

# MAGNETIC SEPARATION BASIC PRINCIPLES AND THEIR PRACTICAL APPLICATION

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## ABSTRACT

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Magnetic Separators have a wide application in dry separation processes, frequently in conjunction with High Tension Separation. Dry processes can frequently be superior to established processes in more commonplace mineral associations. A system of dynamics is postulated and the forces operating are examined, together with a method of evaluating the effect of operating variables.

Practical applications of these theories to obtain optimum results on an individual separator, and various separations using a laboratory roll type separator are described.

Practical Flowsheets are of two main types, the first consisting of a series of scalping operations, the second for rougher, cleaner, and scavenger operations with middling recirculation. Some common separation problems with certain mineral associations illustrate the need for different approaches for different mineral associations. A table of mineral separation characteristics is appended, from which amenability may be tentatively estimated.

## INTRODUCTION

Magnetic separators are widely used, either alone or in conjunction with other wet and dry concentration devices, for the upgrading of a variety of minerals. The high standards of efficiency attainable in dry mills, together with reduced operating and labour costs, are slowly becoming apparent in a wide variety of plants. The combination of wet and dry concentration plant familiar in beach sand mining is finding application for such processes as upgrading a crushed chromite product, and production of clean scheelite, cassiterite, and other concentrates. Other dry beneficiation processes (such as the high tension beneficiation of iron ore, and the beneficiation of asbestos) avoid the use of wet processes completely.

Dry separation processes are likely to be applied more widely as their possibilities become more generally known.

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To date they have been adopted to achieve results where no old-established process was suitable. The table of mineral separation characteristics in the Appendix illustrates the large variety of minerals to which dry processes may be applicable, depending upon the association. It is wise to have any new ore tested for amenability to dry concentration as a standard procedure.

### THE DYNAMICS OF MAGNETIC SEPARATION SYSTEMS

Separation of species of particles having different magnetic properties can be achieved by treatment in a magnetic field which is non-uniform. The strength of a magnetic field may vary both along a line which follows the direction of the field, and in a direction at right angles to that line. A magnetic particle may, therefore, have a force component acting on it in either or both of these directions, and the total magnetic force acting on the particle is the resultant of the two force components.

Other forces acting are gravitational, and inertial, which includes centrifugal, air resistance, and jostling. Non-magnetic particles are subject to entrainment and entrapment due to the tendency of magnetic particles to agglomerate in the presence of a magnetic field.

#### Nature of the Mineral Stream

In dry separations the minerals to be separated are presented to the separating zone in the form of a thin sheet of minerals. This sheet of minerals is passed through the separating zone in such a way that the flux lines are approximately normal to the sheet.

For any given velocity of travel of the sheet, an increase of feed rate will necessitate an increase in thickness of the sheet of material being fed through the separating zone. Increased feed rates will thus hold back a particle which should normally adopt a path making an angle with the direction of travel of the sheet. Also, if a group of such particles overcomes such entrapment by particles of a different kind, the group will tend to entrap or entrain the particles of such different kind.

The sheet of minerals may be caused to traverse the zone of separation by utilizing gravity, or momentum, or by inserting a material carrier such as a belt or a disc.

The sheet of minerals may be dilated when using gravitational or inertial forces to achieve passage, but when using a belt or disc type of machine, the minerals in the sheet are in mutual contact, thus interfering with relative motion between grains.

### Non-dilated Mineral Streams

A belt-type machine uses a non-dilated bed in the separating zone. Magnetic particles are removed from lesser magnetic and non-magnetic material in direct opposition to gravity.

In this case the force  $F$  exerted on a magnetic particle is thus:

$$F = m\alpha H \cdot dH/ds - mg - f_p \quad (1)$$

or

$$m (\alpha H \cdot dH/ds - g) - f_p$$

where

$m$  = mass of particle

$\alpha$  = mass susceptibility for field  $H$

$H$  = field strength (lines per unit area)

$dH/ds$  = rate of change of field strength at the position of the particle, i.e. convergence

$g$  = acceleration due to gravity

$f_p$  = frictional factor or force due to adjacent or superincumbent non-magnetic particles.

The reaction  $f_p$  will vary from zero when the particle is on top of the bed, to a force equal to the force exerted by superimposed particles when the mineral is buried in a bed of lesser magnetics.

### Dilated Mineral Streams

Rotor and cascade type machines carry out separation in a dilated stream of mineral. The degree of dilation is an important factor, for dilation introduces the problem of random motion whilst largely reducing the positional variation of  $f_p$  which was alluded to in discussing the non-dilated

stream. There is instead a frictional factor  $f_a$  which is an inverse function of dilation, as well as being dependent on the rate at which the particle traverses the stream. A comparison with the case of a body moving in air or water under conditions of turbulent flow suggests that resistance due to velocity would be a function of velocity raised to a power greater than one, i.e.:

$$f_a = \phi (v^{1+x}) \cdot \frac{1}{d} \quad (2)$$

where  $d$  = number of particles per unit volume.

The force acting on a magnetic particle in the case of an induced roll type separator as the particle passes through the zone of separation might possibly be represented as:

$$R' = m (xH' \cdot dH'/ds + r'\omega^2 + g') - f'_a \quad (3)$$

where

$r$  = radius of curved path

$\omega$  = angular velocity

' represents an instantaneous value in a definite direction which may also be a changing one.

