MAGNETIC SEPARATION

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1. Introduction:

Magnetic separation employs the difference in magnetic properties of minerals to effect separation between them. The magnetic separation may be for removing ore particles which are magnetic or conversely to remove magnetic impurities from a product which is non-magnetic. Examples are Magnetite from Quartz or Magnetite and Wolframite from Cassiterite.

All materials are affected in some way when placed in a magnetic field, although with most substances the effect is too slight to be detected. Materials can be classified into two broad groups, according to whether they are attracted or repelled by a magnet.

Diamagnetics are repelled along the lines of magnetic force to a point where the field intensity is smaller. The forces involved here are very small and diamagnetic substances cannot be concentrated magnetically.

Paramagnetics are attracted along the lines of magnetic force to points of greater field intensity. Paramagnetic materials can be concentrated in high-intensity magnetic separators. Examples of paramagnetics which are separated in commercial magnetic separators are ilmenite ($FeTiO_3$), rutile (TiO_2), wolframite ($(Fe,Mn)WO_4$), monazite (rare earth phosphate), siderite ($FeCO_3$), pyrrhotite (FeS), chromite ($FeCr_2O_4$), hematite (Fe_2O_3), and manganese minerals.

Some elements are themselves paramagnetic, such as Ni, Co, Mn, Cr, Ce, Ti, O, and the Pt group metals, but in most cases the paramagnetic properties of minerals are due to the presence of iron in some ferromagnetic form.

Ferromagnetism can be regarded as a special case of paramagnetism, involving very high forces. Ferromagnetic materials have very high susceptibility to magnetic forces and retain some magnetism when removed from the field (remanence). They can be concentrated in low-intensity magnetic separators and the principal ferromagnetic mineral separated is magnetite (Fe_3O_4), although hematite (Fe_2O_3) and siderite ($FeCO_3$) can be roasted to produce magnetite and hence give good separation. The removal of "tramp" iron from ores can also be regarded as a form of low-intensity magnetic separation.

The unit of measurement of magnetic flux density or magnetic induction (the number of lines of force passing through unit area of material) is the tesla. Despite the fact that the c.g.s. system is now obsolete, the unit most commonly used is the gauss (G), which is 10^{-4} tesla, and it would appear that for many years to come a knowledge of the "electromagnetic c.g.s." unit (e.m.u.) system will be a necessity for workers in magnetism.

The magnetising force which induces the lines of force through a material is called the field intensity, and by convention has the units oersted in the e.m.u. system (ampere $metre^{-1}$ in SI units), although one oersted is numerically equal to one gauss. When dealing with magnetic fields in air, the value of the field intensity is virtually the same as that of flux density, and the term magnetic field intensity is then often loosely used. On the other hand, when dealing with the magnetic field inside materials, particularly ferromagnetics that concentrate the lines of force, then the value of the induced flux density will be much higher than the field intensity, and it must be clearly specified which term is being referred to. A Table giving the magnetic properties of some common minerals is given in Table-1. This indicates the induction range required for separation of these minerals.[5]

The capacity of a magnet to lift a particular mineral is dependent not only on the value of the field intensity, but also on the field gradient, i.e. the rate at which the field intensity increases towards the magnet surface.

It can be shown that

$$F \propto H \times \frac{dH}{dl}$$

Where F is the force on the particle, H is the field intensity, and dH/dl is the field gradient.

Thus in order to generate a given lifting force, there are an infinite number of combinations of field and gradient which will give the same effect. Production of a high field gradient as well as high intensity is therefore an important aspect of separator design.

2. Magnetic Separators

2.1 Design Principles:

In the design of any type of magnetic separators, therefore besides a field a gradient in the field strength has to be provided to enhance movement of particles in the desired directions. In a field of uniform magnetic flux magnetic particles will converge the flux and orient themselves so that there is a concentrat~~e~~ion of flux in its body but it will not move. On the other hand, by producing a converging field a resulting pull on the particles towards the higher flux area (Fig. 1.). The simplest method of producing a converging field is by reducing the pole area of one pole in a magnet or a V shaped pole over a flat pole. The small area of one pole concentrates the magnetic flux into a very small area giving high intensity. The corresponding pole with a larger area has same total magnetic flux distributed over a larger area. Thus there is a steep field gradient across the gap due to the different intensity levels.

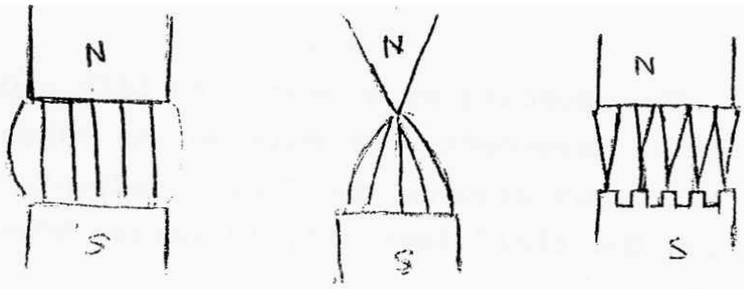

Fig.1. Convergence of magnetic flux due to inequal pole pairs.

Besides the inhomogenity created by the geometry of the pole shape and size design, arrangements are provided to alter the intensity by varying the pole gap or by varying the current in coils of electromagnetic separators, the latter usually being the operating variable.

Commercial magnetic separators are continuous-process machines and operation is carried out on a moving stream of particles passing into and through the magnetic field. Close control of the speed of passage of the particles through the field is essential, which rules out free fall as a means of feeding. Belts or drums are very often used to transport the feed through the field.

The introduction into a magnetic field of particles which are highly susceptible concentrates the lines of force so that they pass through them.

Since the lines of force converge to the particles, a high field gradient is produced which causes the particles themselves to behave as magnets, thus attracting each other. Flocculation, or agglomeration, of the particles can occur if they are small and highly susceptible and if the field is intense. This has great importance as these magnetic "flocs" can entrain gangue and can bridge the gaps between magnet poles, reducing the efficiency of separation. Flocculation is especially serious with dry separating machines operating on fine material. If the ore can be fed through the field in a monolayer, the effect is much less serious, but, of course, the capacity of the machine is drastically reduced. Flocculation is often minimised by passing the material through consecutive magnetic fields, which are usually arranged with successive reversal of the polarity. This causes the particle to turn through 180°, each reversal tending to free the entrained gangue particles. The main disadvantage of this method is that flux tends to leak from pole to pole, reducing the effective field intensity.

Provision for collection of the magnetic and non-magnetic fractions must be incorporated into the design of the separator. Rather than allow the magnetics to contact the pole-pieces, which would cause problems of detachment, most separators are designed so that the magnetics are attracted to the pole-pieces, but come into contact with some form of conveying device, which carries them out of the influence of the field, into a bin or belt. Non-magnetic disposal presents no problems, free fall from a conveyor into a bin often being used. Middlings are readily produced by using a more intense field after the removal of the highly magnetic fraction.

3.0 Magnetic Separators:

Though the commercial magnetic separators are seen in many forms and names, a broad grouping can be made for these as below :

a) Low Intensity
b) High Intensity

both could be either wet or dry operation type. Among these, depending upon function it could be subdivided into :

1) Guard magnet to remove tramp iron etc.
2) To remove magnetics of value
3) To remove deleterious impurities.

The magnetic field may be generated by one of the several ways as 1) permanent magnet, 2) Electromagnet with iron yoke, 3) Solenoid and 4) Superconducting magnet. After some stagnation, recently there has been new spurt in the magnetic separation machine design and manufacture - notable among which are the Wet high intensity magnetic separation(WHIMS) and high gradient high intensity separation (HGMS), Rare Earth magnet permanent magnet separators(Permaroll). Last to join the system is superconducting magnets developments on which are now in just beginning. A current trend in the design of magnetic separators is towards higher capacities per unit so as to obtain lower capital and operating cost per tonne of material treated. Two other parameters for evaluating magnetic separators are the energy consumption per tonne of material treated and the mass per tonne of a machine.

3.(1) DRUM Separator:

Dry Drum magnetic separators are most common - low intensity units in operation used for separation of strongly magnetic particles. The unit consists of a rotating non-magnetic drum containing a number of stationary magnets of alternate polarity, of electromagnets, which are now mostly made with permanent magnets. (Fig. 2a-d).The material to be separated is fed at the top of the rotating drum surface, the non-magnetic fraction leaves the drum by centrifugal throw while the magnetic fraction is retained on the surface and is dropped outside the magnetic field, and are thus deflected. A splitter makes a suitable cut. Usually besides the magnetic and non-magnetic fraction, an intermediate product is sometimes obtained depending on the material characteristics and interlocking and are called middlings. Commercially available drum separators have a wide range of diameters from 300 - 1500 mm and length from 300 to 4000 mm. Coarsely crushed material as large as 8 mm dia can be treated economically at feed rates over 150 T/h per metre of length. Typical radial magnetic induction values for current drum separators are of the order of 500 to 1500 gauss (0.05 - to 0.15 T). Single or multiple units in cascade have been built.

3.2. Wet drum Separators:

Magnetic separators most commonly in use are wet drum low intensity type used in concentration of magnetite ores, and can be of concurrent and countercurrent design. The drum construction is similar to dry drum separator, having a number of electromagnets with 6-8 poles inside a non-magnetic rotating shell with location inside a tank having arrangement for feed and discharge of products as shown in Fig.3 a,b,c. Material is fed in the submerged tank in a slurry form which passes across the face of the drum, when the magnetics are picked up by the rotating drum and discharged in a separate chute. Water spray is usually provided to facilitate discharge at places where no field exists. The feed in these machines are usually ground to below 1 mm rarely exceeding 3 mm for handling and blockage in the discharge orifice.

The tank design varies in the manner of presentation of feed and discharge of products. On the basis of pulp flow, the units are termed (i) Concurrent, (ii) Countercurrent and (iii) Counter rotation. The pulp as a slurry is fed as shown (Figs. 3 a,b,c) and a level is maintained in the tank by adjustable weir pieces and tailing discharge orifices so that about 10-20% of total tailings volume overflows. The Counter rotation drums are usually used in roughing, where maximum recovery is effected, while the concurrent units may be used in roughing or cleaning operations and the countercurrent ones for finishing separators.

The Crockett low intensity separator is an early model where the magnet tank is submerged in a tank over which a belt runs between two drive pulleys (Fig. 3e). The magnetics are drawn up against the belt and are carried out to the concentrate discharge. In both drum and belt separators, the magnet poles are alternate so that the picked up magnetic particles rotate to drop out the entrained gangue particles due to bridging.

3.3 Design of the drum :

The separating drum consists of two main parts: a stationary magnetic circuit and a shell, made of non-magnetic material, which freely rotates round the magnets. The capacity of such a separator is determined by the magnetic induction on the surface of the drum, by the gradient of the magnetic field in the pulp and by the size of the drum.

