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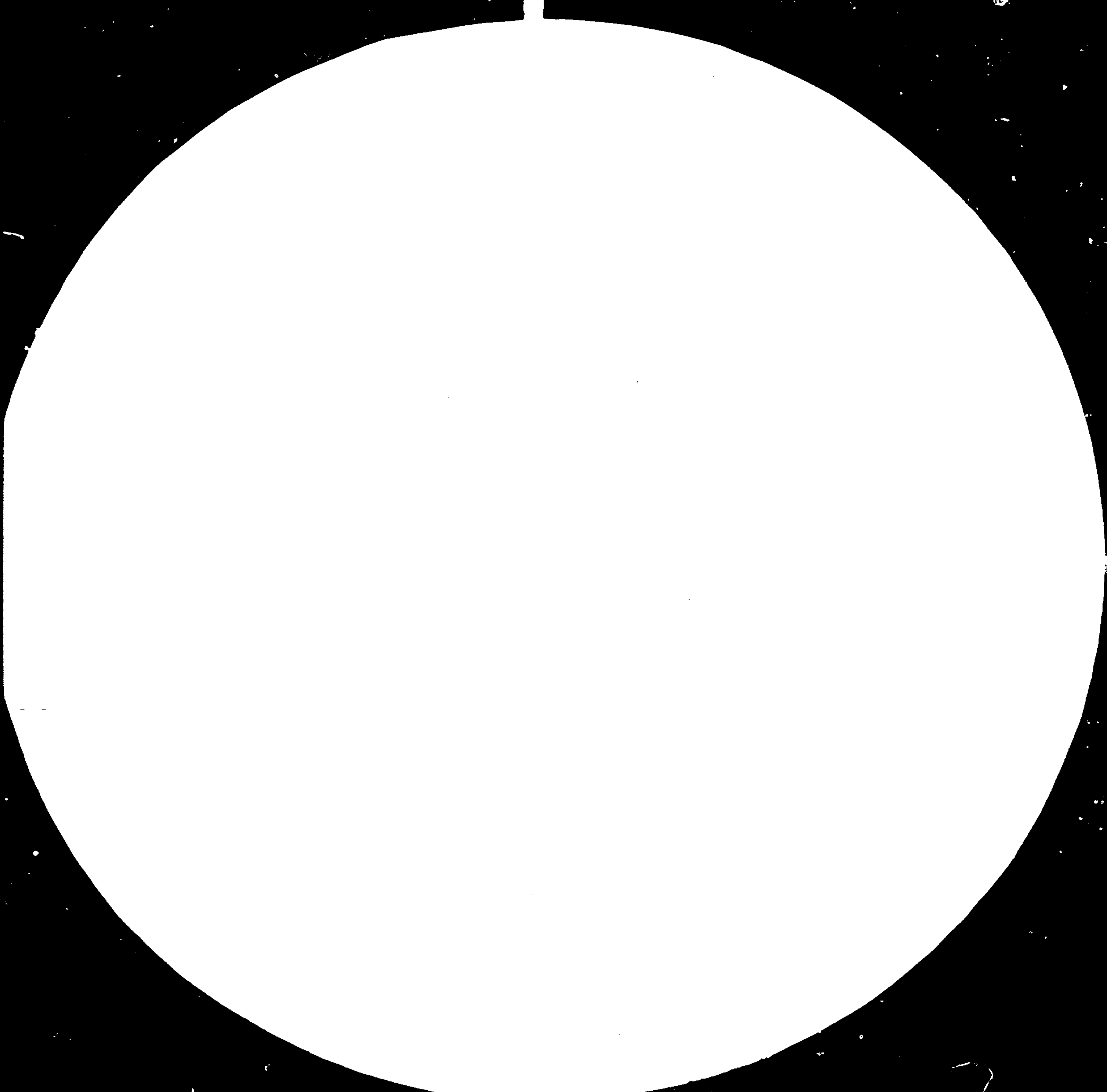

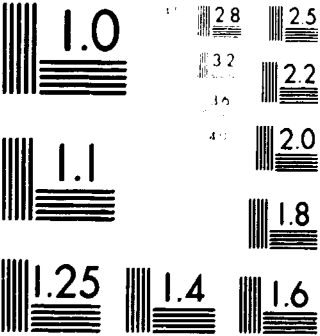

MICROCOPY RESOLUTION TEST CHART

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DRESSING OF NON-METALLIC RAW MATERIALS

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CONTENTS

1. Introduction

The indisputable fact is that the demand for ceramic and other non-metalic raw materials is increasing and the amount of quality materials available for direct processing becoming less and less, and above all, more expensive. This compells the preparing and using of raw material deposits of inferior quality and incluing new dressing methods and technologies.

This means, that the processing methods which are applied must be suitable so as not to influence the properties of finished products in a negative way. Of course, the processing methods applied must be within economically acceptable limits.

All important chemical, technological and mineralogical properties of non-metallic raw materials will be discussed in other papers. In this paper will be shown the most interesting and important dressing methods and their possible combinations.

2. Air separation

Air separation of non-metalic raw materials belongs to most important dressing methods, especially for preparing special fillers for rubber, plastics, paper and other industries.

The engineer or plant operator dealing with air separators must, of necessity, familiarize himself with the basic principles involved in air separation and must be able to analyze separator performance if he desires to approach the subject with any degree of certainity. The engineer is constantly confronted by the necessity of determining efficiencies of such equipment, as well as to ascertain total loads, circulating loads and tonnages of finished product, while the operator is frequently interested in making these same determinations. It is not always feasible actually to measure loads in the ordinary way, and given certain known data, it is customary for those, who have mastered the fundamentals of air separator calculations to compute the unknowns by the use of formulas.

