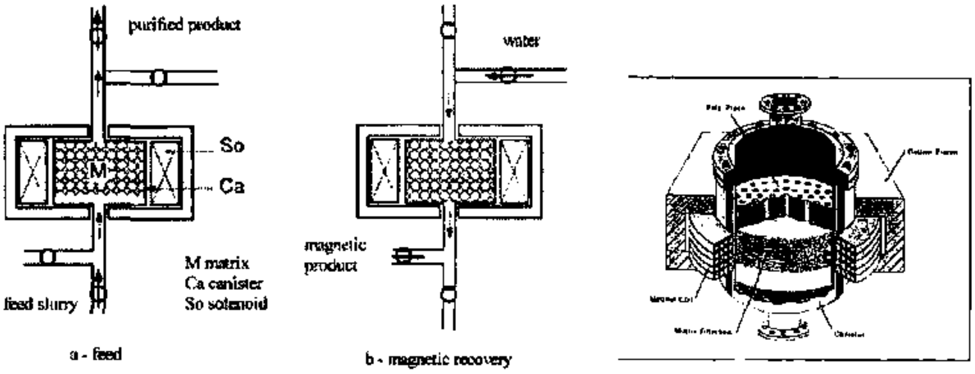


Fig 4: Cyclic HGMS

3.2 High gradient/high field separator

The use of conventional circuits (or permanent magnets) nevertheless has major drawbacks, and the current trend in the treatment of fine products in particular is to replace these magnetic masses by solenoids (copper or superconducting). Solenoid separators offer the advantage of separation inside the induction coil where a steel wool or expanded metal type matrix has been positioned, and which retains the fine paramagnetic particles (Figure 1). The principle of these units is shown in Figure 4.

Solenoid separators with copper windings are available in two versions, one cyclic with capacity up to 100 t/h (Figure 4), and the second continuous with a ring handling up to 800 t/h. The separators are mainly used in the kaolin industry, but also in the purification of city water or the filtration of process water from steel manufacturing or thermal power plants.

3.2.1 High gradient/high field separator with superconducting coil

Like high-intensity separators, high gradient separators present major drawbacks if a magnetic field of more than 800 kA/m is needed for separation:

- high installed electrical power (= 400 kW)
- high power consumption {5 kWh/t on average),
- complexity of the cooling system
- high consumption of de-ionized water (11/kW installed power)
- steel consumption (300 t) to close the field.

Magnetic force densities higher than 10^M N/m^3 are needed to separate low-susceptibility ultrafine particles (< 5 urn). This is unfeasible technically or economically with conventional circuits, and only superconducting coils can achieve the purpose.

A superconducting magnet generates a high magnetic excitation not reduced by iron saturation. This procures the following advantages:

- higher force of magnetic attraction (x25 in some cases), allowing the trapping of particles of about 1 jim,
- lower installed power and power consumption (s 90%),
- lower weight (s 50%) and smaller size of units (= 35 to 40%),
- higher treatment capacities by increasing the field,
- widening of the areas of application of the method,
- replacement of complex and costly treatment schemes.

The use of Nb/Ti 4.2 K superconductors is now quite feasible. The problem is not technical but economic: investment (coil cost) and operation (consumption of liquid helium or cooling cost).

Industrial superconducting units operate today in two modes: extraction matrices and drum. The main manufacturers are Eriez (USA), Carpco SMS (United Kingdom) and Humboldt (Germany).

(a) Extraction matrix separators

These separators are positioned in a field range between 1600 and 4000 kA/m and usually operate in cyclic form in the same say as high gradient copper