Nowadays, design of the drum is closely associated with the development of the permanent magnets used to generate the magnetic field. With barium ferrite permanent magnets, of the energy product of 20 - 22 kj m^{-3}(2.6 - 2.8 MGOe) the thickness of the wall of the drum can be a maximum of 2.0 - 2.5 mm . Therefore, the length of the drum is limited to about 1500 mm. With the increased quality of the barium ferrite with the energy product of 2.8 - 3.2 MGOe (22 - 25 kj m^{-3}) the wall thickness could have been increased to 3.0 - 3.5 mm, and therefore, the diameter and the length of the drum could have been increased to 900 and 3000 mm, respectively.

By combining the strontium and barium ferrites, the wall thickness can be increased to 4 - 5 mm and drum diameter and length to 1500 mm and 4000 mm, respectively.

The capacity of the three types of drum magnetic separators discussed above, depending on drum diameter, is shown in Fig. 3f. and Table 2 .

Table 2. Capacity of drum magnetic separators

Drum diameter	Concurrent drum	Counter rotation drum	Counter current drum
(mm)	Capacity (t/m h)	Capacity (1/m h)	Capacity (t/m h)
600	35	40	-
900	50	60	20
1200		85	30
1500		100	35

The development of new, permanent-magnet materials has increased the magnetic induction available on the drum surface and inside the separation tank. For instance, the earlier system generated 0.16 T on the drum surface and 0.06 T at 40 mm from the drum surface, while new magnetic circuits create 0.22 T on the surface and 0.09 T at 40 mm.

The improvement in parameters of the magnetic circuit and in the design of the separation tanks produced an increase in :

1) the diameter and length of the drum and therefore, the capacity of the machine
2) the gradient of the magnetic field and thus an increase in the efficiency of recovery of fine ferromagnetic particles
3) the depth of the magnetic field and easier recovery of larger grains.

4.0 High Intensity Magnetic Separators :

Weakly magnetic materials can only be removed from an ore feed in magnetic fields much greater than those available in low intensity magnetic separators. Dry high-intensity magnetic separation has been used commercially since the beginning of the century, while wet, high-intensity and high-gradient magnetic separators were developed only recently.

Three types of dry high-intensity magnetic separators are in common use, viz;

(1) the cross-belt type
(2) the induced magnetic roll type
(3) the permanent magnetic roll type.

4.1 Cross-belt magnetic separator

This is one of the oldest types of separator used to concentrate moderately magnetic ores (Fig. 3 a).

Dry material is fed in a monolayer onto the conveyor belt and is carried between the poles of the magnetic system. The belt, with its load, passes between the poles of two or more electromagnets. The lower pole-pieces are flat and immovable, but the corresponding upper pole-pieces are shaped and may be raised or lowered as required for the material undergoing treatment. An endless cross-belt runs around a series of pulleys and across each upper pole-face surface at right angles to the conveyor belt. As the material passes, the magnetic particles are attracted to the cross-belt, are carried with it towards the discharge side and fall into a suitably placed bin. The material may be passed successively between several pairs of magnet poles when it is desired to make several products in one pass. A non-magnetic tailing discharges as the conveyor belt passes over its end pulley. Machines with two to eight pairs of poles are available, and each pair can be adjusted independently by regulating the position of the upper poles and by altering the current through the coils. The height of the upper pole-pieces above the belt should be set at least 2.5 times the size of the largest particle in the feed. The conveyor belt width ranges from 100 to 600 mm, the distance between the conveyor belt surface and the upper belt surface being from 3 to 25 mm, depending on the size and magnetic properties of the feed. Particles ranging from 4 mm to 75 um may be treated successfully, but they should preferably be sized into several fractions.

The main advantage of the cross-belt separator is that several types of magnetic products can be recovered in one pass at increasing magnetic field strength while several separate passes are needed in other dry magnetic separators. Since the electromagnets are independently adjustable the selective removal of different magnetic minerals is possible. Low-intensity magnet can be installed to scalp off any ferromagnetic particles present. For estimating magnetics in a sample, a standard laboratory test unit is the Davies Tube Tester (Fig. 3 b).

4.2 Induced magnetic roll separator :

The induced magnetic roll (IMR) separator consists of a revolving laminated roll formed of alternate magnetizable and non-magnetic discs. The roll is placed between specially shaped poles (Fig. 4)of an electromagnet. The electromagnet induces a magnetic field in the magnetic laminations of a roll forming local regions of high magnetic field gradients as shown in Fig. 1

Material to be treated is fed in a controlled thin stream by a vibratory feeder to the top of the roll. As the roll revolves, the material passes through a narrow gap between the pole of the magnet and the roll and the non-magnetic particles are discharged from the roll. The magnetic particles are attracted to the roll, and discharged into a separate chute when they enter a non-magnetic region. Ferromagnetic material can be removed with a separate magnetic scalper before feeding to IMR, to prevent plugging the gap.

The gap between the feed pole and roll is adjustable and also the setting of the splitter is of great importance. The typical values of magnetic induction on the surface of a laboratory IMR as a function of the gap width.

It is a general practice to ensure that each successive roll is of greater magnetic induction than the preceding roll. This is achieved by adjusting the poles so that a smaller gap between the pole and the roll is produced on each successive roll.

Because of variations in the character and size of the materials it is difficult to express capacity in terms of mass. However, in most applications capacity ranges from 2 to 3 t h^{-1} per metre of roll length. Material to be treated must be dry, free-flowing and for best results should be within the size range of 2 mm to 100 um. The gap should be adjusted in such a way that it is approximately equal to 2.5 times the average grain size.

Induced magnetic roll separators are marketed by several manufacturers, e.g. Carpco, Eriez and Reading. The maximum length of the roll is 0.75 m, except for the Carpco separator which is 1 m in length. This separator uses hollow rolls which reduce the eddy currents during rotation, (most other IMR use solid rolls). Fig. 4c shows a 3-roll IMR.

Although the recovery of ilmenite from beach sands is the biggest application, IMR separators have been successfully applied in numerous other branches of minerals treatment, viz. the production of high-quality (i.e. low-iron) materials for the glass and ceramics industry. They often constitute the final finishing part in the flowsheet, and the removal of magnetic impurities from andalusite, feldspar, wollastonite and other minerals is well proven.

IMRs are also used for concentration of the industrial minerals (chromite, iron ores, monazite, wolframite etc.).

There are two principal technical limitations for IMRs, namely: relatively low capacity per unit and limited particle size range. The limitations are related to the maximum allowable air-gap and to the need to feed a thin stream of particles. To permit unobstructed flow through the separator it is desirable to increase the air gap for larger material flow and for increasing particle size. It should be noted, however, that increasing the air-gap means reducing the magnetic field, thereby limiting the thickness of the material layer fed onto the roll, and reducing the capacity.

4.3 Permanent Magnetic roll separator :

The most recent development in the field of permanent magnet separators, conducted by E.L. Bateman Ltd., resulted in the design and manufacture of the Permroll separator. The active part of this separator is a roll consisting of disks of Sm-Co, or Nb-Fe-B permanent magnets interleaved with mild steel disks. The most favourable ratio of the widths of the magnet and of the steel is 4 : 1. Mild steel gives the most satisfactory results and special steels usually do not improve the performance of the separator. The magnet in this configuration generates magnetic induction upto 1.6 T on the surface of the roll and field gradients of the order of 300 $T\,m^{-1}$. For an easy removal of magnetic particles the roll is covered by a thin belt supported by a second (idler) roll, as shown schematically in Fig. 4 e Below the conveyor is a hopper which collects the discharging material while adjustable splitters divert the different fractions into collection pans placed beneath the hopper.

4.4 Submerged roll permanent magnetic separator :

The need for a wet separation for diamond recovery led to the development of a Sm-Co permanent magnet submerged roll separator. (Fig. 4f) The feed is discharged as a thin film by the feed launder over the belt travelling over the magnetic drum. The drum is partially submerged in water where the magnetics cling to the belt and are transported to the magnetic collection chamber discharged by separating belt.

4.5 Ferrous Wheel Separator :

In this unit a magnetic matrix contained in a vertical rotating ring which passes over permanent magnets at the feed point below and at washing point higher up.

Magnetic particles in feed entering below are trapped in the matrix and come out, discharging at the top where no magnetic feed exist. The advantage is that it combines some capability of high gradient matrix separator, where not too large field is needed but the power consumption is low for drive only.

5.1 Wet High Intensity High-Gradient Magnetic Separators :

Several factors and limitations in dry magnetic separation has led to the development of wet high intensity and high gradient magnetic separators; among them are -

(1) Need to dry materials, which are commonly wet ground;
(2) Sizing requirement and feeding in monolayers;
(3) Limits of separation at very fine sizes;
(4) Dust pollution;
(5) Need for a sufficiently high field.

Jones in 1955 developed the first unit using the Frantz's matrix which was the starting point on a series of developments basically depending on generation of high gradient in a matrix placed in magnetic field. A simple type is shown in Fig. 5 (a) where expanded metal magnetic elements are packed in a container between the pole pieces of a electromagnet. Material is fed at the top, when the magnetics are trapped and nonmagnetics flush out along with the slurry flow. The magnetics are taken out by switching off the current and flushing again. A continuous version of the same unit is shown in Fig.(5c). Here the magnetic elements are housed in an annular carousel (rotor) running between the poles of an electromagnet. The feed enters the point between the magnet poles, where the non-magnetics flow out. The trapped magnetics move along with the rotating matrix and are flushed out outside the magnet poles at a point of minimum field. The intermediate magnetic products discharge between this and the tails port. The products are collected by annular launders, with splitters placed suitably.

A number of units are offered, basically working on the same principles. The only difference being in the manner of magnetic matrix material, generation and configuration of magnetic field, rotor arrangements etc. (Fig. 6,7). The units may have one, two, four or larger number of poles and stacked multiples of rotors to effect roughing-scavenging -cleaning operations as desired. The matrix may be of groved plates, punched sheets, steel balls, steel wool etc. The free gap should be 2-3 times the largest particles in the pulp. The magnetising current may be varied and manufacturers usually provide magnetic induction charts depending on pole/matrix configurations used. (Fig.8).

The units have large capacity usually of the order of 1-5 tonnes/H for laboratory/Pilot models to over 100/150 tonnes/H for large models. Most wide applications have been found for Jones magnetic separators, manufactured by Humboldt Wedag Ag, mainly for iron ores.

Other units available are (a) Carpco high gradient magnetic separator, (b) Eriez high-gradient magnetic separators, (c) Boxmag-Rapid magnetic separators. A new design where the carousel rotates between vertical pole process is designed by Ore Research Institute, Prague called MRVK unit. The matrix is made up of rods. Capacity of these units are given in Fig.9.

5.2 Solenoid Magnetic Separator:

Frantz ferrofilter was the first ironclad solenoid magnetic separator. The matrix consists essentially of screens fashioned from thin sharp ribbons of magnetic stainless steel. It works in cycles, with magnetic trapped material is backwashed, used for Kaolin industry, for magnetic contaminant removal from industrial slurry, wastes.