The effect of random motion may be studied by observing the spread of material when it is passed through a machine with no flux operating. However in the absence of flux the mean free path of mineral grains is greatly reduced. The effect of random motion may be mitigated by imparting velocity of greater order than the transverse component of the random velocity. Such added velocity through the separating zone must be sufficiently low, however, to allow a particle to make a crossing of the mineral sheet during the period when it is under the influence of the forces causing the separation, and to have a residual kinetic energy to ensure its arrival in the intended position, or alternatively to remain under the influence of the separation force until clear of the residual stream.

Entrapment occurs when a flux density is used which is far greater than that necessary to remove a magnetic fraction occurring in the material under treatment. The bunching together of magnetic particles under such conditions may physically "imprison" non-magnetic particles occurring in

the midst of a group of magnetic minerals at the time the group is placed under the influence of the magnetic field. Entrapment is apparently more dependent on absolute field intensity than on degree of convergence.

Entrainment occurs when the velocity with which a mineral class diverges from another mineral class, moving under the influence of a different set of forces, is so large that it causes velocity transfer to some members of the second class in sufficient degree to cause them to report in a position different from where they would have reported under the influence of the separating forces alone. Some of the velocity transfer takes place through the induced air stream as well as by direct collision and friction.

The centrifugal force term is introduced to cover the case where the rotor tangential speed is greater than the speed with which the minerals approach the separating zone. It is observed that the minerals are speeded up, and hence the thickness of the sheet is diminished, where it is most under the influence of the magnetic forces. This may be due to mechanical rather than magnetic action, except in so far as magnetic particles adhering to the rotor increase its roughness.

Increasing the rotor speed decreases the proportion of magnetic product per pass and reduces the density of the mineral stream. By imparting increased momentum to the non-magnetic portion, it makes it more difficult to divert the non-magnetic particles from their proper trajectory.

#### DISCUSSION OF FORCES OPERATING IN AN INDUCED ROLL SEPARATOR

The various forces acting on a magnetic particle in the case of a top fed induced roll separator are shown in Fig. 1 for three positions of the particle. The sources of the forces acting are three, magnetic, gravitational and frictional, yet five different forces are shown:

$f_m$  = force due to magnetic attraction of rotor.

$f_n$  = force due to variation in intensity of magnetic field at right angles to direction of field.

$f_g$  = force due to gravity.

$f_p$  = frictional force generated by motion relative to non-magnetic particles.

$f_c$  = circumferential force due to acceleration by rotor.

In the diagrams only a single particle is shown, but it should be remembered that it is surrounded by other particles.

Position A in Fig. 1 represents the approach to the separating zone. The mineral stream should be flowing evenly,

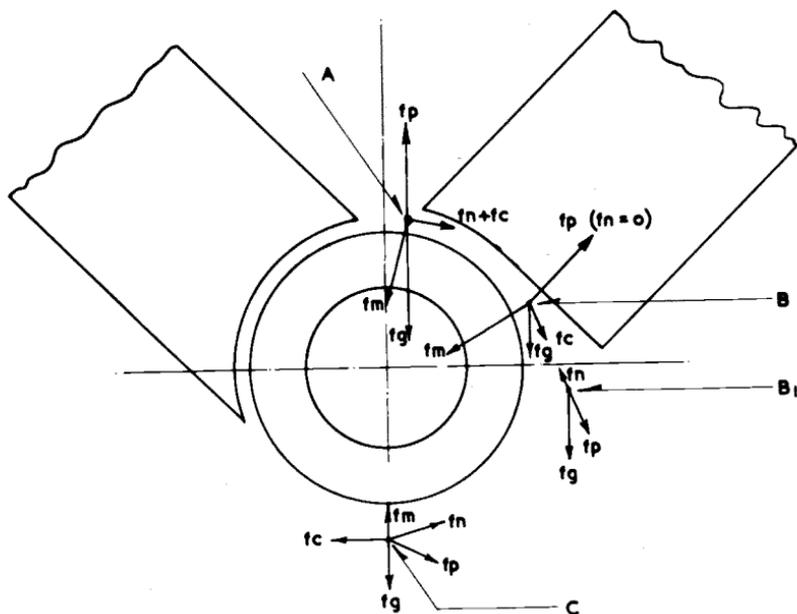


FIG. 1.

$f_c$  = circumferential acceleration effect due to rotor speed.

$f_g$  = force due to gravity.

$f_m$  = force on magnetic particle due to magnetic attraction of rotor.

$f_n$  = force due to variation in intensity of magnetic field at right angles to direction of field.