While not incumbent upon the investigator to defend the use of mathematics in treatiing an engineering subject, it may be said at this juncture that a critic comes forward with the pronouncement that formulas are af academic interest only in this connection, and results, not abstruse calculations, are what count in the long run. Granting that certain problems associated with separatoe performance may by solved by the application of simple arotmetic, or that results may be approximated by the employment of rule-of-thumb methods, it does not follow that formulas are no value ehen properly applied. Frequently problems are encountered which do not lend themselves to such casual treatment as has been suggested, and here is where the formula steps into the picture.

The formula, like the straight line, is the shortest distance between two points, and, once having been jotted down in the notebook, no effort of nemory is required to bring it into play, and inasmuch as all formulas employed in the connestion with air separations are equally applicable to other separation devices, such as screens and wet clasifiers, they are of general interest. Manufacturers of separators do not make a practice of publishing formulas and in response to numerous requests they are given here in the hope that they may be of value to many of those interested in the subject. As it has also been asserted that such formulas are purely empirical, which is not the case their derivation will be given.

Air separator in open circuit.

Dealing first with a separator in open circuit, there are three tonnages, which are given consideration, and these are designated as follows:

Total load = X
Finished product = Y
Tailings product = Z

It is also customary to designate the percentages of fines in separator feed and products as follows:

Per cent. fines in feed = A
Per cent. fines in tails = B
Per cent. fines in finish = C

In the following discussion, for the sake of convenience and uniformity, loads will be considered in tons per hour and fineness in terms of material passing 200- mesh, although, of course, any unit of weight or of fineness may be employed.

From the simple open circuit of separator it is oovious that

$$X - Y = Z$$

and $$Y + Z = X$$

or $$Y + /X - Y/ = X$$

It is also self evident that the total amount of fines going into the separato must equal the total amount coming out of the machine. The total input of fines is then represented by AX, the fines in the finished product by CY and the fines in tailings by BZ, or as it may be aexpressed, $B\,/X - Y/$ therefore:

$$CY + B\,/X - Y/ = AX$$

$$CY + BX - BY = AX$$

$$CY - BY = AX - BX$$

$$y\,/C - B/ = X\,/A - B/$$

$$y = \frac{X\,/A-B/}{/C-B/} \quad /1/$$

/Formula for abtaining tonnage of finished product/.

Therefore, knowing thevalue of X and determining the values of A, B and C by sampling and screening, we are able to compute the tonnage of the finished product, Y. However, the total load on the separator is seldom know in advance, and we are more likely to know the tonnage of the finished product.

Transposing formula /1/ we have:

$$X = \frac{Y\ /C - B/}{/A - B/} \qquad /2/$$

/Formula for obtaining tonnage for total load/.

Formula /1/ is developed at this stage principally for the reason that the value of Y as given is necessary in the development of the formula tor the efficiency which follows.

The efficiency of eny selective apparatus, such as an air separator, is naturally the ratio existing between the amount introduced into the machine in a given interval of time. If we feed a separator X tons of material carrying A per cent. fines and recover Y tons carrying C per cent. fines, then the efficiency /E/ is

$$E = \frac{CY}{AX} \qquad /3/$$

But it has just been shown that

$$Y = \frac{X\ /A-B/}{/C-B/}$$

and substituting this value for Y, the formula becomes

$$E = \frac{CY\ /A-B/}{AX\ /C-B/}$$

Cancelling X,

$$E = \frac{C\ /A-B/}{A\ /C-B/} \qquad /4/$$

/Usual formula for efficiency/.

Consequently, by screening samples of separator feed, tails and finished product, the efficiency may be determined at once without regard to tonnage, which determination is not possible by arithmetical methods, where tonnages must be known.

Separator in closed circuit with grinding mill.

In other case where is separator in closed circuit with a grinding mill obtaining its original feed from an outside source, such as a preliminary grinder. Here the tonnage of original feed must of necessity equal finished tonnage, or

tonnage original feed = Y

It thos case we have also a circulating load to deal with, the tonnage of circulating load being equivalent to the tonnage of tails, or

tonnage circulating load = Z

and Z = X - Y

If we know the amount of original feed going into the separator, or if we know the amount of finished material Y coming from the machine, and represent the ratio of total feed to the separator, X, to the finished tonnaxe, Y, by R, we have

$$R = \frac{X}{Y}$$

Substituting in this equation the value of Y as given formula /1/, we have

$$R = \frac{X}{\frac{X\,/A-B/}{/C-B/}}$$

or $$R = \frac{X\,/C-B/}{X\,/A-B/}$$

and cancelling X,

$$R = \frac{/C-B/}{/A-B/} \qquad /5/$$

Consequently, knowing Y, the total load on the separator can be determined very readily by multiplying Y by R.

Also by transporting formula /4/ we find,

$$B = \frac{AC\,/1 - E/}{C - AE} \qquad /6/$$

In a similar manner we also determine

$$R = \frac{C}{AE} \qquad /7/ \qquad X = \frac{CY}{AE} \qquad /8/$$

$$\text{and} \quad Y = \frac{AEX}{C} \qquad /9/$$

Using a case with separator in closed circuit with grinding mill, an example will be given.

Original feed to the separator carries 45 % of 200- mesh material and amounts to 60 tons per hour. The total separator feed runs 60 % 200-mesh, separator finish 90 % 200- mesh, tails 36 % 200-mesh, and these are reground in a tube mill to 72 % 200- mesh.

To determine load, feed and efficiency.

It is desired to know total load on the separator, the tonnage of tube mill feed and separator efficiency.

$$\text{From } /5/ \qquad R = \frac{/0{,}90-0{,}36/}{/0{,}60-0{,}36/} = 2{,}25$$

Then total load

$$X = 2{,}25\ Y$$

or $X = 2{,}25 \times 60 = 135$ tons per hr.