5.3 Cyclic high-gradient Magnetic Separator:

The first industrial high-gradient magnetic separator which grew from Frantz's concept and from an investigation into the removal of weakly magnetic discolouring agents from clays was designed and built by Magnetic Engineering Associates (now Sala Magnetics) in 1969. Fig.10a shows schematically the essential elements of such a separator. The system comprises a canister filled with a matrix formed of compressed mats of magnetic stainless steel wool. The canister is placed in an iron-clad solenoid which generates a magnetic induction of upto 2 T. The thin fibres of the matrix create a high degree of the non-homogenity of the magnetic field and produce a large magnetic force acting on the magnetizable particles.

The slurry is pumped vertically upwards through the matrix with the magnetic field switched on. The magnetic particles from the slurry are trapped onto the surface of the magnetized fibres, while non-magnetic particles pass through the canister. When the matrix has become loaded with magnetic particles the flow is halted, the magnetic field is reduced to zero and the magnetic fraction flushed from the matrix.

Such cyclic devices are very useful in applications where a pulp to be processed contains a small fraction of magnetic particles, preferably very fine so that their mechanical capture by straining is avoided, and very weakly magnetic so that the blockage of the matrix by magnetic flocs is avoided and low flowrates can be used. In the opposite case the duty cycle of such a cyclic machine would be very low and the filamentary matrix would be susceptible to clogging as a consequence of the straining mechanism. These machines found a wide-spread application in the kaolin industry and in waste water treatment.

5.4 Continuous Solenoid magnetic separators:

These include the first unit development Sala-HGMS Carousel separator which has been improved further and multipole machines have been built. In these machine the coil is a saddle type covering the matrix, which minimises stray field as no iron core is used. They are also less heavy for the same reason. The induction claim is upto 2 T with 250 KW per head and capacities upto 200 T.

The SOL magnetic separator developed by Krupp GmbH having axial solenoid that generates a magnetic field in the direction of motion of the carousel. It has comparatively low mass and give less strain on the rotating system.

The VMS separator developed by Ore Research Institute in Prague has the magnetic field generated by horizontally oriented solenoid wound with a watercooled hollow copper conductors and a vertical rotor to carry the matrix material.

6.0 Super Conducting Magnetic Separators :

Although high-gradient magnetic separators that use the resistive magnets meet the technological requirements of the mining industry, their cost-effectiveness is impaired by high energy consumption and by considerable mass owing to massive iron yokes or cladding. These disadvantages however can be overcome by using superconducting magnets which offer a number of advantages.

a) Superconducting magnets can produce high magnetic induction in large volume at low energy consumption. If operated in persistent mode, they consume no energy at all, while in non-persistent mode they consume only a small amount of energy as a consequence of energy dissipation in the resistive leads that supply the electric current. A factor of five to ten in power reduction is easily possible for a superconducting machine, compared with a conventional machine of the same processing capacity. The power is required mainly for liquifaction of helium rather than for ohmic losses in the coil of the magnet.

b) Since iron cladding is not needed the machine can be made physically smaller.

c) The superconducting coils can be arranged in such a way that a sufficiently large field gradient can be generated without using a matrix,while still maintaining high magnetic induction outside the magnet.

Although the advantages of superconducting magnets seem to be convincing, a number of problems still hamper a genuine large-scale application of superconductivity in mineral processing, viz:

1) The actual saving of energy is not as high as was assumed, due to the energy needed for cooling.

2) The method of cooling has not yet been proved: refrigeration is still unreliable, even under laboratory conditions, and direct cooling by liquid helium, though reliable, is expensive and complicated, since the helium vapours must be recovered if the process is to be economically viable.

3) Since a magnetic separator is usually a small part of a complex flowsheet, any saving in energy can be easily offset by increased unreliability and unexpected expenses caused by forced shut-downs.

4) The need for magnetic induction greater than 2 T has never been convincingly demonstrated in matrix separators, and it seems improbable that, except for some isolated applications induction greater than 2 T will be required. It is claimed that by enhancing magnetic induction

to well over 2 T it would be possible to increase the flow velocity v_o at the same rate (and thereby the production rate) by keeping B/v_o constant. Although this outcome of a simple theoretical model has been supported by isolated experiments, it is doubtful whether this rule would be generally valid, even in those applications in which non-magnetic fraction is the valuable product, and it is certainly not true for those applications in which a magnetic fraction is the useful product.

Table Comparison of resistive and superconducting magnets for magnetic separators.

	Resistive solenoid magnet	Superconducting magnet
Energy consumption	High	Low
Magnetic induction	Limited by the avail-able cooling, usually upto 2 T	Upto 15 T
Mass	High	Low
Conductor	Hollow copper conductor	Superconductor (Nb-Ti)
Cooling	Direct water cooling	To 4 K(liquid helium)
Iron return frame	Important for short coils	Not required
Reliability of operation	High	Low to modest
<u>Capital costs</u>		
Magnet	High	High
Power supply	High	Low
Cooling	Low to medium	High
<u>Running costs</u>	High	Low to medium
Cyclic matrix separator	Well proven	In operation
Continuous matrix separator	Well proven	Not designed, yet
Open-gradient separator	Not suitable	Two types a) drum separator b) split-pair separator

Although superconducting magnetic separators have been built in various laboratories, and large-scale cyclic HGMS and reciprocating canister HGMS machines are in operation, superconductivity has made no considerable impact on mineral processing as yet.

Classification of magnetic separation process and its selection basis as given by J.Svoboda is given in Figs. 11 & 12. A few typical examples of magnetic separation application flowsheets are quoted in Figs. 15 & 16. Comparison of different types of magnetic separators for a specific application in phosphate recovery is given in Fig.17.

For a good study coverage on the developments in Magnetic Separators including Superconducting magnetic separators, excellent reference is available in the book entitled, 'Magnetic Methods for the Treatment of Minerals' by J. Svoboda published by Elsevier,Amsterdam in 1987 in the series 'Developments in Mineral Processing', from where many materials for the present write-up has been drawn.

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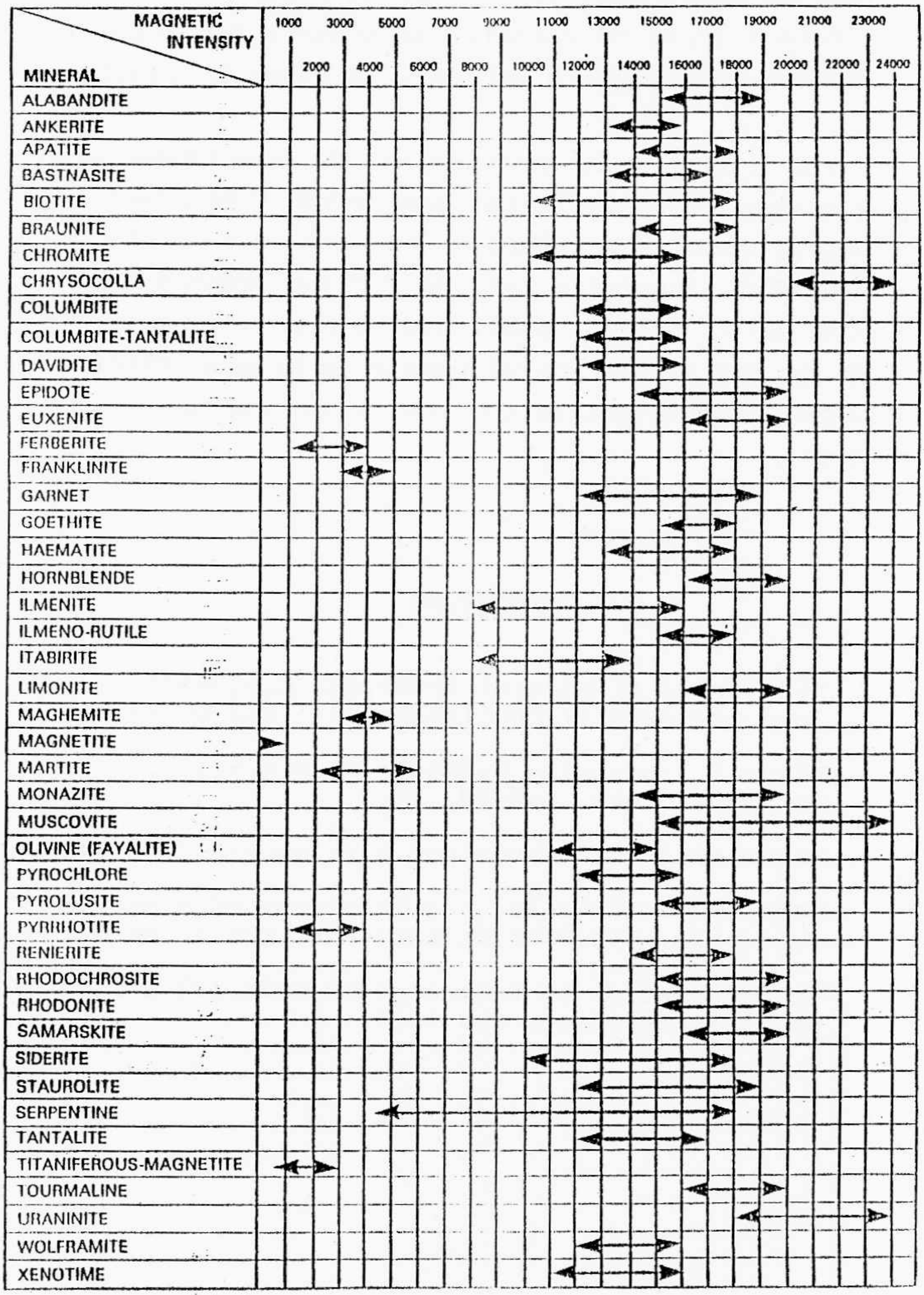
PARAMAGNETIC MINERALS

Table 1—Magnetic Induction in Gauss Required to Extract Discrete Minerals



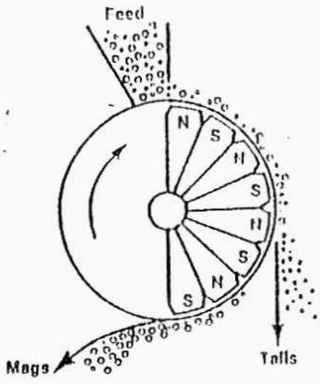


Fig. 2a Dry drum separator.