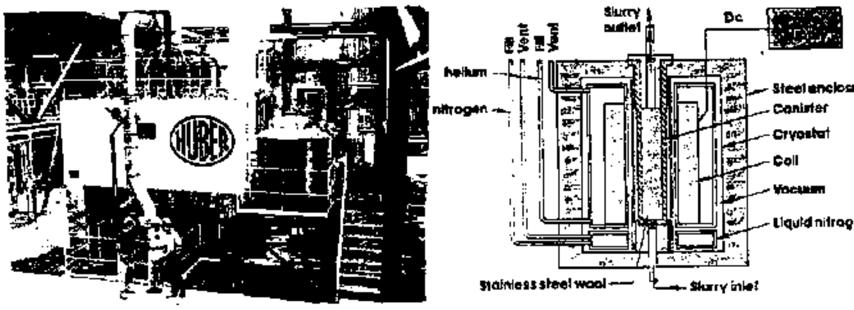


Figure 5: Eriez superconducting separator

winding separators. Their technology is the same, but the copper winding is replaced by a superconducting Nb/Ti winding immersed in an isolated enclosure containing liquid helium. Several insulating layers and a thermal wall cooled by liquid nitrogen surround the helium container to minimize helium consumption. A helium gas recovery or liquefaction system may be added. The separator developed by Eriez (Figure 5) resumes this system. This type of separator has been in operation since 1986 at J.M. Huber Corporation on mines in Georgia and South Carolina (USA) to purify kaolin clays.

These separators operate with a field of 1600 kA/m with installed power of about 60 kW (compressor and cryogenerator included). The canister, filled with a steel wool type matrix, is 2.14 m in diameter and 0.5 m deep. The magnetic system (coil/cryostat), surrounded by a light mild steel envelope to close the field, weighs 2301.

The liquéfier (compressor, gas recovery, cryogenerator) produces 201/h of helium.

This first commercial installation provides some idea of the operating costs, and demonstrates the advantage and superiority of superconducting windings in comparison with copper windings. The gain in electric consumption ranges from 80 to 90% (according to whether a liquéfier is incorporated), representing savings of about 150,000 dollars per year in 1988. The liquid helium consumption announced by the manufacturer are (without liquéfier) 2 liters/cycle (field build-up, holding and demagnetization) for a field build-up time of 1 min.

Two operating cycles are necessary for kaolin treatment per hour (capacity = 200 t/h). These systems also help reduce the costs of the installation in the sense that the ground occupancy and weight are reduced by 35 and 45% in comparison with conventional high gradient separators.

In 1990, Eriez installed 3 m diameter separators (5001) for the Hubert company.

The *Cryofilter/HGMS* systems (Figure 6), like the one developed by Carpco SMS (United Kingdom), comprise a mobile canister and operate continuously. This canister 'train' set in motion by a hydraulic system consists of alternating separation canisters and empty boxes to facilitate movement inside the coil. When a canister is in the field, it is fed and then taken out of the system for washing, and the next canister is positioned at the feed point.

These separators, which develop a field of 4000 kA/m in a 0.5 m diameter coil for a length of 1.3 m, have been installed in the United Kingdom, Germany and Brazil to treat kaolin (30 to 50 t/h). These units weigh 45 t, are equipped with a helium recycle system, and have installed power of 10 kW.

(b) Drum separators

These open gradient separators resume the design of the magnetic drums in which the ring of permanent magnets is replaced by a series of superconducting coils with flat windings.

The *Descos* separator (Figure 7) marketed by KHD Humboldt Wedag develops a magnetic excitation of 2600 kA/m (3.2 t) at the surface of the drum. The