Total tube mill feed,

$$Z = X - Y$$

or $Z = 135 - 60 = 75$ tons per hr.

Efficiency

$$E\ /4/ = \frac{0{,}90\ /0{,}60-0{,}36/}{0{,}60\ /0{,}90-0{,}36/} = 66{,}67\ \%$$

Other possibility is, when the original feed by- passes the separator. Here the original feed must equal Y as before, and in this case the tube mill feed is a composite, whereas the separator feed in the second case is a composite. Calculations are made for this case as already indicated.

In the next example is represented an actual problem encountered in a plant where a pair of separators, running in paralell, were handling a original feed from preliminary grinders carrying 48 % 200- mesh. The separator finish ran 93 % 200- mesh, and tails 43 % 200- mesh. It was ascertained that the tube mill was grinding at the rate of 50 tons per hour. Not being convenient to measure the tonnage of separator finish, tonnage and original feed, the problem was to compute the amount of finished material coming from separators.

These examples of dealing with separator formulas illustrate the ordinary problems encountered in separator work, and it is apparent that no particular skill is required in the application of the formulas, as they are extremly simple, yet they provide at once a means of eliminating a guesswork and approximations.

They will be found of particular value in the design of grinding plants in which grinding units are employed in closed circuits or where separating devices are to be used for the purpose of scalping mill feeds in ordinary open-circuits operations. They are of equal importance in checking the perfomance of existing separator installations where it is desired to determine accurately the results accomplished, or to forecast the results which may be anticipated from proposed changes in hook-up.

It may be mentioned in passing that errors either in screening samples or in recording the results of such screening may be readilly detected by the application of formulas for computing loads or efficinecies at various points of the screen scale.

3. Drying and heat treatment

Many industrial minerals are subjected to some from of heat treatment before they reach marketable form, and the equipment used for this purpose may make up a substantial part of the capital cost of the whole treatment plant, besides contributing significantly to direct operating costs, mainly trough fuel consuption.

Most commonly minerals are heat treated for one fur four purposes. The most elementary, but probably the least frequently encountered, is simply to heat the mineral to a given temperatureto facillitate subsequent processing.

For instance, raw material, such a nepheline syenite may be heated before they are passed to magnetic separators for impurity removals. Here the object is to render the minerals in the crude ore more susceptible to separatoin. Minerals may also be raised to an elevated temperature to bring about drying. Examples in minerals treatment are legion, with the drying of sand on the one hand and of fine clays on the other representing two extremes of ease of processing.

Roasting or calcination may follow drying, or may be practised independently, when it is necessary to induce more profound changes in a mineral, such as those involving deep-seated alterations in crystal structure or chemical composition. Examples of calcination reactions may be found in the manufacture of quicklime from limenstone, in which a chemical reactions takes place, and in the production of periclase from magnes ite, where alterations in crystal structure are important. Malting and sintering are brought about by heating the mineral to a temperature close to or above its fusion point and may be precesed by both drying and calcination reactions. The purpose of entering the fusion regime varies, crude sulphur may be melted as a preliminary to purification with adsorbents. Minerals such as perlite are raised to higher temperatures and caused to bloat through the formation of steam arising from chemical denydration reactions occuring within the particles.

Table 1: Some examples of minerals heat treatment (1)

mineral	process	purpose of treatment	solid exit conditions		typical equipment
			temp.°C	moistrure %	
kaolin	drying	provide commerc. acceptable product	50-90	0,5-10	spray dryer- drum dryer belt dryer- rotary dryer fluosolids dryer
ball clay	drying grinding	provide fine dry poweder	50-90	0,5-3	drying grinder,ring dryer
bentonite	drying	provide dried product	50-80	2-12	rotary louvre dryer
limestone	drying heating calcination	filler lime production	1300	0,2-1 0	rotary dryer/heater fluid bed; shaft kiln rotary kiln, calcination kiln
gypsum	plaster manufacture	removal water of crystal	160	5	rotary kiln; fluid bed screw conveyor dryer pneumatic conveying dryer
graphite	drying	remove moisture from wet process graphite	50-90	low	rotary dryer

Table 1: Some examples of minerals heat treatment (2)

mineral	process	purposo of treatment	solid exit conditions temp. °C	moisture %	typical equipment
feldspar	drying	dry concentrates	50-90	$< 0,5$	direct fired rotary dryer
barytes	drying	dry concentrates and crude		< 1	fluid bed dryer film dryer, rotary dryer
quartz sand	drying		100	0,5-3	rotary dryer; fluid bed
diatomite	drying calcination	dry concentrates remove organic matter			rotary kiln; drying grinders
kaolin	calcination	molochite production	1000	0	direct fired kiln
tripoli	drying	dry mill feed			air dying; rotary kiln
magnesite	calcination	dead burned or caustic magnesite	1200-1700	0	direct fired rotary calciner; multi-hearth furnace
fluorspar	drying	dry concentrates	50-90	low	direct fired rotary dryer

Simultaneous partial melting of the mineral leads to foams which becomes strong on cooling and are useful as lightweight aggregates. Futhermore, the fusion reactions occuring in bloating are preceded by drying and then calcination. Thus the division chosen here must be seen as somewhat arbitrary, with one merging into the other as the mineral temperature is increased. Some examples of heat treatment processes applied to some typical minerals and of the typical equipment used, are set out in table

Whatever the purpose of the treatment, heat must be supplied to the mineral if its temperature is to be raised. Whilst other methods of heating are available, such as electrical resistance heating, frictional heating, and dielectrical heating, industriacl mineral are almost invariably heated by conduction or radiation.