$f_p$  = frictional force generated by motion relative to non-magnetic particles.

without undue turbulence on to the rotor. There is very little dilation of the stream, but the accelerating force is acting in conjunction with  $f_n$  to thin out the stream. Experiments indicate that  $f_m$  is rather small at this point owing to the tendency of the flux to "short circuit". This is not detrimental however, as it results in a force approximately tan-

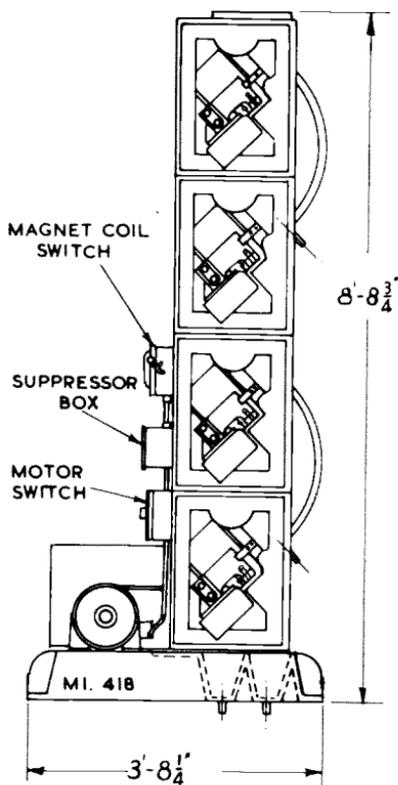


FIG. 2. Multi-Unit High Intensity Induced Roll Magnetic Separator.

gential to the rotor, allowing the stream to dilate a little without actually fouling the adjustable pole face. Strongly magnetic particles lying on top of the mineral stream may be attracted to the tip of the pole if the variables of flux, gap and rotor speed are not suited to the character of the mineral being separated.

In position B, the force  $f_m$  is comparatively large, particularly for particles nearest the rotor, and falls off rapidly for positions near the face of the pole. It does not, however, reverse its direction at the surface of the pole face, provided the rotor is finely laminated. As a consequence of this radial variation of  $f_m$  there is also a radial variation of  $f_c$ , the term

which represents the force largely responsible for dilation of the stream. The magnitude of  $f_c$  and the consequent centrifugal force is dependent on the amount by which the peripheral speed of the rotor exceeds the speed of the minerals. The phenomenon is best utilized in the roughing pass, for strongly magnetic minerals and to minimize entrainment of non-magnetics.

The frictional force  $f_p$  is shown at right angles to the general direction of the mineral stream, in any particular stratum in which a particular mineral finds itself. This would no longer hold true once a particle is approaching the weaker regions of the magnetic field.

Point B1 illustrates a position where the particle is in a region of parallel flux lines, the only magnetic force acting is a retardation due to  $f_n$  with a consequent  $f_p$  in the opposite direction, due to the free falling non-magnetic particles. The result is a further lowering of the trajectory of the non-magnetics.

At a point like C, only the strongly magnetic portion of a mineral mixture should be found. If the main stream of magnetics is coming so far around, it is probable that entrainment is occurring. Reduction of flux would reduce entrapment in such a case and increase in rotor speed would minimize entrainment. It will be observed that  $f_m$  is quite small at position C, but flux distribution studies have shown that reversal of field occurs only a short distance in front of the lower point of the back pole.

In the case of non-magnetic particles the forces acting are  $f_g, f_p$ —which is dependent in the amount of entrapment and entrainment as well as on the rate of movement relative to surrounding particles, and for non-magnetic particles acts towards the rotor—and finally  $f_c$ , which acts while significant amounts of magnetics are present. Since in the zone of separation  $f_c$  is following a curved path, it seems reasonable to assume that the acceleration of a non-magnetic particle away from the rotor is specified by  $r\omega^2 - f_p/m$

where  $r$  = mean radius of curved path

$\omega$  = angular velocity of magnetic complex

$m$  = mass of particle.

After leaving the zone of separation the non-magnetic particle follows a steep trajectory mainly under the influence of gravity, although the trajectory is slightly affected by the rotor speed, as may be easily demonstrated.

### The Semi-lift Roll Type Separator

Figure 3 represents the original form of the semi-lift type separator, used for the removal of strong and medium magnetic materials. An improved version of this type of separa-

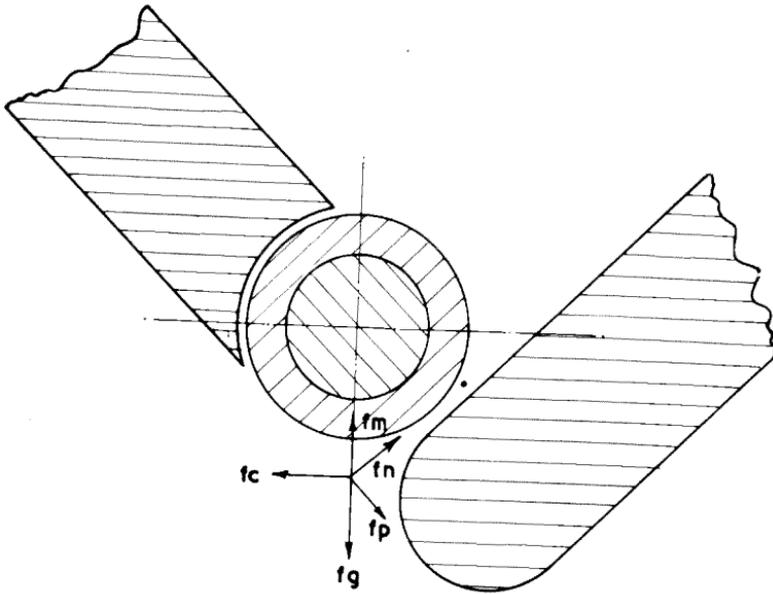


FIG. 3.

tor has recently been put into production following plant tests, in which more than 3,000 lb. of heavy mineral per hour was passed through an 18-in rotor machine with rutile losses of only 1.0 per cent in the magnetic product.