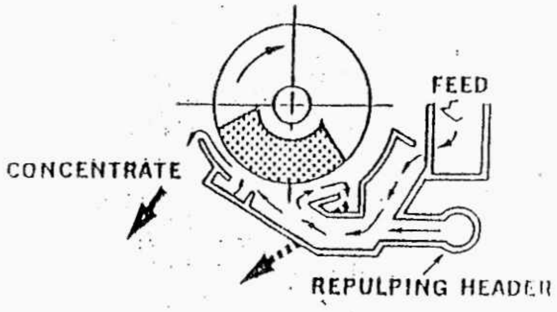


Fig 2b
The counter-current or Steffenson tank

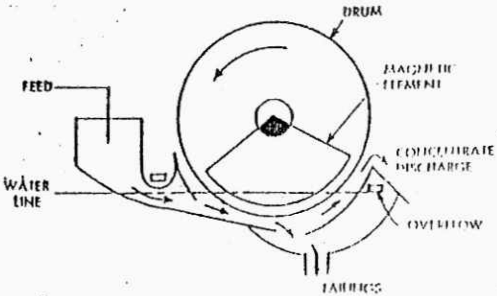


Fig 2c
CONCURRENT

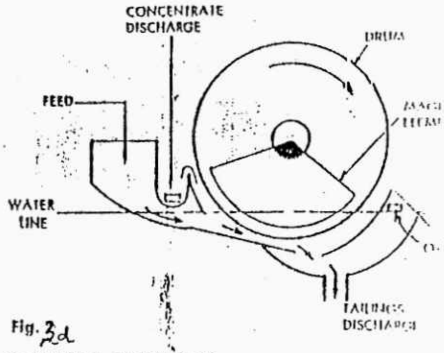


Fig. 2d
COUNTER-ROTATION

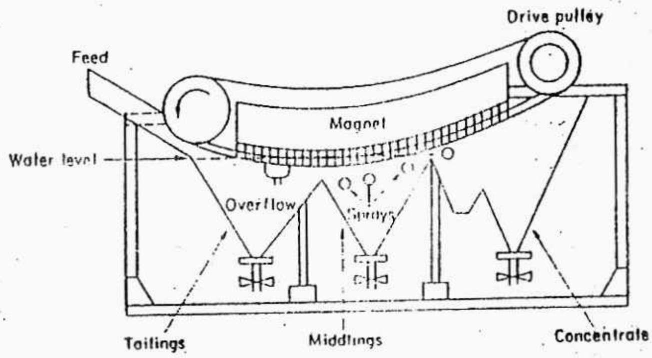
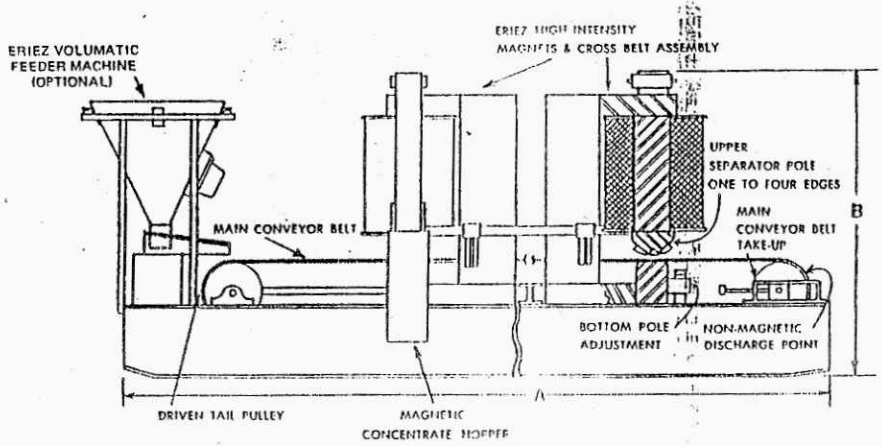


FIG. 2e Crockett low-intensity magnetic separator.

Fig. 2. Low Intensity Magnetic Separator.
(a) Dry drum type; (b) Counter-current; (c) Concurrent and (d) Counter-rotation type wet drum separator; (e) submerged belt separator.



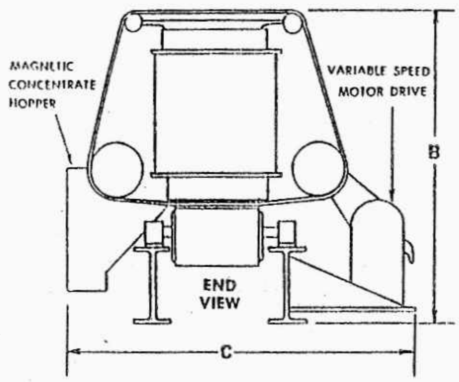


Fig. 3 (a) Laboratory cross-belt type separator Dry high intensity

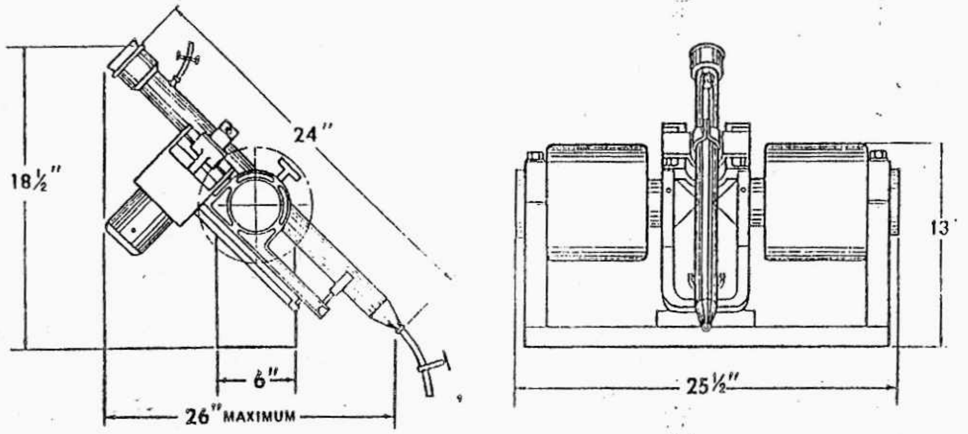
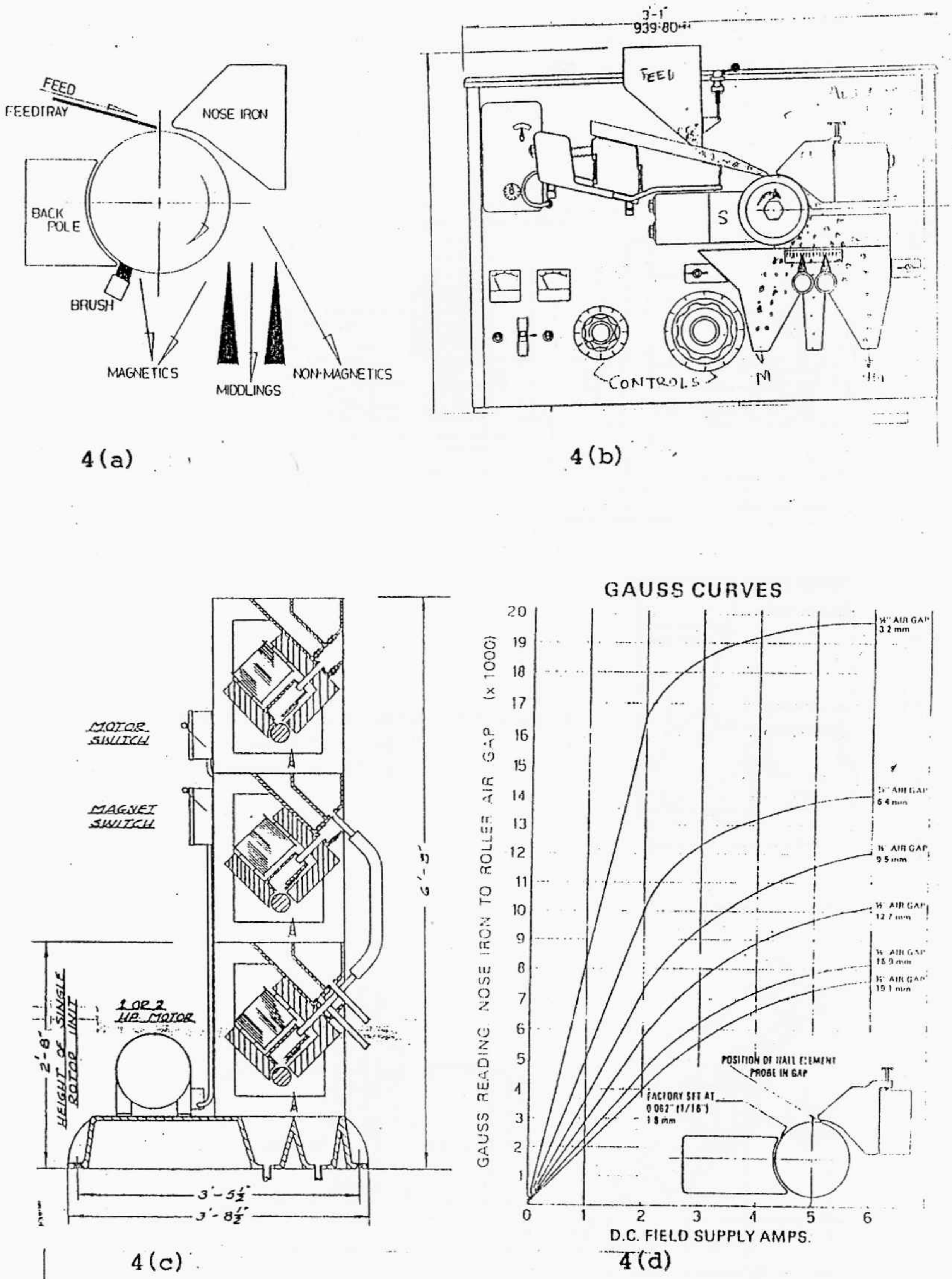


Fig. 3 b. Laboratory Davies Tube tester.



4(a) 4(b)

4(c) 4(d)

Fig. 4. Induced roll magnetic separator.
(a) operating principle; (b) Lab model;
(c) Pilot Plant 3 high unit
(d) Typical induction curve.

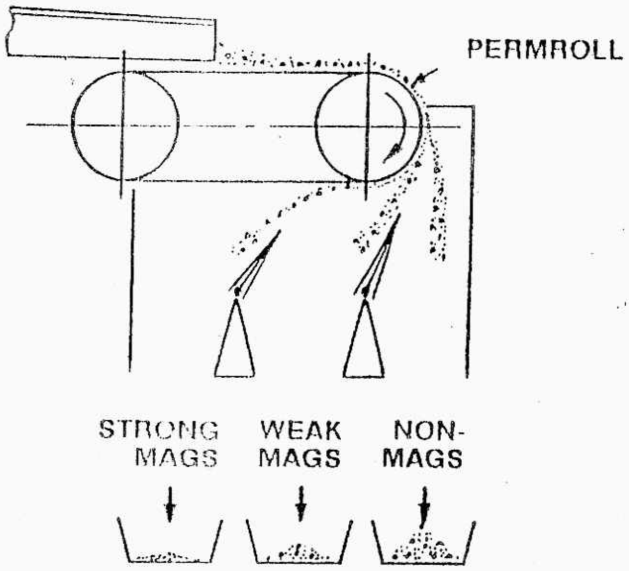


Fig. 4 e Operation of Permroll magnetic separator (courtesy of Ore Sorters Ltd.)