Chemical reactions often occuring during calcination. These can be either exothermical or endothemic, the former leading to the production of heat, and the later to the consumption. The chemical reaction may occur at temperatures only slighly above the boiling point of water, as is encountered in the removal of water of crystallisation from some salts, or it may procees only at high temperature, as is exemplified in the chemical reaction ivnolved in lime-burning, which proceeds satisfactorilly only at temperatures above about 900°C and is endothermic, absorbing much heat.

Again, many complicating factors exist. Examples may be found in phosphate rock calcination and in limeburning. Rock phosphate can be dried to 2-3 % residual moisture content using a drying gas temperature of 140°C, but temperatures of about 1000°C are needed to remove organic matter present in the crude rock. The rate at which residual air in the cobustion gases used for drying can difuse into the particles, thus oxidising the organic impurities, can be important in determining the rate at which calcination proceeds.

High temperatures and special types of equipmenr are normally required for mineral treatment process involving sintering and melting. The heat balance requirement is that sufficient heat be supplied to raise the solid to its melting point (during which operation both drying and calcining reactions may occur), and the further heat (the latent heat of crystallization) to turn the solid (or in sintering reactions, a part of it) into a liquid, and then the further quantity of [illegible] to raise the liquid so formed to a temperature sufficiently above its melting point as to enable the melt to be further handled without premature solidification. Where sintering is involved, it may anly be nesessary to raise the mineral to a temperature sonewhat more than two-thirds towards its melting point. Here the atoms constituting the mineral crystals are often mobile enough to migrate across junction points and thus to weld them. The samo heat transfer mechanisms apply as previously outlined, but because of the higher temperatures generally involved, radiatiot tends to play a more dominant part than conduction.

Equipment selection for the heat-treatment of raw materials tends to be carried out by a process of elimination. Several options may be found feasible, and so the final choice has to be made on the basic of operating experience, capital and operating cost etc. Local conditions, especially with respect to fuel cost and availabillity, may strongly affect the later. When new processes are being considered, smale-scale tests on pilot plants, often available at the plant suppliers, are frequently needed to assist rational selection and to demonstrate the characteristics of the heat-treated product.

The factors of greatest significance in equipment selection are: the maximum temperature the mineral must reach, the nature of feed materia - moisture content, particle size, chemical composition; the heat-treated desired-moisture content, particle size, chemical and physical conditions. Other factors taken into account when selecting equipment are: the physical characteristics of the mineral during heat-treatment; compatibility of the mineral with fuel combustion products; particle size chenges during treatment in relation to product size specifications and dust-loss prevention; corrosion and abrasion problems both from the equipment viewpoint and with regard to product contamination; undesirable heat sensitivity in the minerla; scale of operations; types of available fuel.

No real satisfactory methods of classifying heat-treatment equipment has been evolved. A most important distinction can be found between direct and indirect heating. Where there is direct heating, hot gases recunting from fuel combustion are brought directly into contact with the mineral. When indirect heating is practised, the hot combustion products are passed through a separate compartment, heating its walls which both contain the mineral a transfer heat to it. Directly heated equipment can be made to fuction in the same way as indirect equiplment by the use of an axternal heat exchanger, but this is unlikely to be more economic than selecting the appropriate indirect heat treatment unit.

In most cases tere are used following types of dryers and kilns:

tray and tunnel dryers and kilns
hearth dryers and calciners
direct rotary dryers and calciners
drum or film dryers
pneumatic-conveyor dryers
spray drying and roasting
fluid bed drying and roasting
shaft-kiln calciners
and special furnances for melting and miscellaneous processes.

4. Photometric separation

Photometric concentration in its simplest form is the oldest process known to mineral dresser. Agricola called in 1556 this process as hand sorting. In a present time existing optical separators in different sizes and types. This functions are:

- presentation of the particlos for inspection
- optical inspection of the particles and conversion of the optical signal into an electronic signal
- decision making on whether the signal is significant
- removal from the feed of those particles which were recognised as removable.

The optical inspection is a main part of this dressing process. Agricola s plant used human eyes for inspection with their inherent subtlety. An eye can simultaneously see colour, shade, shape, lustre and transparency. These criteria are almost always sufficient for the optical recognition of a mineral.

In mechanising the optical inspection an inanimate unintelligent photometer takes place of the human eye. Its only advantage is that it can work beyond the visible light range. To make the recognition and decision making meaningfull we have to reduce to the simplest terms the optical quality we are looking for.

The method of particle inspections has also to be simplified.

Photometric proporties of a mineral particle surface were listed above as: colour

shade

lustre

transparency

The first three are referred as a surface reflecting properties. During any surface inspection the particles are illuminated and the reflected light is monitored with a light sensor.

Colour and shade are the most generally usable criteria for discrimination between mineral particles. However, colour is a confusing quality. To begin with the same colour can be obtained in different brightnesses or shades. Then the colour of the light incident on the surface also affects the appearance of the reflected light. Furthemore no known light sensor has the samo sensitivity to the light radiation of all colours. Only a spectrophotometer can therefore be relied on to give a true representation of colour.

Fortunately in optical separation we are only interested in comparative measurements. Therefore, so long as the same light illuminates all the surfaces being compared and the same type of sensor measures the light reflected from each surface, the spectral distribution of the incident light and the spectral response of the light sensor are not of direct interest, as long as they are adequate in the spectral range of interest.

To assess the colour of a particle completely it would be nesessary to determine the spectral response of each particle over the complete range of light radiation. This is impracticable and unnecessary in practice. Usually it is sufficient to isolate a narrow spectral range from the total reflected light using optical light filters and then to measure the intensity of the reflected light in that range.

In using a monochromatic photometer to detect colour differences between surfaces, the choice of filters is critical and is chosen to emphasize the solour diferences. Typically a minimum 5 - 10 % surface reflectivity difference is required on a commercial type photometric separator. (Reflectivity of Magnesium Carbonate is 100 %).