The minerals flow in a stream down the surface of the adjustable pole. The magnetic minerals, as they approach the influence of the grooved rotor, are lifted toward the surface of the mineral stream, owing to their apparent loss of weight, and the buoyancy of the lively bed of moving material. As the magnetic particles pass through the narrowest part of

the gap they are attracted to the rotor and pulled round in a path which is convex downward. Non-magnetic particles fall away in a natural trajectory if they are at the bottom of the bed. The machine was first developed to overcome the problems of separating strongly magnetic materials in an induced roll separator, where build up of strongly magnetic particles on the point of the pole piece could occur, particularly where magnetite scalpers were not employed. The problems of entrapment have now been overcome to the extent that maximum flux may be used on mineral mixtures containing strongly magnetic fractions as well as on those having less susceptibility.

#### PERFORMANCE CURVES

Two types of performance curve are discussed below:

- (I) Movable Splitter,
- (II) Fixed Splitter.

There is a large number of variables involved in the setting of a magnetic separator, so that it is difficult to decide upon a set of variables to produce some guide as to performance by a series of tests.

The following variables are possible:

##### *Minerals:*

- A. Magnetic Susceptibility.
- B. Relative Proportions.
- C. Absolute and Relative Grainsize.

##### *Separator:*

- A. Gap.
- B. Field Current.
- C. Rotor Speed.
- D. Splitter Settings.
- E. Feed Rate.

#### **Movable Splitter Curves—Significance**

The effect of these variables can be studied by the preparation of a number of curves of the type shown in Fig. 4, which shows the amount of material reporting at each position in the receiving hopper.

Inspection of the curves of Fig. 4 will show that both the magnetic and non-magnetic curves are of the peaked type. The curves overlap, but the maxima of the two curves are separate.

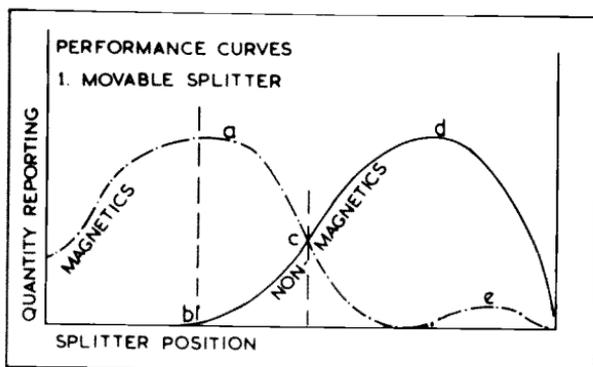


FIG. 4. Performance Curves.

It will be observed that there is a slight rise in the proportion of magnetics at the extreme end in the non-magnetic portion of the field. This is due to those magnetic particles which were unable to penetrate a thick mineral stream and came under the influence of the movable pole. The diagram does not indicate a very efficient separation, but shows the essential elements in an exaggerated form.

*Application of Curve:* Minerals to the left of point *b* are virtually free of non-magnetics. A split made here would enable the removal of about 40 per cent of the magnetic material without loss of non-magnetics.

By moving the splitter along to the right slightly, a much larger portion of the magnetics could be removed with the loss of a non-magnetic portion which might be small enough to be tolerated. This would therefore be the type of splitter setting adopted for the scalping type of flowsheet (Fig. 7).

For the complex type flowsheet (Fig. 8) a greater proportion of the magnetics would be removed up to point *c*.

It should be obvious that the distribution of later stages of the flowsheet can be profoundly altered by the splitter setting of preceding stages. If such curves are available the choice of splitter setting is greatly simplified.

*Methods of Improving the Distribution:* Gap and field current together determine flux. It is slightly better practice to use wider gaps rather than decreased field currents for laboratory work, where current consumption is not important.

Increase in flux will move peak **a** to the left. It will also reduce or eliminate peak **e**, and it will tend to move the non-magnetic curve to the left.

Overlapping of the two curves is increased by increased feed rate. Increase in rotor speed improves the separation of the two curves and reduces the height of the curve from **b** to **c**, but also moves the peak **a** to the right, and increases the possibility of peak **e** occurring.

A slow rotor speed moves peak **a** to the left, greatly steepens curve **ace**, reduces height of peak **e** but increases height of **bc**, by an amount dependent largely on feed rate.

### Fixed Splitter Performance Curves

Figure 5 represents a pair of curves from a family of curves which were produced in the course of testing the semi-lift type separation.

A series of tests are made using a series of rotor speeds in the usable range. Splitter setting, field current and gap are held constant. Similar curves are obtained for three dif-

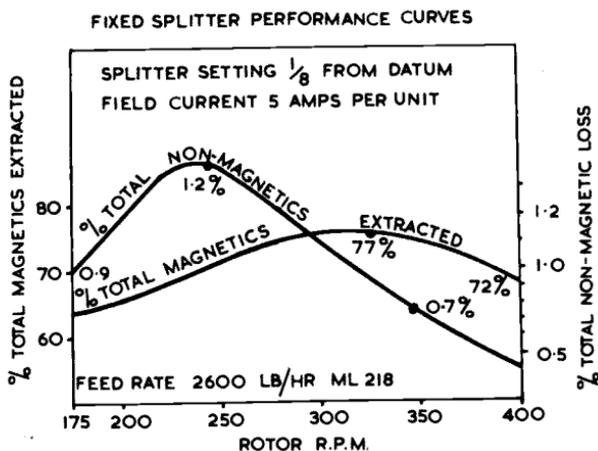


FIG. 5. Fixed Splitter Performance Curves.

ferent values of field current. Comparable groups of curves are obtained using a different splitter setting for each group. Losses are determined by splitting out samples and testing on the laboratory separator.