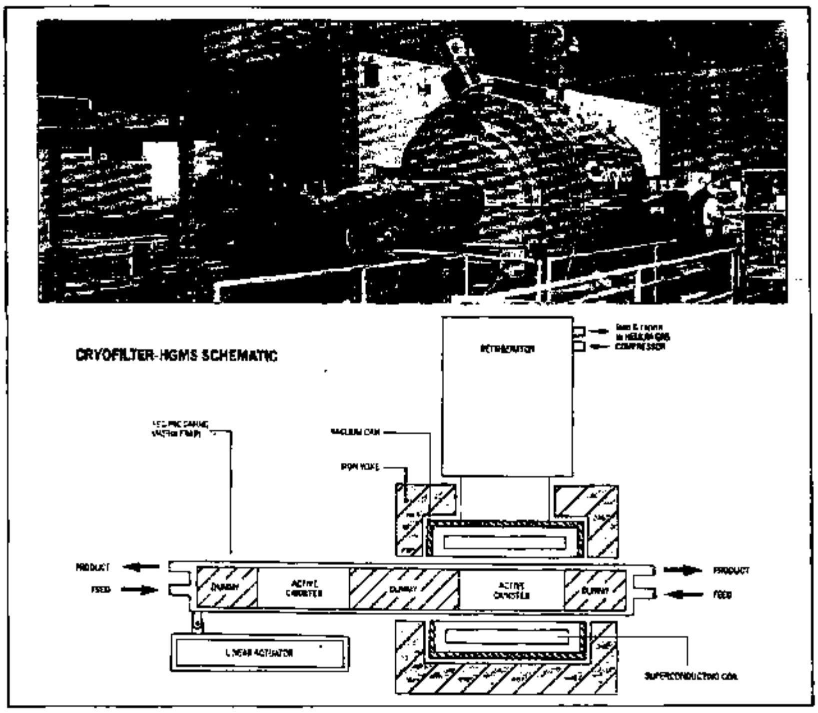


Fig 6: Carpco cryofilter

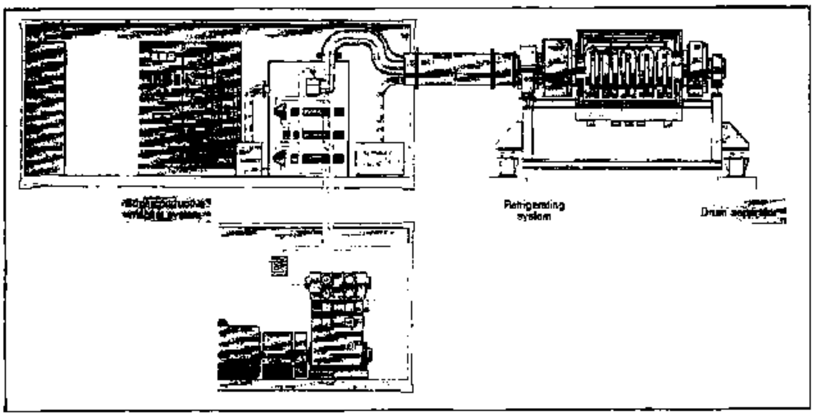


Fig 7: Descos magnetic

superconducting windings are placed in a cylindrical tank made of insulating materials, containing liquid helium and kept under vacuum. The unit is equipped with an extremely flexible and easily maintainable self-contained cooling system. The drum, made of reinforced carbon fiber, is 1.20 m in diameter and 1.5 m long. The separator can operate with the dry or wet method, with capacity of about 100 t/H, It can handle particle sizes down to ? 100 urn.
A pilot unit has been tested successfully on various ores and industrial minerals (magnesia in Turkey, bauxite, phosphate).

(c) Main fields of application of SMHG The application of these techniques has extended magnetic separation to ores that are not economically upgradable by other methods, and to other branches of activity. This method has pushed back the technical limits of separation towards ultrafine particles and for similar, if not better, purification yields, offering an economic advantage by lowering operating costs. This application can be found in;

- the purification of products for the glass or ceramics industry, which demand a high purification degree {kaolin clays, sands, nephelinic syenites),
- removal of sulfides from powdery coals for thermal or electric power plants,
- purification of process water (metallurgy and steel), city water, cooling water for electric, thermal and nuclear power plants, with high throughputs of around 500 m^3/h per m^z of canister surface area,
- extraction of particles present in chemical synthesis processes, in energy fluid or steam feeds of electric and thermal power plants,
- mineral concentration, such as ultrafines of Fe, Mo, W, rare earths and metallic residues for recycling,
- purification of miscellaneous industrial fluids (surface treatment industry, hydrometallurgy, oil industry) in environmental and recycling areas,
- treatment of used catalysts,
- use in biochemical, biological (plasma production) and agrifood areas.

3.2.2 Choice, comparison and costs

(a) Separator selection criteria

The choice of a separator is guided by a number of criteria common to the different types of treatment (energy availability, water supply, hourly throughput, ease of maintenance, availability of wear parts, technological environment etc), but, above all, by two criteria: the magnetic properties of the minerals and their particle size distribution. The magnetic properties guide the user to one of the available classes of separator:

- high magnetic (ferri- and ferromagnetic), low intensity,
- low magnetic (paramagnetic), high intensity or high gradient (closely associated with the particle size distribution).

For complex mineralogical combinations where two types of substance co-exist, high and low intensity separations must generally be considered.