In the foregoing it has been assumed that each particle is entirely of one colour or shade; similar colour determinations can be applied to middlings or intergrown particles. However, with these for succesfull colour discrimination the discolouration of a minor constituent of the particle has to be intense to facilitate detection. Frequently the refraction of light in the dust coating of particles interferes with efficient inspection. To overcome this effect the particles may heve to be wetted to reduce refraction and to "develop" the colour. Significant surface coatings of dirt or slime of course have to be washed off before considering optical inspection.

The lustre of a particle surface is a valuable diagnostic feature to the human observer. However, in photometric inspection specular direct light reflection from a shiny surface into the light sensor observing the particle is liable to mask the small changes in reflectivity due to colour or shade changes. Tjis is undesirable. Earlier commnets refers entirely to difused reflection from the particle surface. Specular reflection can be avoided by illuminating the particles with diffused light /therefore making the specular reflected light diffused/. The optical inspection units in existing sorting machines are usually constructed to provide uniform diffused illumination of the particle surface and to avoid direct illumination.

An alternative possible technique is the use of polarized light to illuminate the particle with polarizing filter in fron of the light sensor, crossed with respect to the light source filter. In this way the direct specular reflection is blocked off from the light sensor and only diffused reflected depolarized light is monitored. However, specular reflection is not always a detrimental effect and in fact the National Coal Board in Britain has developed sensors which differentiate between hard and bright coal on the basis of lustre.

Transparency can be a vuluable optical recognition feature of minerals. The principle used in the depolarization of *plane polarized light in the course of internal reflection* within a translucent particle.

So far this principle has only been used in sorting diamonds from gravel. Light can only reach the sensor when a translucent particle is placed between the crossed polarizing filters. Direct light from the light source is prevented from reaching the light sensor. The functional specifications of optical sorting machine are as follows:

feeding:	by vibrating feeder
particle acceleration:	by gravity
lining up the pieces:	by the combined action of a vibrating trough and the "V" shaped groove of the carrier belt
delivery of particles for viewing:	by conveyor belt
location of inspection point:	air
illumination of particles:	diffused
method of spectral range selection:	optical filter in photometer
method of inspection:	the particles are seen through a stationary horizontal slit as they fall through the viewing area
type of background:	matching
method of colour detection:	monochromatic photometer using photocells
method of product seggregation:	by air jet switched on-off at high speed

To ensure that the rejecting air blast does not blow dirt on the lens system, the ejector does not operate untill the reject particle has cleared the optical zone.

Optical sorting is particularly effective in the preparation of industrial minerals where the product in frequently priced by colour. Often the only alternative to optical sorting is hand picking. Know applications include concentration of barytes, dolomite, felspar, flint, flint clay, gypsum, lime, limestone, magnesite, rock salt and talc.

Industrial minerals are often amenable to sorting in the 6 - 20 mm size range by virtus of the usually course liberation size. By using optical concentration one or more of the folowing benefits may be obtained.

1. Superior grade of product may be produced by treatment of current concentrate product.
2. Production capacity may be increased by recovery of a marketable product from current waste.
3. Mine life and production may be increased by retreatment of waste dumps.
4. Mine life may be extended and production costs may be lowered by avoiding the need for selective mining.
5. Preconcentration may be possible in some metal producing mines by separating vein rock from country rock.

5. Classifying of non-metalic raw materials

In the mineral dressing and chemical industries the design of comparable equipment show broad differences in complication and sophistication. The ultimate aim of the designer is to achieve simple and clearly understood designs even for the most complicated process functions. But, in paralell with the trend tosimplification the bodyof scientific and technical knowledge does not decrease, it rather increases. The hydrocyclone is a particularly good example of the development of a separation principle which has reached optimal function characteristics in a simple design.

Hydrocyclones belong to the class of wet mechanical separators; they are used for the treatment of suspensions, slurries and sands. In certain ceases they can be applied as separators for those suspensions of fine particles in liquids which result unavoidably from processes of raw materials treatment. The degree of clarification of the fluid phase and prethickening of the solid phase to obtain barely pumpable slurries is limited by the correlation between the particle size dostribution and the 50 % cut point size of cyclone. The sorting of suze particle size distributions in a suspension stream. Suitable suspensions are created initially by adding a carrier liquid - ussually water - to bulk particles with the intention of using a wet classification method.

The separation methods using hydrocyclones are characterised by two significant points. On the one hand they are operated continuously, which by the way- makes a flow control necessary. On the other hand they use high centrifugal accelerations which is the reason for the remarkable fact, that good separation effects are obtained under high load conditions although residence time of the suspension within the cyclone body is low.

To use the hydrocyclone to its best advantage, carefull attention must be given to the hydraulic design of the cyclone body and the adjacent sections of the piping system of the process plant. Here lies the high degree of requiored "know how" which might, at first sight, lead to the opposite of the simple looking design. But the simple shape of the cyclone reduces the number of degrees of freedom of the geometric and hydraulic parameters to a relatively small number. Troughout the history of hydrocyclone development badly designed homemade cyclones have brought undeserved discredit to t is kind of device. However, the carefull detailed work of the specialist designers has brought the hydrocyclone in the last decade to a high standard of development.

The applications of hydrocyclones in raw materials dressing arise from its ability to separate particle suspensions in accordance with particle size and solid concent.ations. As mentioned, the main application lies in flow classification.

These applications include the elimination of oversize particles, e.g. in the closed circuit grinding process, and for the desliming.

These operations are important in the fields of industrial minerals dressing. Hydrocyclones have been used succesfully in kaolin, coal, glass and foundry sand refining. Scalping to eliminate the wear caused by coarse fractions, and attemping to prevent damage to post-connected apparatus are important, e.g. protection of calander cylinders in the pulp and paper industry. Fine particle elimination (clay components and milling dusts), called desliming, is very important in gravel washing plants and ahead of flotation cells. In all these cases the concomitant thickening of the coarse fraction to a pumpable sludge is desirable.