The curve shown in Fig. 5 shows the operation of the effect of entrainment of non-magnetics at low rotor speeds. At higher rotor speeds this is overcome by the centrifugal force effect with a marked drop in losses and also a marked increase in the amount of magnetic material thrown clear of the rotor.

*Preparation of Movable Splitter Performance Curves:* The quickest method of obtaining the necessary data to produce a pair of distribution curves of the moveable splitter type is to remove the standard receiving hopper, and substitute a receiver divided into a large number of compartments by thin closely spaced splitters with spigots to remove, weigh and test each product separately.

If a single splitter is used, it may need to be extended sufficiently to cover the entire range of possible splits. A series of runs should be made with all conditions constant, other than a progressive movement of the splitter to measured positions from left to right and from right to left.

Products from each pass are separated and weighed as magnetics and non-magnetics. Quantities in each position are determined by difference and the mean of the runs from left to right and right to left used to supply the final figures for drawing the curve.

The variable under study is then altered systematically and a further pair of curves is produced in the same fashion.

#### OPERATION OF LABORATORY SEPARATOR

Rules may be derived from the foregoing considerations for the manipulation of a laboratory roll type separator. Laboratory tests plus economics and product specifications will in turn allow the derivation of satisfactory plant flowsheets.

#### Scalping

If magnetite is to be determined, it should be removed by means of a rotating field permanent (alnico) magnet separa-

tor. If strongly magnetic ilmenite is present it is best removed using a semi-lift type fitting.

Rotor speed should be medium to high if the separation is difficult, gap medium with flux sufficient only to remove a reasonable portion of the magnetics. The splitter should be set on the magnetic side of the visual split. The magnetic product should be examined for signs of non-magnetic minerals. The aim is to set the splitter at the equivalent of point b in Fig. 4.

If a semi-lift type fitting is not available the induced roll type may be used. In this case, a large gap should be used for the first pass, with a rotor speed of 300 to 400 r.p.m. in the case of beach sands. Sufficient field current should be used to secure a reasonable diversion of the magnetic particles. Highly magnetic particles tend to entrap non-magnetic particles if too much flux is used; also a certain amount of the magnetic particles may adhere to the point of the movable pole piece. This material may be caught separately by reducing the flux after passing the sample and repassing at a reduced field current setting.

### Three Rotor Method

If strongly magnetic minerals have been removed or are absent, the most expeditious method of securing a magnetic and a non-magnetic product is to use a rougher; cleaner, scavenger flowsheet. Three receiving pans are desirable.

Figure 6 illustrates the method graphically. (The terms cleaner and scavenger are used in relation to the recovery of a non-magnetic product such as rutile.)

Conditions should be set as follows:

*Rougher*: medium field, medium gap, medium rotor speed 250-300 r.p.m.

*Scavenger*: medium field, medium gap, high rotor speed 350-450 r.p.m.

*Cleaner*: strong field, reduced gap, low rotor speed 150-200 r.p.m.

These settings are for beach sand minerals and do not necessarily apply for other minerals. They are given to illustrate the relative order of magnitude only.

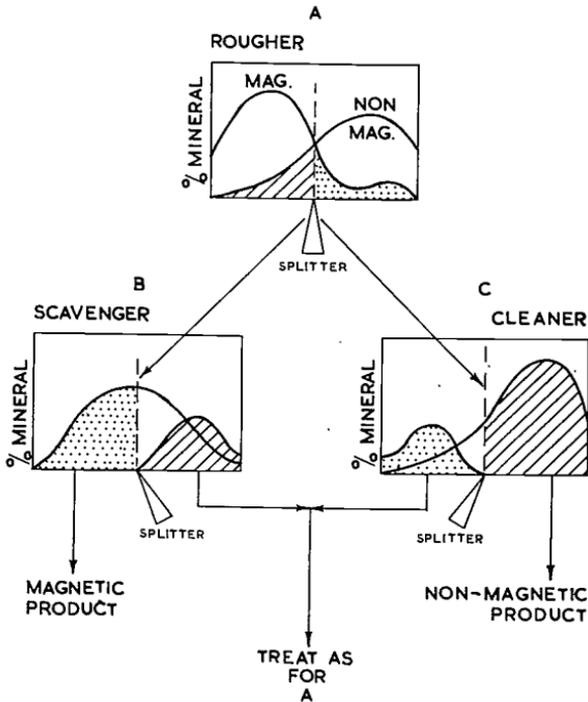


FIG. 6.

It is possible to extend the method further so as, for example, to separate an ilmenite, leucoxene and a rutile, by using just sufficient flux to remove ilmenite in the first three stages, and applying a further stage operation with increased flux to the rutile, leucoxene product from the first cleaner stage.

### Magnetic Fractionation

Useful separations can sometimes be made by careful use of variables to make a graded set of products. Two or more passes are made at each setting, before increasing flux slightly. The various products may then be repassed again in a similar fashion.