Depending on the mineralogy (composition and liberation mesh), it is often necessary to have an accurate knowledge of the susceptibilities of the minerals to be treated or of the mixed grains. This knowledge, while providing information on the separator to be used, can also indicate the quality of the finished product (chemical quality/recovery).

The choice of the method or equipment can also be guided by the objectives: quality of the concentrate or recovery. In similar case, some manufacturers can provide an answer by a particular use of their separators {low centrifugal intensity, high gradient or use of wide air gaps in Jones type separators).

The particle size criterion (closely associated with the mineralogical criteria and magnetic properties) determines the treatment mode (dry or wet), and also the type of separator. As a rule, coarse-grained materials are treated by the dry method and fine materials (from 500 urn) by the wet method.

For treatments (concentration, but primarily purification) of ultrafine products (< 50 um) in the fields of industrial minerals and environment (fluid purification), high gradient separators with extraction matrices are necessary.

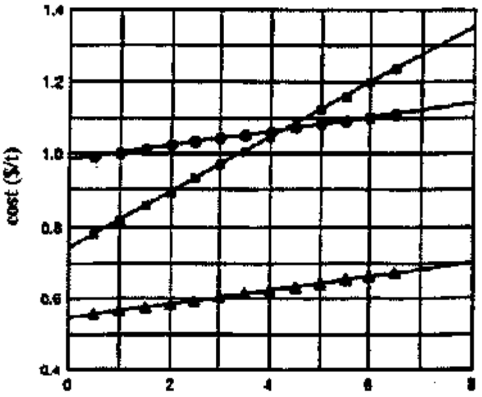
(b) Economic data on magnetic separation

Figure 8 and Tables 2 and 3 show the main economic data (investment and operation) of the different separators.

Investments

The cost of a separator depends on its magnetic system and its size. The latter is determined by the manufacturer in the light of the batch test results or pilot tests designed to identify the type of separator and the ideal separation conditions for the objectives set (throughput, feed, water, cutoff .field). As a first approximation and from manufacturer data, it may be observed that:

- the low-intensity magnetic separator is the cheapest: 800 to 1200 FF per hourly ton treated,
- the high-intensity dry magnetic separator is the most expensive (15,000 to 80,000 FF per hourly ton treated).



power cost (VkWh)

- copper coil
- superconducting coil

A superconducting coil with mobile canister

Fig 8: cost per ton/energy

This cost is penalized by the low unit throughputs (max 6 t/h), which often demands multiplying the number of separators and increasing the size of building. On the contrary, for 'high-intensity' separators with ceramic magnets, this cost can be halved.

The cost of a high-intensity magnetic separator for the wet method ranges from 5000 to 30,000 FF per hourly ton treated.

For a capacity of 900,000 tfyear (7600 h) of iron ores, K.HD recommends a capital outlay of about 0.44 DM/t {1.50 FF/t) including equipment (separator, pumps, piping), building and installation. This cost is based on a depreciation period of ten years at 10% interest. For higher capacities, the capital cost can be reduced to 0.30 DM/t.

The cost of high-gradient separator (copper or superconducting winding) ranges from 10,000 to 100,000 FF per hourly ton treated (Eriez superconducting separator: US$2.2x$10^6$). The price of high-intensity high-gradient separators depends on the magnetic design of the circuit, the weight of low carbon steel used to close the field, and the associated cooling system.

As a rule, it can be said that the cost of a winding will depend on:

- its diameter and height (conductor weight),
- the weight of steel for field closure,
- the field developed,
- installed power,
- type and shape of conductor,
- associated cooling system.

Table 2: Comparison of magnetic separation techniques
Permanent magnet, electro-magnet, superconductor

	permanent magnet	electro-magnet (resistive coil)	superconducting coil
consumable energy	low	high	low
magnetic induction	160 to 1200 kA/m	limited to 1600 kA/m	> 4000 kA/m
separator weight	light	heavy	light
field source or con due lor	ceramic permanent magnet	hollow resistive copper conductor	Nb/Ti superconductor
cooling	none	air or de-ionized water	liquid helium
field closure head (mild steel shielding)	none	large	none
dependability	excellent	high	depending on cooling system: high to medium
investment	low	high	high
field generator	medium	high	high
installed capacity	very low	high	low
cooling	none	low to medium	high
operating cost	low	high	low to medium
cyclic separator	-	well-established	established
continuous separator	well-established	well-established	not established