For celaning washwaters and other waste waters, however hydrocyclones are less common, because of the limitations associated with classification applications. Nevertheless, in non-metalic and ore washing plants, in a later case in bypass circuits, hydrocyclones are used to some extend.

Hydrocyclones have proved to be good classifiers of coarse particles recovered from wash waters in ore mills. Some industries also use hydrocyclones for prethickening to increase the solid capacity of screens, filters and centrifugals or to reduce the loading of sedimentation basins and gravity thickeners. Plastic producers use cyclones when handling granulated polymers.

An important application is the sorting of minerals by heavy media processes, either to handle the fine mineral suspensions in the quasi stable heavy media fluids or to regenerate these liquids for use in circulating systems. Because of the large amount of literature on this subject these problems will not be discussed in detail.

Because they heve no rotating parts hydrocyclones can be built from materials that are difficult to machine, i.e. those that tend to be most resistant to abrasion and corrosion. Cyclones which have to handle corrosive liquids are made from stainless steel, porcelain or injection moulded polymers (e.g. polyamids).

To resist abrasion, hydrocyclones are made from grey or white cast iron or even iron plate with rubber lining. When installing large numbers of small cyclones it is very important to connect them in parallel in such a way that all single units are fed with suspension at the same pressure and flowrate. This is done by arranging them in an annular group. Only with a smallest cyclones, of with thousands may be needed, may it be necessary tu built true multicyclones, which have not only a common feed chamber but also hermetically sealed common chambers for overflow and underflow. Medium size cyclones are connected in annular distributor arrangements (spiders) with a common feed chamber but open chambers for separate discharge of overflows and underflows of all individual cyclones.

Although hydrocyclone techniques have been highly developed further advances are still possible. For example, the components inside the body of the hydrocyclone can be arranged to achieve better streaming or to improve division into ranges of different characteristics.

But there is a danger of sacrificing operational versatility which is typical of simple cyclones. A cyclone with a restricted vortex stream must be run under constant conditions in respect to pressure and feed capacity as well as feed concentration. Even nozzles cannot be exchanged without rearranging the inner components. With standard cyclones the range of optimum function in broad with respect of several parameters such as pressure, diameter relationships of the nozzles, feed concentration and viscosity. Cyclones modified internally may get somewhat better separation results but the range of operating conditions is narrower.

Nevertheless, some methods of dividing the cyclone volume have proved to be succesfull, e.g. Krebs double cyclone with a main cyllindrical body and a separate cone beneath. The cyclones with an additional chember for introducing washing water are also interesting.

Its lack of rotating parts is still the dominant advantage of the cyclone. The idea of feeding the suspension by rotating impellers instead of using tangential feed pipes under pressure, has been abandoned because of abrasion problems and the reduction of the separation effect. Also, the full possibilities of fitting the cyclone body with rotating inner walls driven by the fluid itself have not yet been realised. This arrangement would have replaced the typical vortew flow pattern with the shearing forces with a solid rotating mass. Perhaps the idea merits further exploration but the compromise between the two principles- cyclonic and centrifugal- would have to be investigated.

Cyclones fed with suspensions under pressure, via stationary worm-like impellers, have hitherto given poor separations. This is a pity because machines of this type are easier to construct, particularly in small sizes. Still greater problems have been caused by the axial cyclone which uses a similar fixed impeller together with a paralell current of fine and coarse fractions so that the underflow discharges concentrically with the overflow from the end oppsite to the feed zone. In this device no secondary vortex is generated inside the cyclone which obviously in important for the cut point of the unit. The further development in the direction of higher operating pressures may have some succes in the future if the problem of increased abrasion is solved and if energy costs could be reduced.

One succesfull construction technique which will surely influence future developments in the manufacture of cyclones with very smooth inner surfaces. The improved performance of these cyclones appears to be connected with the laminar boundary layers in the liquid at these surfaces. It is well known, that these layers are important in all problems of flow technique (e.g. the design of aircraft and rockets).

In the case of cyclones it is therefore necessary to manufacture carefully formed geometrical shapes to avoid secondary eddies. The flange connections between the cylindrical and conical parts of the cyclone must be quite smooth, with no seams. The change from cast iron to rubber lining was the first step in this direction. However, some handwearing natural rubbers which are vulcanised under hot and humid conditions develop a rough surface which is unsuitable for fine particle classification. For this duty rubber must be vulcanised in very smooth moulds.

The nuclear energy industry has contributed to hydrocyclone development. Small cyclones of 4 to 5 mm diameter vith 1 - 2 mm diameter nozzles are used to separate corrosion product from the recycled liguefied radioactive fuels. These machines are not yet used for other duties but they open up the possibility of reaching cut point values in the range of 2 microns.

To summarise, it is obvious that the development of hydrocyclones is still in full spate and that new fields of application will be created, especially those involving fine and very fine particles.

6. Flotation of non-metalic raw materials

In the preparation of feldspar, especially from raw material containing pegmatite, the flotation process is gaining in importance, side by side with the previously used mechanical and electrostatical methods. The first industrial application of feldspar flotation, at a plant in Maine, USA, was reported by O'Meara, Norman and Hammond in 1939, when feldspar was removed from a hydrofluoroacid suspension, using lauryl amine hydrochloride as a collector. This process has so far proved to be the most suitable for the feldspar-quartz flotation and is employed in maly plants for the stage-by-stage winning of commercial feldspar, quartz and mica concentrates from pegmatite. A feldspar flotation in Findland, the first in Europe. even produces the feldspar concentrates with diferent K_2O / Na_2O ratios. Scientific investigations on the separation of the individual feldspar minerals from each other by flotation have up to now only been carried in the USSR.