A recent industrial application is in the production of a premium grade chromite by the removal of a small amount of high iron material.

## Flowsheet Preparation

The laboratory roll type separator may also be used to design plant flowsheets successfully, subject to confirmation by pilot plant tests. For the Carpco M.I. type separator, throughput in grams per minute times 1.41 equals lb./hr./18 in. rotor. Large samples may be run by rigging a glass funnel in a stand to feed the laboratory machine hopper.

Standard flowsheets may be tested and have proved in practice to provide good correlation.

### CRITERIA FOR CHOICE OF FLOWSHEET TYPE

#### Ratio of Concentration

The degree of contamination in the product from any one pass is partly determined by the concentration of the contaminant in the material fed to that stage.

#### Purity of Product

Product specifications also naturally affect the choice of flowsheet, and can be the cause of considerably increased complexity when both magnetic and non-magnetic products have to comply with strict specifications.

Australian east coast beach sands contain an ilmenite which is at present unsaleable owing to the presence of chromium compounds.

Hence the problem is to obtain an economic recovery of non-magnetics (rutile) whilst permitting the loss of some rutile in order to obtain maximum throughput for a given capital investment.

If, however, as in the case of a recent U.S. specification for a rutile-ilmenite separation, it is necessary to hold the rutile in the ilmenite to less than 0.5 per cent and the ilmenite in the rutile to less than 0.5 per cent, a rather different type of flowsheet is adopted (Fig. 3).

Variation in feed grade and composition can occur in a given deposit. The maximum extent to which such variations can extend should be determined during the plant design stage. To overcome this requires either surplus capacity on average material or else flowsheet flexibility plus the pre-

sence of an experienced metallurgist able to recognize and compensate for such variations as they occur.

### Scalping Type Flowsheet (Fig. 7)

This method entails making a series of separations in which magnetic fractions are removed in decreasing order

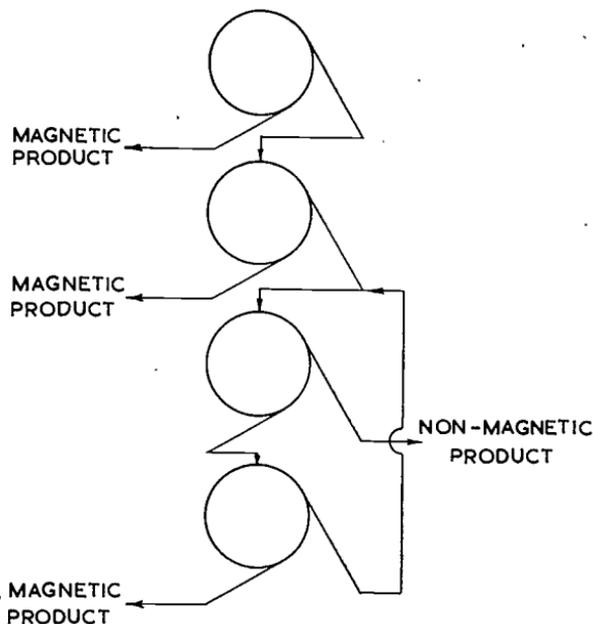


Fig. 7. Scalping Type Flowsheet.

of susceptibility, the machines being set so as to produce a magnetic product carrying a minimum of non-magnetic material whilst still maintaining a useful percentage removal of magnetics, i.e. the broadest possible range of magnetic types is removed without suffering the ill effects of entrapment and entrainment.

The scalping type of separation may, if desired, be limited to the first one or two stages, for example a permanent magnet or auxiliary pole magnetite scalper; or may be extended to all but the last stage or stages. Successive stages have reduced amounts of material to be treated and hence separa-

tion may be carried out at reduced feed rates, which improves the separation.

When using a scalping type flowsheet it is desirable to set each stage so as to make one of the two products as clean as possible. If at any given stage neither product is satisfactory, both the products will require further treatment. This entails additional equipment so that the flowsheet no longer belongs in the scalping type category.

### The Complex Flowsheet (Fig. 8 and Fig. 9)

This type is essentially composed of rougher, cleaner and scavenger sections, usually with recirculation of one of the

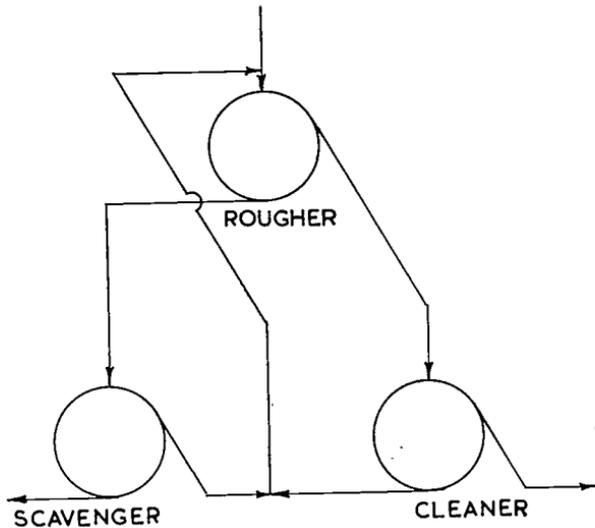


FIG. 8. Basic "Complex" Flowsheet using Rougher, Cleaner, and Scavenger.

scavenger products or with a scavenger, cleaner stage to obtain more suitable settings on the stream of material from the scavenger.