Operating costs

Operating costs for separators are mainly due to the energy expenditures of the coils (HIMS and HGMS), engines and ancillanes (pumps, blowers, distributor) and wear parts (matrices). For low

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intensity, the energy cost is very low (0.05 kWh/t), and for high intensity it ranges from 0.05 kWh/t (permanent magnet) to 2.5 kWh/t (electro-magnets). For high gradient (copper solenoid), it can reach 20kWh/t. It is around 0.6kWh/t for a superconducting coil, considering the installed power of the cooling system.

For superconducting separators, it is too early to advance precise Figures today for investment and operating costs of this type of unit. The cryomagnetic equipment of IRM coils or particle accelerators, and magnetic separators developed by Eriez and Carpco (Figure 8) provide the only basis for comparison available today.

From the investment standpoint (Table 3), it appears that, in so far as a change in the value of the magnetic field on the axis of the coil does not significantly affect the separation results, the design and construction of the coil can be simpler and cheaper than the coils designed for scientific research (in fact approximately the same as the copper coils designed to treat the same flow rates).

Table 3: Comparison (1990) of magnetic systems (1)

data	separators		
		superconducting coil	
	copper coil	4K(2)	77 HTC (3)
power required:			
separation (kW)	270	0.007	0.007
cooling <kW)	30	60	3 to 4
total (kW)	300	60	3 to 4
weight (t)	490	230	<230
ground area <ro')	50	17	<17
capital (MS)	1.6 to 1.7	1.7 to 1.8	1.5 to 1.6
annual operating cost (kS/year)	81	15.8	1.1
annual capital (kS/year)	425.6 to 452.2	452.2 to 478.8	399.0 to 425.0
total annual cost (k$/year)	506.6 to 533.2	468.0 to 494.6	400.1 to 426.1

Coats In US dollars (1).

(1) For magnetic induction of 2 t, an electricity price of 0.05 S/kWh, a capacity factor 50%, levelling factor 1.20. and a fixed load factor of 26.6%.

(2) Superconductor operating at 4 K.

(3) High-temperature superconducting ceramic (HTC) operating at 77 K.

From the operating standpoint, two criteria must be considered:

- power consumption: this is approximately zero compared with a copper winding,
- cooling cost.

If a cryogenic fluid is used, the cost to the user is the price per liter of the cryogenic fluid delivered to his plant. These prices depend on many parameters (geographic location, quantity, recovery, in situ liquefaction) and, depending on the cooling system, can be estimated between 20 and 50 FF/liter of liquid helium. Depending on the cryostatic techniques used, consumption could vary from 0.05 to 5 l/h. In the worst case, the annual operating budget corresponds to the cost of associated self-contained cooling (= I.7x10^{6}FF). The extra investment cost in this case is offset by the lower operating costs.

Nevertheless, at the present time, the use of a cryogenic environment demands techniques that are fully controlled, and their cost and Performance could be significantly improved by a series effect. Economic studies conducted so far tend to imply that a superconducting separator outclasses a conventional separator above 1200 h of operation for a field higher than 400 kA/m. Moreover, in some specific treatment cases, the extra value obtained on the finished product can also offset the increase (investment and operation) caused by the use of this technology.

4 THE USE OF MAGNETIC SEPARATION TO PURIFY A FLUID LOADED WITH METALS

The performance offered by high-field/high-gradient magnetic separation in the mining field has led to the application of this process to the purification of industrial waste, particularly in the area of surface treatment.

In connection with the purification of urban or industrial liquid effluents, magnetic filtration considerably shortens the time required for sludge/liquid separation. For fluids containing dissolved metals, purification includes a metals insolubilization phase. This applies to process waters from surface treatment facilities which represent a large volume, and where the metallic ion concentrations are too high for direct discharge into the natural environment, but not high enough to make the precipitation and dehydration of the metallic hydroxides economically feasible.