In the kaolin industry, flotation has only been of minor importance. Carrier flotation is employed at the Mc Intyre, USA. The fine grained rutile contained in kaoline is deposited on the surface of a coarser carrier and floated off, leavind the purified kaoline. The flotation method for separation non-metalic used are similar to know methods in ore beneficiation and for this reason will be not more detailed discussed.

7. High intensity magnetic separation

Despite the fact that the ability of magnetite to attract iron and steel has been known for over 2500 years, detailed studies of magnetic properties of rock and minerals started only in the latter half of the last century, when the theory of magnetism and methods of its estimation became sufficiently advanced.

All substances, including rocks and minerals, can be sub- divided into three groups according to their magnetic prperties- ferromagnetic, paramagnetic and diamagnetic.

Ferromagnetic minerals possess very large positive values for magnetic susceptibility, which changes markedly in relationship to the strenght of the magnetizing field. Each of the minerals of this group is characterized by the hysterezis loop a specific form. Magnetite, pyrrhotite and a few others are ferromagnetic minerals. Recent investigations have established that the cation Fe^{3+} is the carrier of the ferromagnetic properties and that ferromagnetic minerals have a metallic bonding. Paramagnetic minerals are distinguished by relatively smallpositive values of magnetic susceptibility. These minerals, as well as diamagnetic ones have a ionic or covalent bond. The majority of minerals fall into this group.

Magnetic characteristics of minerals and their accurate determination achieved special interest principally on account of the development of magnetic and electromagnetic methods of ore concentration.

As well as the differences in specific density of minerals and mineral raw materials were a base for their separation, so the different magnetic properties serve to their benefication. The separation of sroungly magnetic ores, especially of iron ores has become a current dressing process since many years. On the other hand the separation of slightly magnetic raw material has not yet been accepted as a widely applied benefication method. One of the main reasons is the fact that a magnetic field of high intensity must be applied in separating weakly magnetic minerals, besides size of particles of minerals to be separated must be taken into account as well as the resulting relatively lower output of magnetic separators, higher consuomption of power and futher technical parameters connected especially with construction of separators. In wet magnetic separation the molecular attractive forces between particular particles have not a substantial effect on the result of the process. Nevertheless, complementary forces originate and act here, the most important of which is the resistance of the milieu against the transit of particles; the decreasing of their sizes brings about increase of the resistance.

Therefore smaller particles migrate slower under the influence of magnetic forces that the large ones. Consequently the magnetic and non-magnetic particles fail to get separated within the short time of their transit through the magnetic field of the separator.

High intensity-high gradient magnetic separation can be applied for beneficiation of many industrial minerals to improve quality by removing weakly magnetic impurities and to maintain close tolerances in quality specifications. New products may be produced and marginal reserves of industrial minerals can be increased. There are also cases when minerals can be concentrated by the association with or impregnation of magnetic material. One example of this kind of application will be given together with several purification application examples in the following section.

There have been attempts to apply conventional high intensity magnetic separation for purification of industrial minerals for limited success. The impurities are generally very weakly magnetic and are often of small particle size. The advance of the new high gradient magnetic separation technology expands the technical possibilities far beyond previous limitations. One good example of the different capabilities will be given later. Another is the development of magnetic separation to high brightness kaolin clay, which is the subject for another paper.

For most applications other than high quality clay and very fine filler beneficiation, the continuous high gradient magnetic separator would be the preferred device from a technical and economic point of view. When the content of the magnetic product increases, and with higher flow rates, the collecting matrix will become loaded more rapidly, which reduces the duty cycle for a batch-operating machine as the rinse and flush times will vary to a lesser extent than the feed time. The processing of coarse materials is more reliable with a continuous method due to less settling problems. Industrial minerals applications which have been demonstrated on a laboratory scale are:

- Beneficiation of high brightness kaolin clay
- Upgrading of ceramic clays
- Cleaning of glass sand, quartz/feldspar products and fluorspar
- Cleaning of nepheline syenite
- Cleaning of baryte, wollastonite, asbestos
- Brightness beneficiation of talc, chalk and other calcium carbonates, and baryte
- Cleaning of crushed, incinerated glass flotation products
- Cleaning of kyanite
- Upgrading of bauxite and other alumina raw-material
- Beneficiation of (iron-rich) spodumen

Some contaminants, such as organic matter, cannot be removed magnetically while bleaching is more effective. In general, the higher the GEB rating of the feed material, the less the increase in brightness achieved by magnetic separation. But a few points at the top of the scale also mean a groat increase in the value of the product.

The purification of ceramic clays has attracted relatively little interest as most of those are related to small capacity plants. However, for large plants the economics of applying high gradient magnetic separation are more than justified, and English China Clay has now a large installation for the production of potting clay. In oder to maintain close tolerances for the quality it would not always be necessary to use the highest magnetic field intensity available or low flow rates (long retention time). In fact, many ceramic clays respond favorably at as low magnetic field as 5 to 10 kg (0,5 to 1 tesla). In such instances, even small capacities would be of interest. One example of a typical test result is given here. A ceramic clay sample containing 2,15 % TiO_2 was processed in the high intensity magnetic separator and the content was reduced to 0,42 %. By using a conventional magnetic separator the TiO_2 content was reduced to 1,95 % only.

One of the problems in testing glass sand samples is the difficulty in obtaining valid chemical assays of the product.