When the recirculation of a material is required and it necessitates additional capacity, the recirculated material may respond better to a different setting of the machine than to that of the machine in which it originated.

In this case the material should not be remixed prior to retreatment, but rather it should be fed to a separate circuit

with provision for surges to bleed off into the main circuit, and vice versa. However recirculation of a product which is the result of randomization may be sometimes used to alter the relative concentration of the two phases and thus utilize the laws of mass action in a sense, by diluting the concentration of the deleterious constituent.

The complex flowsheet will probably require a scalping stage ahead of it, or else in the highly magnetic product section.

### CHOICE OF FLOWSHEET

Two basic types of flowsheet are illustrated in the accompanying diagrams. The first type (Fig. 7) represents a series of scalping operations with the addition of a stage of scavenging of the final magnetic product. The second type (Fig. 8) which has been called "complex" in this paper, consists of a roughing stage, followed by treatment of each of the products on a cleaner and scavenger with the circulation of a middling back to the rougher stage.

Where indicated by test work, various combinations of these basic types may be used.

#### Application of Scalping Type

Where one of the two products may be made sufficiently pure in a single pass, in a significantly large amount, a scalping stage may be used. This is most likely to occur in the case where a magnetic product is being sent to waste, carrying only a small amount of non-magnetic material which it would not be economic to extract.

In the diagram (Fig. 7) the flowsheet is shown with a scavenging rotor treating the magnetic product of the third rotor. This enables the splitter to be set to make a clean non-magnetic product on the third rotor.

#### Application of Complex Type Flowsheet

This type of flowsheet is applicable where both non-magnetic and magnetic products are saleable, and where it is difficult to produce a clean magnetic product in one pass, at a sufficiently large rate of throughput.

The rougher split is made where the natural split occurs; unless it is necessary to favour one particular branch of the separation because of separation difficulties to achieve a better balance in the amounts of feed to various parts of the flowsheet. An actual flowsheet is shown (Fig. 9).

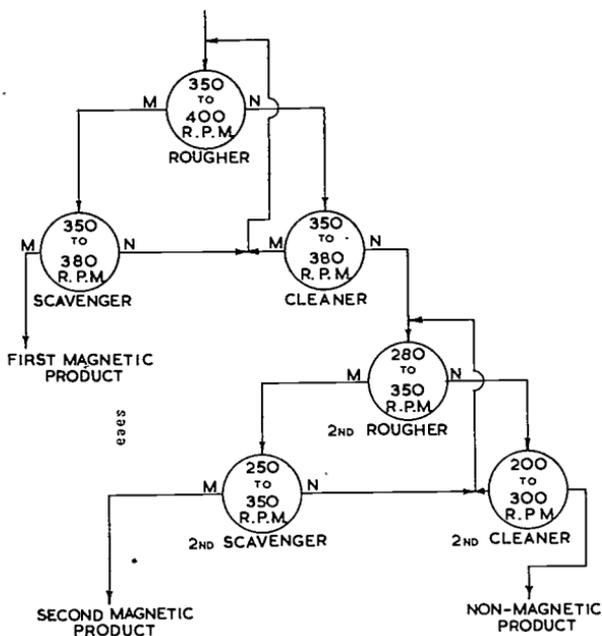


FIG. 9. Two-stage Complex Flowsheet.

### The Unstable Flowsheet (Fig. 10)

This diagram represents an attempt to save equipment by fully loading both the cleaner and scavenger rotors, where a 50/50 split is being made in the rougher section, for example. Any variation in the relative proportions of either magnetic or non-magnetic constituents will overload one of the lower rotors.

Hence feed rates to the roughers have to be reduced.

### THE SETTING OF ROLL TYPE SEPARATORS

#### Zircon Cleaning

The simplest type of separation is possibly that of zircon cleaning, where a small amount of magnetic material has

to be removed from a non-magnetic material of comparatively low unit value. A small loss of zircon may be tolerated provided the removal of magnetics is satisfactory, and the feed rate is satisfactory. Both the modern, small rotor machine and the old fashioned 6-in. diameter rotor type machine are capable of performing this operation, although the latter type penalizes the user because of the high field currents

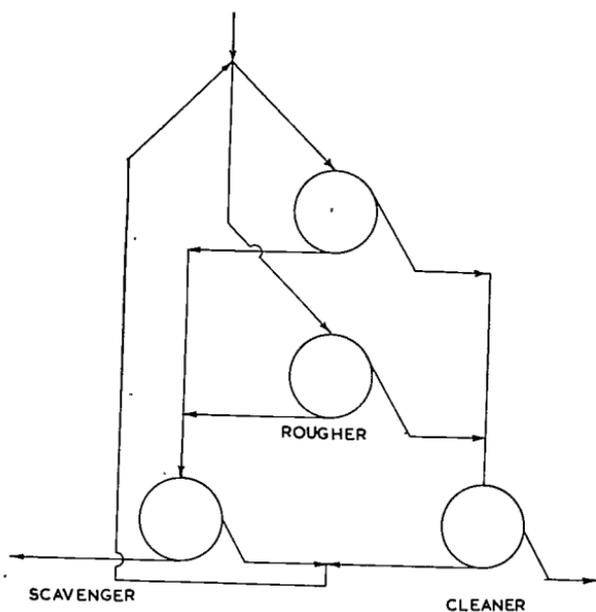


FIG. 10. Unstable Flowsheet.

required to energize the large amount of iron employed in its construction.