In the precipitation phase, the addition of an iron salt as an inorganic coagulant lowers the residual contents in the effluent. If the composition of this iron salt is carefully selected, the hydrated iron oxide which coprecipitates with the metals plays the role of a magnetic carrier, and the fluid can be

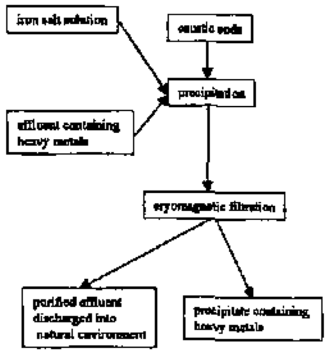

Fig 9: Treatment of surface treatment effluent

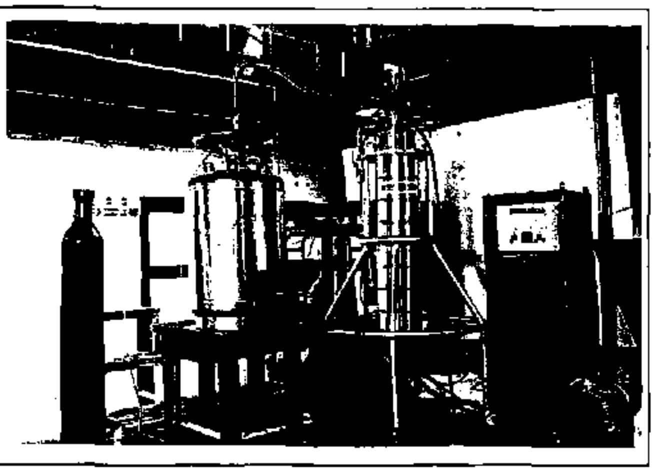

Fig 10: GEC/Alsthom superconducting separator

treated directly in a cryomagnetic filter, without a need for a sludge sedimentation and settling stage.

The preparation of the polluted effluent with a mixed solution of ferrous and ferric salts allows the precipitation at ambient temperature of a 'crystallized' phase approaching a magnetite structure (Figure 9). A cryomagnetic separator purify the effluent thus treated (Figure 10).

Magnetic filtration helps to trap these precipitates in a 'compact filter' matrix type while the totally purified effluent can be discharged into the natural environment. Once the matrix is saturated, it must be cleaned to resume the purification cycle. Unlike the mineral industry, this operation cannot be performed by rinsing with pressurized water and interruption of the magnetic field.

In purifying fluids loaded with metals, this step is performed under a field by circulation of an acid solution in the canister, which solubilizes the floes and detaches diem when they lose their magnetic properties. The metallic ions go into solution in the rinsing phase, which is enriched commensurately with heavy metals.

This solution, which takes place without cutting the magnetic field, offers a threefold advantage:

- smaller sludge volumes,
- lower operating costs of the separator (energy cost, helium consumption),
- possibility of metals recovery by electrolysis or electrochemical methods.

Table 4 gives an example of the purification of the washing badis of a surface treatment facility, and of used catalyst containing vanadium.

Table 4: Cryomagnetic purification of industrial baths

melal present in effluent	concentration before treatment <mg/l>	concentration after treatment (mg/l)	% purification
Cu	21.3	0.04	99.8
Zn	18.6	0.05	99.8
V	38.6	2.0	100.0

4 CONCLUSIONS

While magnetic separation has remained confined to the mining field for nearly two centuries, it has gradually occupied a significant place in the last fifteen years, in a number of industrial sectors. It is found in its simplest technological form In nearly all types of industry (food, pulp and paper, steel, chemicals) to deal with problems of equipment protection, regeneration and purification of various materials.

The new high-gradient and/or high-intensity separators can not only purify useful mineral substances like kaolin clay, talc, glass and ceramics, but also operate in the environmental field in treating urban and industrial waste water, waste from conventional thermal and nuclear power plants, coal dust from blast furnaces etc.

Magnetic separation thus contributes effectively to solving pollution problems which are omnipresent in the industrial world today.

For ore upgrading, advances in magnetic separation make it competitive İn terms of performance and operating costs with the physical processes normally used (floatation or gravity) and it supplants these processes in a number of cases.

Although, in some fields, such as medicine and chemistry, the applications of magnetic separation have so far only been investigated in the laboratory, the research and progress achieved, particularly in superconductivity, tend to imply that magnetic separation has a brilliant future before it.

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