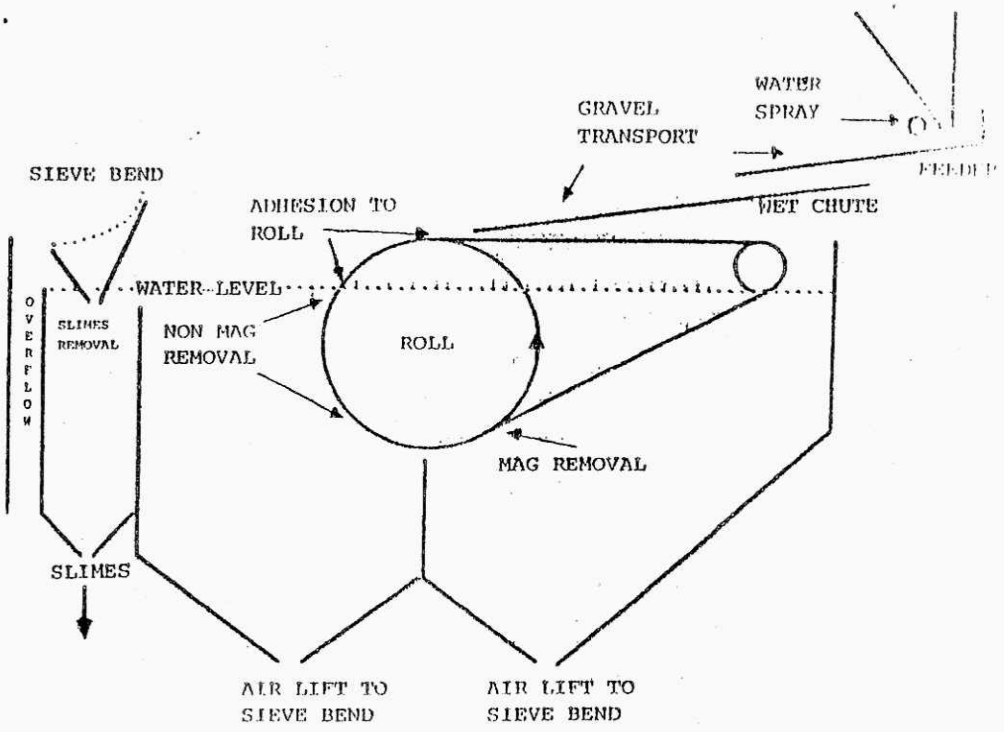


Fig. 4 f The schematic diagram of a wet submerged roll permanent magnetic separator (after Hyland [H33]).

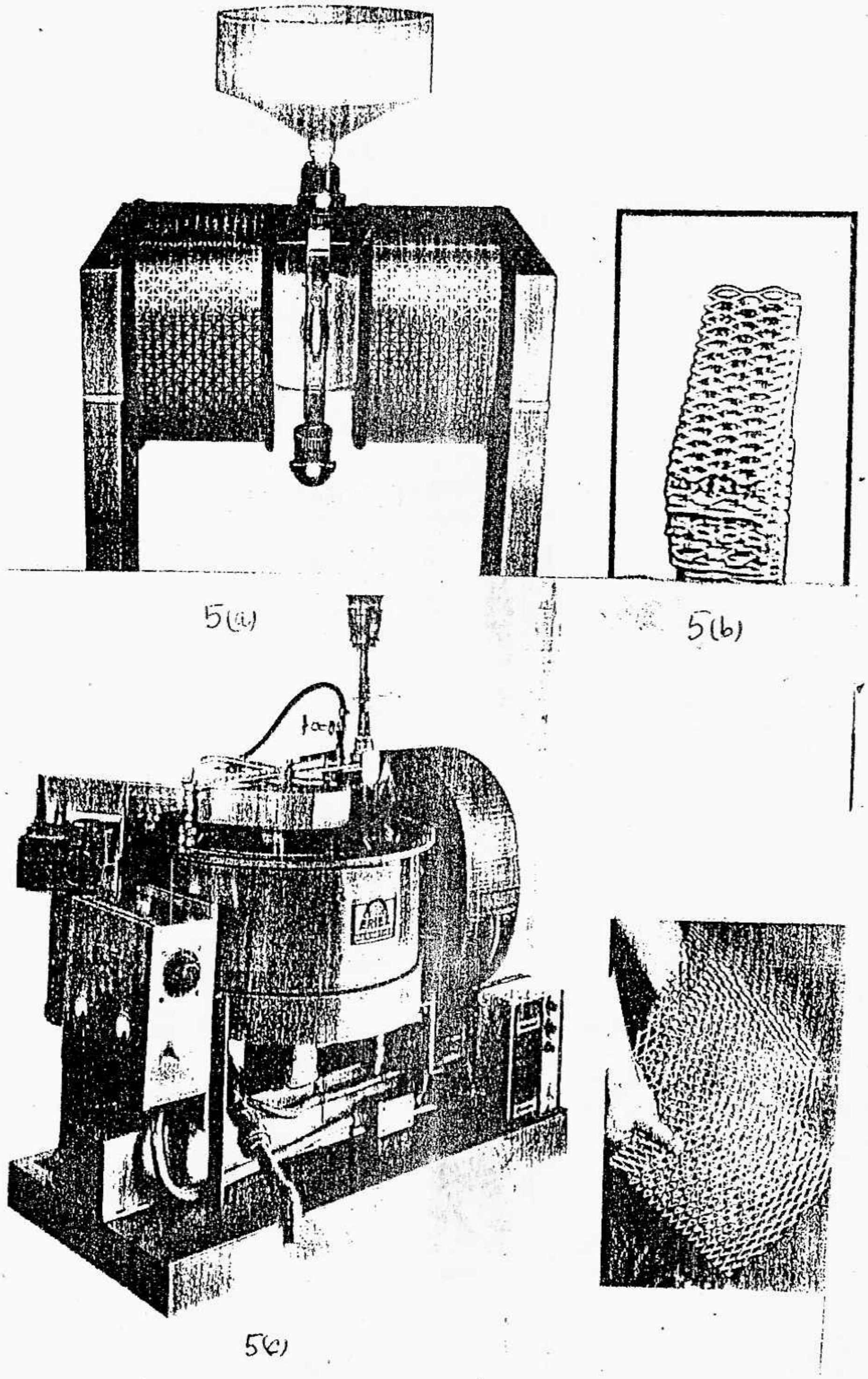


Fig.5. Wet high intensity magnetic separator
(a) Bench scale unit. (b) Matrix elements
(c) Continuous carousel model of
Eriez Magnetics.

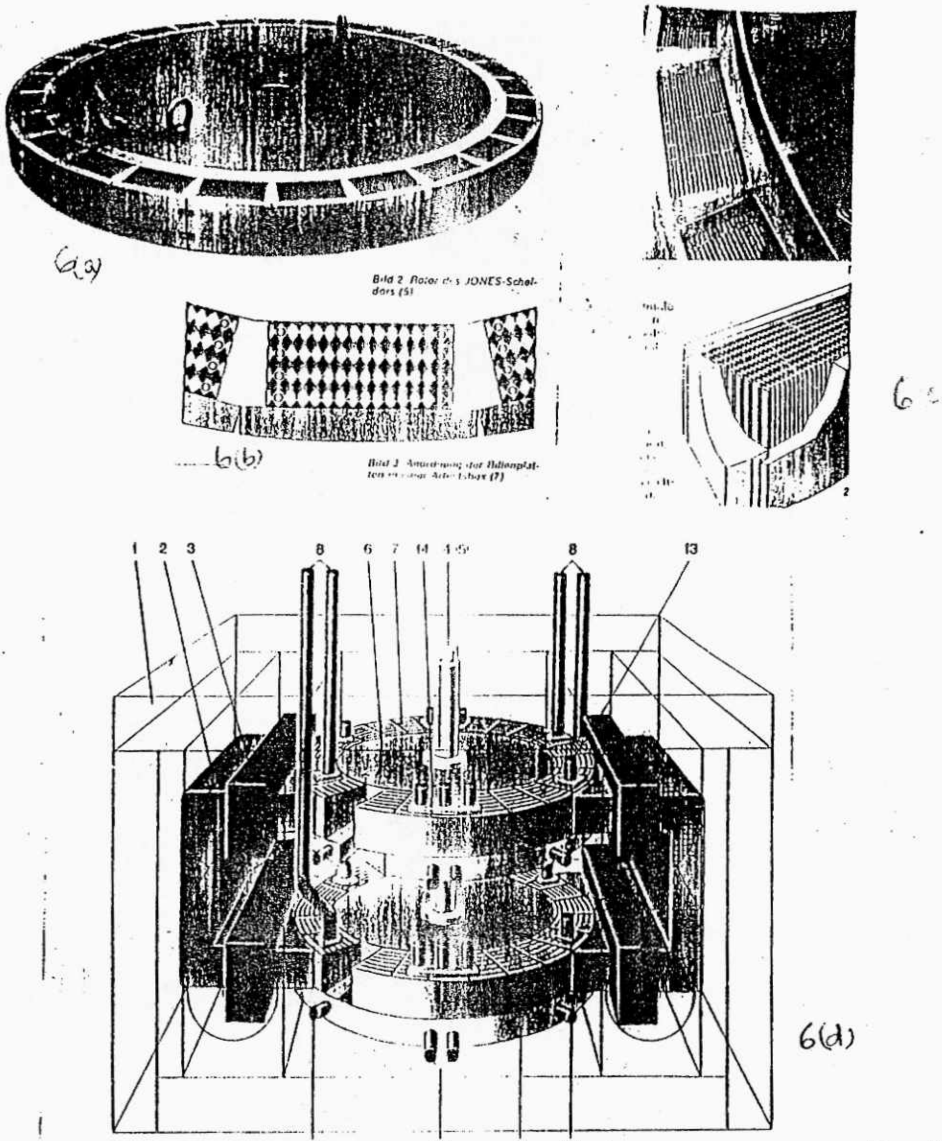


Fig.6. Jones Wet high intensity separator(a) Rotor (b,c) Grov
matrix plate arrangement.(d) Schematic of a 2 pole 2-stage uni
(After Humboldt Wedag)