The gap is set so as to be the minimum necessary to pass the desired feed rate and still have the pole clear of the mineral stream. In the case of Carpcoc induced roll type separators, this gap would be about  $3/16$  in. for the first pass, with the field current set to remove garnet and monazite without undue loss of zircon. For the second pass, the gap would be set at approximately  $5/32$  in. and the maximum field current would be used. This would serve to remove the zircon having magnetic inclusions and other weakly magnetic minerals. Rotor speeds would be in the low range.

Tremendous bending force is exerted on the rotor due to the greatly increased flux with small air gaps. The machine should not be stopped with the field current switched on or a permanent set may be put in the rotor.

A complex flowsheet (Figs. 8, 9) will reliably produce a better grade of zircon, but with a slight increase in the number of separators required.

### **Removal of Strongly Magnetic Materials, such as High Iron Ilmenite**

Both semi-lift and deflection type roll separators are used in this work. Belt type separators work in this field also, but for reasons of poor throughput, and other reasons discussed elsewhere, do not merit much discussion. Chief precautions to be observed in the use of belt separators are: to avoid overloading the belt, or else strongly magnetic material will not be removed soon enough, and at later stages where fluxes are more intense it will agglomerate and act broom fashion to sweep non-magnetics off the belt; and, secondly to use minimum satisfactory flux in the early stages to avoid entrapment and sweeping.

Induced roll (deflection type) separators are operated in this application with large gaps and just sufficient flux to remove a worthwhile proportion of the magnetic material. Rotor speeds are high to obtain the centrifugal rejection of low- and non-magnetics.

Care must be taken not to seek too great a proportion of the magnetics or else entrainment can occur. This type of machine works best in this service in the absence of highly magnetic material. Magnetite and highly magnetic ilmenite tend to build up on the tip of the movable pole.

The semi-lift type separators were designed to cope with mineral mixtures containing moderate to large amounts of highly magnetic fractions. The aim is to remove the highly magnetic fraction using moderate intensities, prior to passing the material under treatment to the high intensity separators.

Rate of throughput should be such that the high intensity machines are kept fully loaded. This indicates that a rate of

throughput greater than that of the equivalent high intensity machines is desirable in the semi-lift type.

The proper function of the semi-lift machine should be kept in mind, viz. the efficient removal of as much as possible of the strongly magnetic material only.

Attempts have been made to build semi-lift type machines capable of removing a wide spectrum of magnetics. One such machine was tested and found to be capable of removing 60 per cent of the ilmenite from a rutile-ilmenite mixture in which only 20 per cent of the ilmenite was strongly magnetic. However the obvious penalty was paid; feed rate was necessarily low, as a consideration of the problems of entrapment and entrainment would show. Velocity through the separating zone had to be reduced to allow the removal of such a large proportion of the material in a single pass.

A definite upper limit on the feed rate was observed, at which time the separation failed completely. Apparently turbulence and the build up of too thick a sheet of minerals was responsible.

The following conclusions summarize this stage of a flow-sheet:

The semi-lift roll type machine is the most suitable for the removal of high-magnetics. It is desirable to remove most of the high-magnetics prior to high intensity separation. The semi-lift roll type machine is more compact and has much greater capacity than a belt or disc type separator. Because of smaller gap and lesser amounts of iron, much less electrical energy is necessary to energize the field. Hence for separations of strongly magnetic ilmenite the semi-lift type is more economical.

### **The Removal of Moderately Magnetic Materials**

Assuming the absence of strongly magnetic minerals by prior removal, it is next necessary to consider the range of susceptibility of the remaining minerals.

The broad principle may be stated that it is desirable to remove, in a single stage of high intensity induced roll separation, only minerals within as limited a range of sus-



ceptibilities as possible, and still have a worthwhile proportion removed.

Even where this "worthwhile proportion" extends over a considerable range of susceptibilities, no serious difficulty is encountered unless the most susceptible mineral of the series is present in sufficiently large proportion to cause entrapment and entrainment losses, due to its being separated in a field much stronger than necessary.

In this case the most susceptible minerals must be considered a worthwhile proportion in any case.

For this type of separation, rotor speeds are desirably high, to impart linear kinetic energy to the non-magnetic fractions and thus render them more difficult to deflect by the cross-moving magnetic particles.

Field strength is high enough to strongly attract and deflect magnetic particles. Pole gap is slightly more than the minimum necessary to clear the mineral stream. The splitter is set to ensure a clean magnetic product.

Feed rate is comparatively high on the initial pass.

When a series of separations is being made by a series of passes, the feed rates on succeeding passes may be progressively reduced, in accordance with the amounts of magnetics removed in the preceding passes.

Successively reduced rotor speeds and gaps with increased fluxes may be used as the minerals of lower susceptibility are removed.

Splitter settings are made to produce a clean magnetic product in each stage except the last stage, where it is probable that a clean non-magnetic product may be desired. In this case it may be desirable to scavenge the small amount of magnetic product.

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