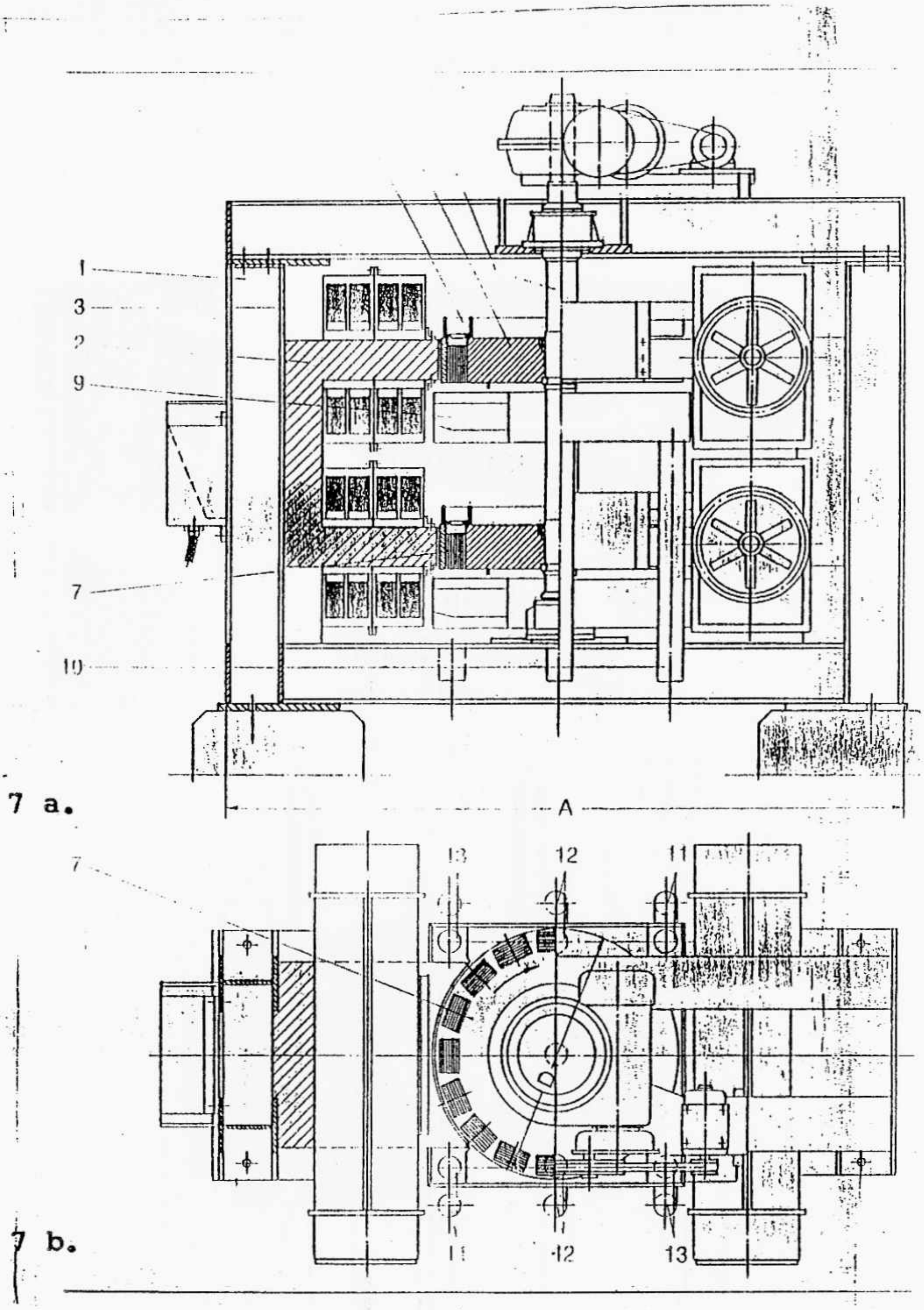


Fig.7. Cross Sectional View of the Z pole 2stage Jones Separator.(After Humboldt Wedag)

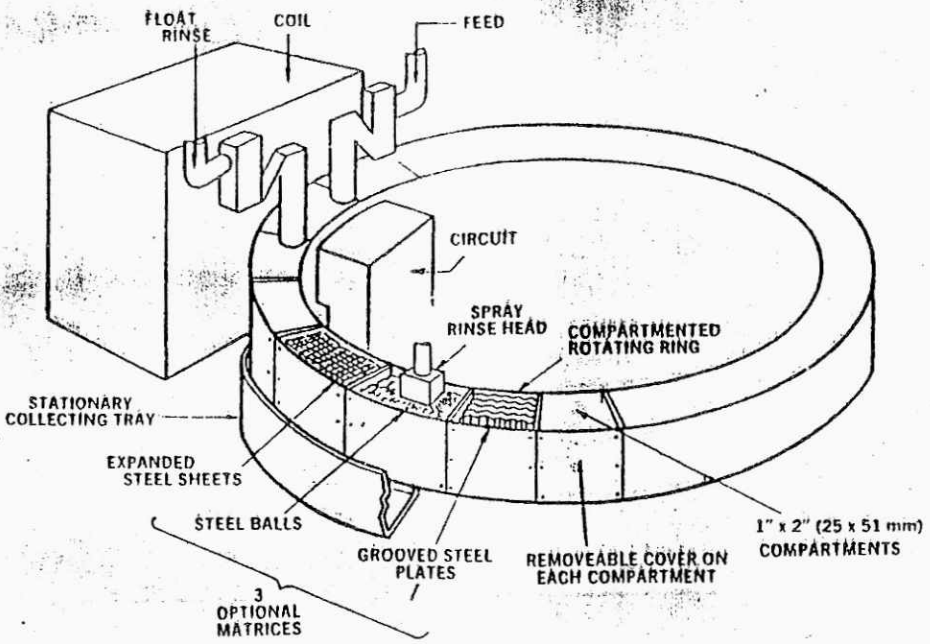


Fig. **7c.** Single-head Eriez high-gradient magnetic separator courtesy of Eriez Magnetics, Inc).

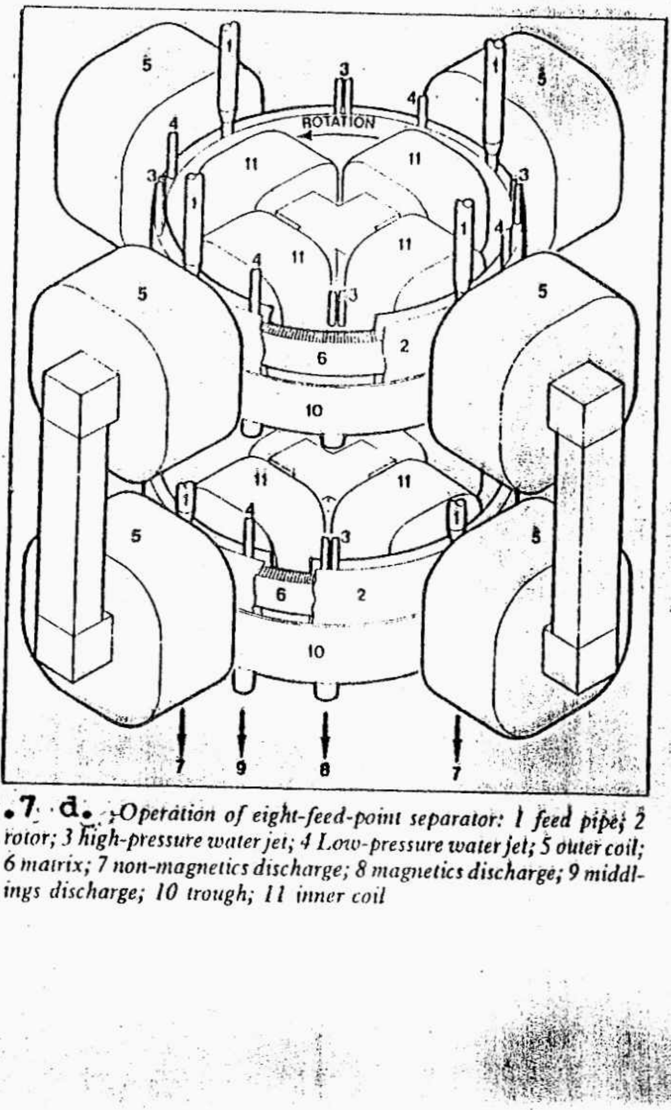


Fig.7 d. *Operation of eight-feed-point separator: 1 feed pipe; 2 rotor; 3 high-pressure water jet; 4 Low-pressure water jet; 5 outer coil; 6 matrix; 7 non-magnetics discharge; 8 magnetics discharge; 9 middlings discharge; 10 trough; 11 inner coil*

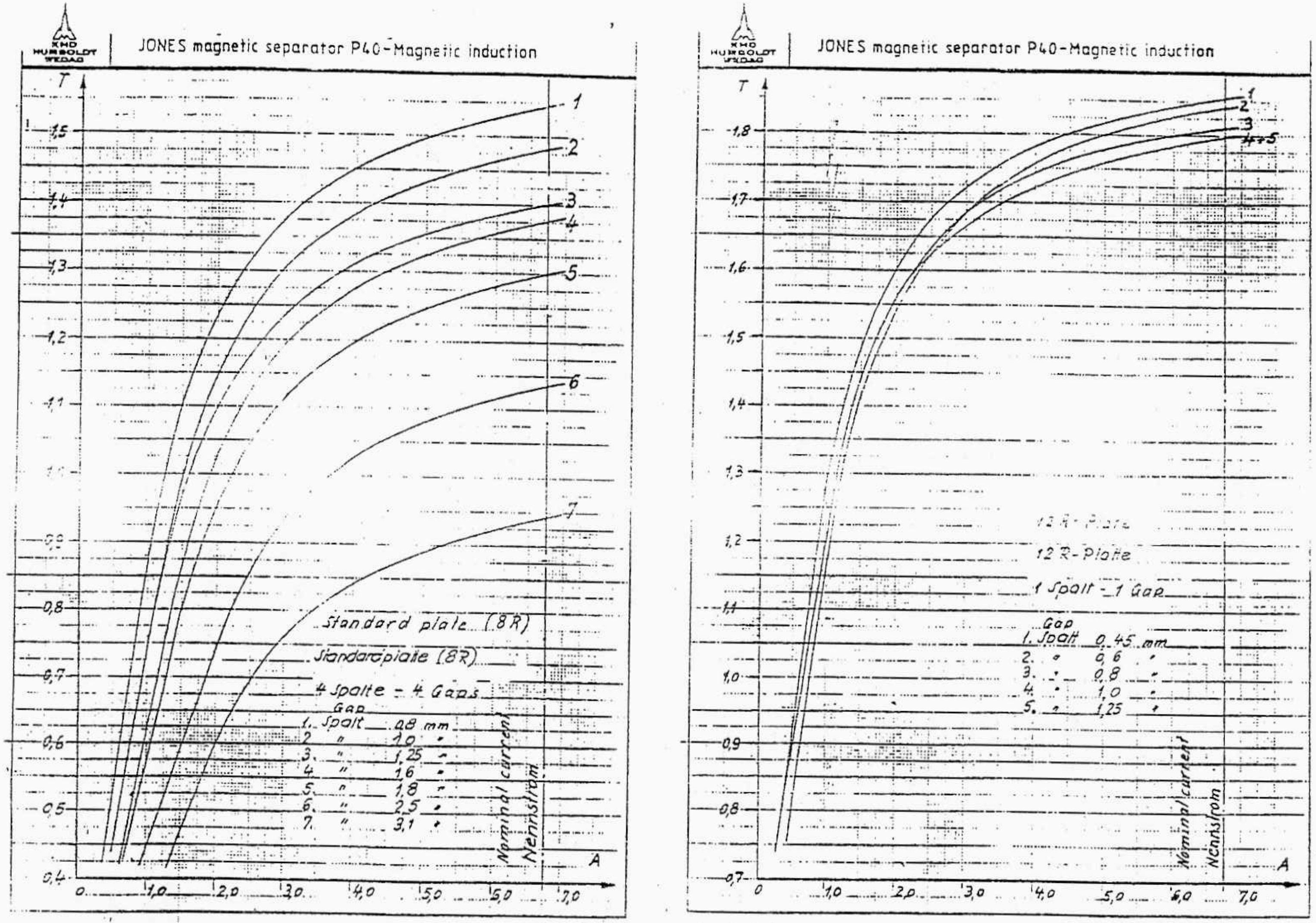


Fig. 8. Magnetic Induction in a lab model Jones Separator Model P-40 showing variation due to no. of grooves in the plates and spacers

(a). Types of Jones double-rotor high-gradient magnetic separators

Type	Capacity (t/h)	Mass (t)	Rotor diameter (m)
DP 335	180	114	3.35
DP 317	120	98	3.17
DP 250	75	70	2.50
DP 180	40	41.7	1.80
DP 140	25	29.2	1.40
DP 112	15	22.4	1.12
DP 90	10	16.2	0.9
DP 71	5	13.4	0.7

(b). Eriez carousel magnetic separators

Model	Capacity (t/h)	Ring diameter (m)	Input power (kW)	Mass (t)
CF-10	1	0.76	3	5.7
CF-50	5	0.90	12	11
CF-100	10	1.24	32	13.6
CF-200	20	1.69	70	20
CF-400	40	2.70	140	30
CF-600	60	3.10	180	46
CF-1200	120	3.10	360	90 *)

*) two-deck unit

(c). Boxmag-Rapid carousel magnetic separators

Model	Capacity (t/h)	Mass (t)	Input power (kW)
HIW1	5	6	8
HIW2	10	10	16
HIW4	20	18	18
HIW8	40	32	65

(d). The specifications of MRVK magnetic separators

	MRVK - 2	MRVK - 4	MRVK - 6
Background magnetic induction (T)	0.9	0.9	0.9
Throughput (t/h)	10 - 14	20 - 30	30 - 45
Water consumption (m^3/h)	12	24	36
Mass (t)	18	45	55

Fig.9. Capacities of WHIMS as suggested by Manufacturers
(a) Jones 2 rotor. (b) Eriez, (c) Boxmag Rapid, (d)

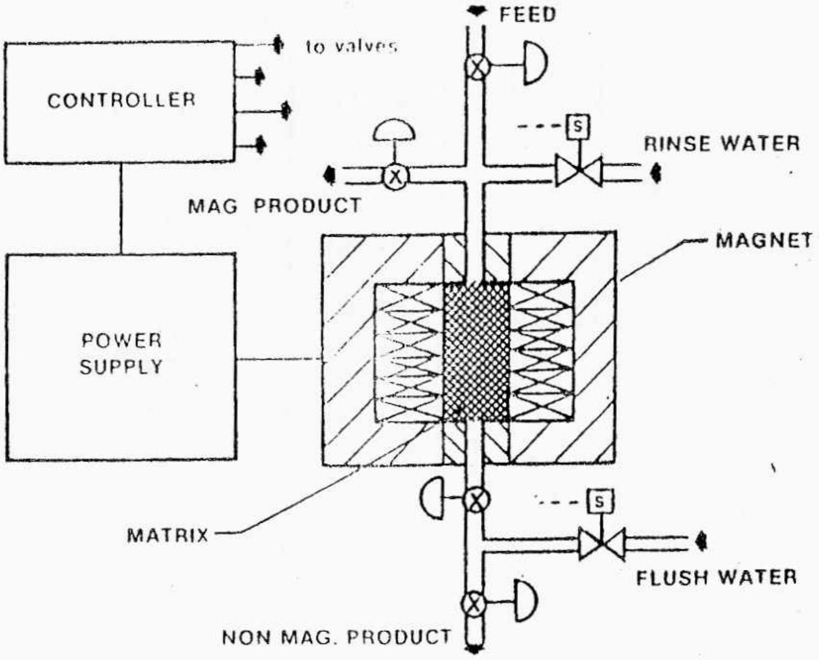


Fig. ~~2.42~~ 10(a) Schematic diagram of a small cyclic SALA-HGMS magnetic separator (courtesy of Sala Magnetics).

TABLE 2.10

Technical characteristics of various cyclic high-gradient magnet separators, for kaolin beneficiation (matrix height 150 to 500 m max. magnetic induction 2 T)

Model	Mass (t)	Matrix diam. (m)	Matrix area (m^2)	Feed throughput	Power input (kVA)	Manufactur
EO-20-84	340	2.1	3.6	115 m^3h^{-1}	400	Eriez
107-30-20		1.07	0.9			Sala
152-30-20		1.5	1.8			Sala
214-50-20		2.1	3.6			Sala
5 PEM		0.13	0.01		200	PEM
84 PEM		2.1	3.6	100 th^{-1}	400	PEM
120 PEM		3.0	7.1	200 th^{-1}		PEM

Fig. 10. SALA- HGMS Schematic diagram and Table showing particulars of various units.

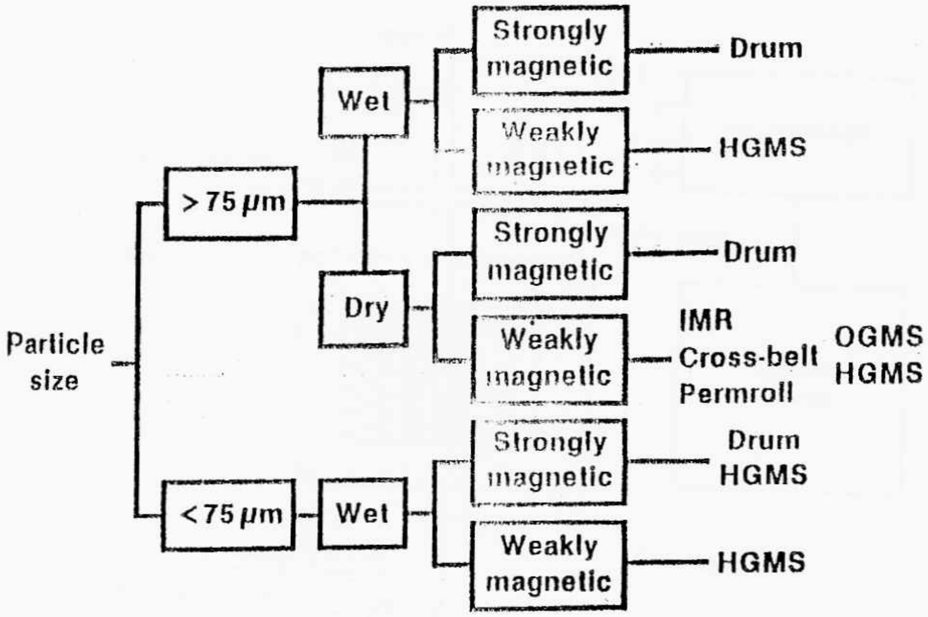


Fig. 11 Classification of magnetic separation processes.

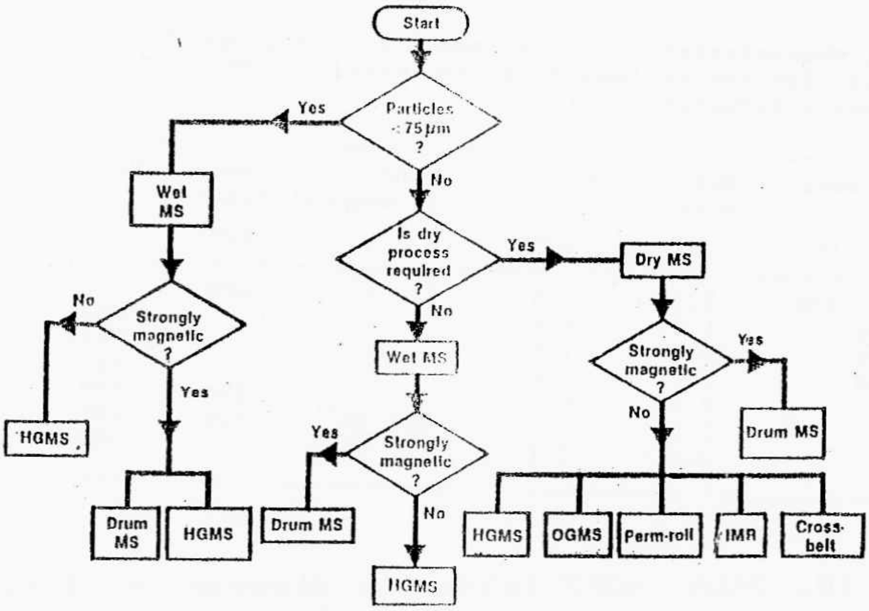


Fig. 12 Selection of the magnetic separation technique.

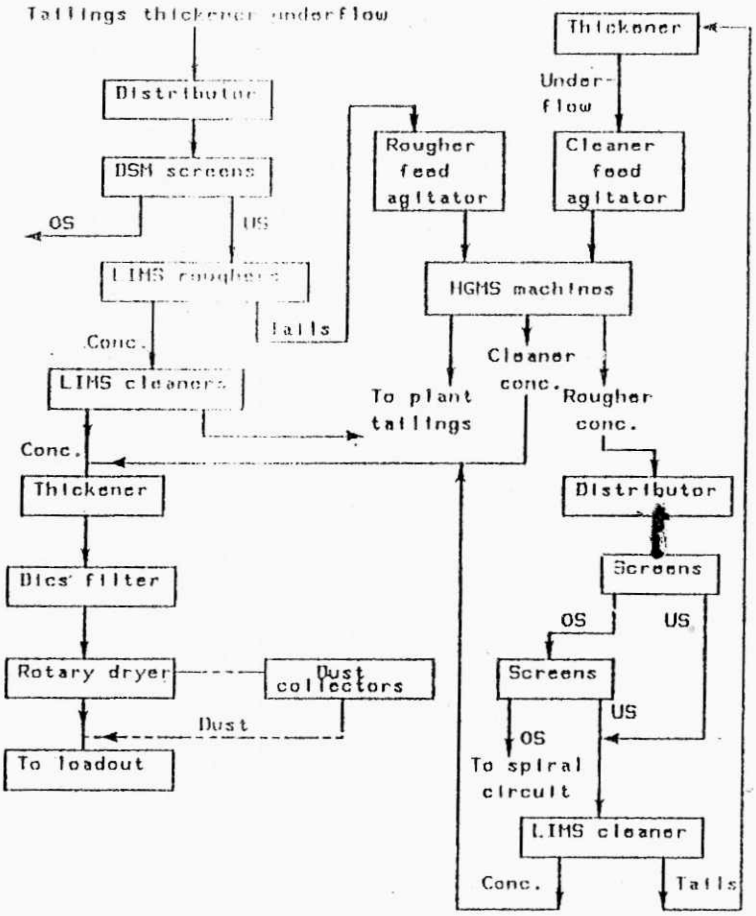


Fig. **13** Flowsheet showing magnetic separation process at Wabu Mines [B34].

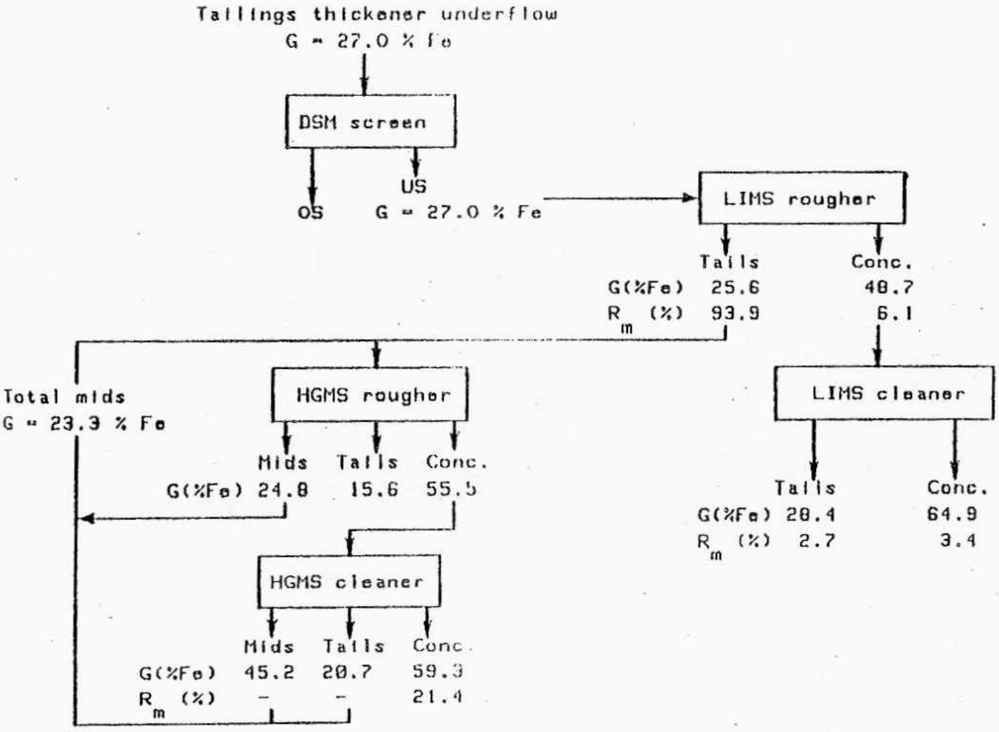


Fig. **14** Metallurgical performance of a magnetic separation circuit at Wabush Mine [B34].

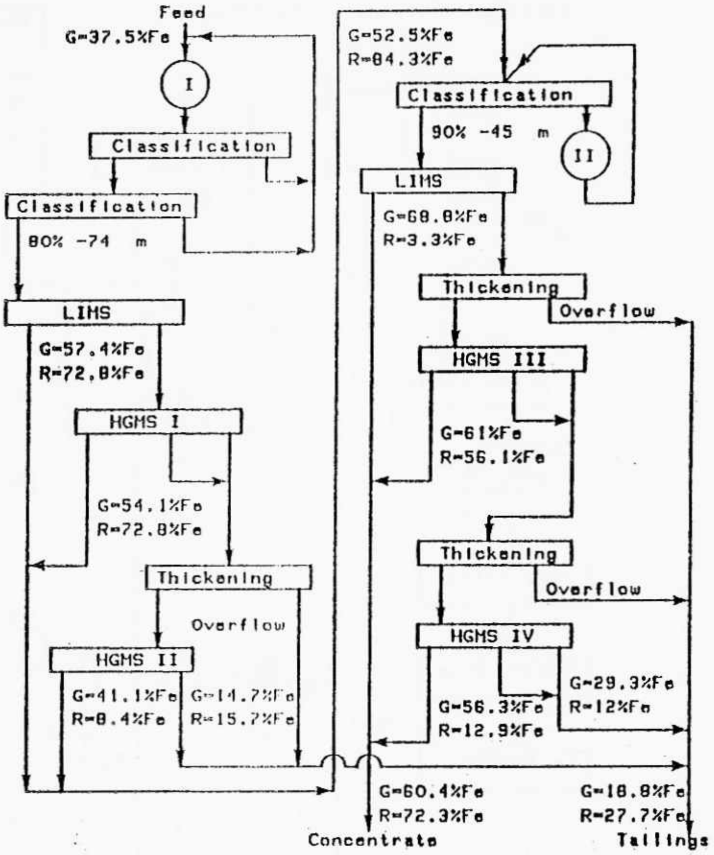


Fig. **15** Flowsheet showing recovery of oxidized quartzites (Krivoi Rog) by HGMS using electromagnet with iron yoke. R_m - mass yield (%), G - grade (% Fe), R -recovery (% Fe). (After Maliy et al. [M27]).

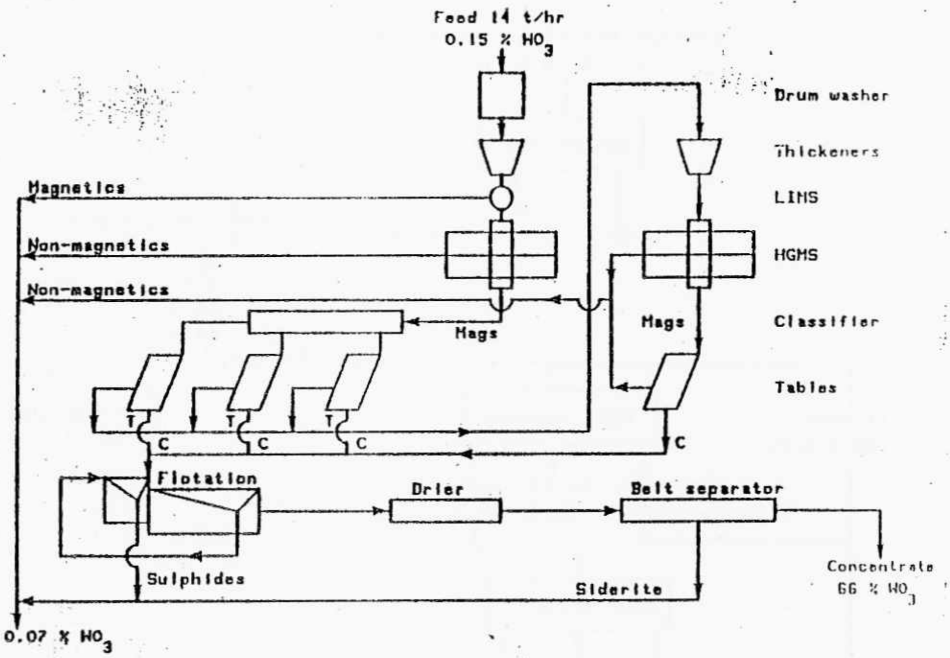


Fig. **16** Recovery of wolframite at Puquio Cocha plant (Peru) [W36].

Fig.17 ..

Comparison of different types of magnetic separators, as applied to phosphate recovery (after Roux et al. [R3])

Attribute	Type of separator			
	Induced-magnetic roll	Permanent-magnet roll	High-gradient matrix	Open-gradient superconducting
1. Stage of development	Very high	Early	High	Early
2. Track record in practice	Proved	A few prototypes in plant service	A few machines in plant service	None
3. Capacity per machine	Low, 4 t/h	Low, 8 t/h	Very high, 400 t/h	High, 60 t/h
4. Ore distribution system in plant	Very complex	Very complex	Very simple	Simple
5. Mass, kg/(t/h) of feed	2190	440	4116	41
6. Power consumption, kWh per ton of ore	2,0	0,6	5,6	0,5
7. Tolerance to ferromagnetics	Low, scalper required	Low, scalper required	High, no scalper required	Very low, scalper required
8. Tolerance to oversize particles	None, rolls severely damaged	Impervious to oversize	Low, matrix clogs	Very high
9. Method of cooling	By air	None required	By water	By liquid helium
10. Effect on environment	Plant requires air conditioning	None	Slight heat output	Slight heat output
11. Maintenance	High on rolls and bearings	Could be high on rolls, low on bearings	Low	Low
12. Metallurgical performance				
12.1. Sensitivity to ore variation	High	Low	Low	Very high
12.2. Recovery of fine apatite	Poor	Very poor	Good	Very poor

TIME TABLE

Third Short Term Refresher Course
Indian Institute of Mineral Engineers
Venue: Institute for Miners & Metal Workers Education, Puri
10-17th Dec., 1989

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DAYS          9.00   10.00     11.00     12.00     13.00¦14.00     15.00     16.00      17.00
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MON           Inauguration <----Mineralogy---->< ---Classification and Material Balances-------->
(11.12.89)                       NC                                      TCR

TUE           <----Flotation-------><----Plant design---><--------Coal Preparation------------->
(12.12.89)         KSN                      LP                                MV

WED           <---------------------Visit to R.R.L., Bhubaneshwar----------------------------->
(13.12.89)

THU          <---El. Separation---><--------Process Control-------------><--Computer Applicn.-->
(14.12.89)         DDM                      VRK                                    DDM

FRI          <-------Exptl. Design-----------><---------><--------Mag. Sepn.--------><---------->
(15.12.89)          HP, SCM                        GUEST             NC                   GUEST

SAT          <---------------------Visit to IRE Plant,Chatrapur------------------------------->
(16.12.89)

SUN          <--Closing Session--->
(17.12.89)
---------------------------------------------------------------------------------------------

NC  : Mr. N.Chakravorty, Dy. Director, NML; TCR : Dr.  T.C.  Rao, Director, R.R.L., Bhopal
KSN : Dr. K.S. Narsimhan, Dy. Director, R.R.L.,(Bbsr), LP : Mr. L. Prasad, Ex. Officer, TRF
MV  : Dr. M. Vanagamudi, Asst. Prof., ISM, DDM : Prof D.D. Misra, HOD, Deptt. F & ME, ISM
VRK : Dr. V R Radhakrishnan, Prof, IIT (Kgp), HP : Mr. H.Patnaik, Asst. Director, NML
SCM : Mr. S.C. Maulik, Asst. Director, NML

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 8:30 A.M.          Break Fast         3:30 P.M.          Tea
 11:00 A.M.         Tea                5:30 P.M.          Tea
 1:00 - 2:00 P.M.   Lunch              8:30 - 9:00 P.M.   Dinner
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