Even when sophisticated sampling techniques and adequate sample preparation methods are used, various laboratories will report different assays on the same product. For example, after careful checking, one laboratory reported a content of 0,093 % Fe_2O_3 for a particular sample, while a second reported 0,076 % for the same sample, and a third reported 0,063 %. In one case, the iron content of an optical-quality quartz was reduced to about 10 ppm, which demonstrates that the practical limit for high gradient magnetic separation of minerals is dominated by the degree of liberatoon of the magnetic contaminants, and that even ultra-fine, weakly magnetic particles can be separated.

Cleaning of feldspar and quartz products for ceramic use is similar to glass sand applications.

Purification of nepheline syenite is similar to glass sand applications, although the mineralogical properties of this material seem to prevent reduction of the Fe_2O_3 content to ultra low levels. For ceramic end-use, however, this does not seem to be too important as practically all visible dark mineral particles are removed thus eliminating stain problems. In one comparative test, a nepheline syenite sample containong 1,0 percent Fe_2O_3 was cleaned to a content of 0,186 percent at an 80 percent weight recovery; with another high intensity separator, a content of 0,36 percent Fe_2O_3 was obtained; and with yet another, a content of 0,30 percent resulted.

Upgrading of baryte products to high quality filler or for chemical use is demonstrated. A sample with less than 90 % $BaSO_4$ and about 2 % of R_2O_3 (Al_2O_3 and Fe_2O_3) w processed through a high intensity separator and a product with 90,5 % $BaSO_4$ and 0,63 % R_2O_3 at high Ba recovery was obtained.

Wollastonite and asbestos cleaning are other possibilities demonstrated with a less efficient wet high intensity magnetic separator.

The beneficiation of talc, chalk and other white minerals to improve the brightness is similar to the kaolin clay applications. However, the results on talc are sometimes not impressive as the wet processing interferes with the special properties. On chalk the brightness improvement has been more significant, up to about 4 brightness points in some cases. Reduction of iron from 0,090 % Fe to 0,020 % Fe at product recovery of more than 99 % is a further illustration. Specialty quality of baryte can be achieved for use as a filler in paper manufacturing.

The cleaning of incinerated, crushed glass from a waste recycling process will make the product suitable for glass-making use. A large plant for extensive waste recycling is under construction in Rochester, New York, USA. It is reportedly the first of its kind with the high recovery of all contaminants. The start-up will be during 1979.

One Carousel Separato Model 185-10-00 will be used to maintain the iron content of the glass material to a level less than 0,01 % Fe. The capacity for this small machine is 16,6 TPH for one magnet only. The machine can be equipped with two magnets to double the capacity.

The cleaning of kyanite to low levels of iron content is important to maintain good refractory properties. In one demonstration it was shown that high gradient magnetic separation was capable of obtaining the same results as a magnetizing roasting followed by low intensity magnetic separation. Tremendous saving would be realized if a high gradient magnetic separation process were substituted for the roasting as the cost for the kiln process with its expensive reducing atmosphere would be eliminated.

Several applications exist for bauxite processing, and reductions have been achieved at high process capacities and relatively low magnetic field intensity from about 11 % Fe_2O_3 to about 5 %, while other ores with 5 % Fe_2O_3 and 2 % TiO_2 could be upgraded to about 1,5 % Fe_2O_3 and 1,4 % TiO_2, respectively.

A related application is the processing of anorthosite. A tailings material obtained in pilot flotation operation for Cu and Ni minerals contained 20,5 % Al_2O_3 and 0,5 % Fe_2O_3; using the magnetic separator, a final product was obtained of 28,1 % Al_2O_3 and 2,1 % Fe_2O_3 at an 82 % recovery of Al_2O_3.

Successful results are reported for test on phosphate materials of both sedimentary and magmatic origin. The most attractive application seems to be cleaning of phosphate concentrates obtained by flotation. In one case the feed, a flotation concentrate of a sedimentary deposit sample, had more than 5 % Fe_2O_3 and more than 0,3 of the ratio $\frac{1+Al}{P_2O_5}$. It was possible to reduce the iron content to 1,79 % Fe_2O_3 and 0,026 for the ratio $\frac{1+Al}{P_2O_5}$ at high recovery. The final P_2O_5 content was 39,9 %.

On a sample of magmatic origin it was possible to reduce the dolomite content by virtue of unusual high amount of iron in this mineral. On a flotation concentrate with 0,04 % K_2O, 0,38 % Fe and 0,47 % MgO, the nonmagnetic product from the high intensity separator had a content of 0,02 % K_2O, 0,07 % Fe and 0,15 % MgO. The content of P_2O_5 in the final product was 40,0 % at high recevery (92 = %). Interesting reductions achi[illegible] on samples from other parts of the flowsheet were also realized.

The impregnation of iron in minerals may in some cases make it possible to magnetically recover such minerals equipped with such a "magnetic handle". One oxample will be given here. Spodume in one lithium mill tailings sample has been recovered at about 80 %, giving a product with 0,92 % Li for further processing, while final tailings contained 0,046 % Li.

While pure spodume cannot be recovered magnetically, the iron content in it, in this case, generated a sufficient magnetic susceptibility for its recovery by high gradient magnetic separation. Other examples are the separation of (iron-rich) feldspar from quartz and iron-containing dolomite from a phosphorite concentrate metioned above.

The applications of most interest, at least initially, are for high value minerals and in cases where conventional methods have failed to meet the technical requirements. This is more related to the usual conservatism in the mineral industry in accepting new process methods than to the economics of high gradient magnetic separation. High intensity magnetic separation had a reputation to be relatively expensive, but the new high gradient magnetic separation technology development often makes the total process economics more attractive than before. Being a physical process, the costs for chemicals and subsequent costs for environmental control are reduced to a similar extent as for currently used conventional high intensity magnetic separators. In some cases, expensive leaching processes can be eliminated. The high recovery and efficient separation for the high intensity magnetic separators reduces the losses of valuable minerals making the total economic picture brighter than in many cases before.

It is inherent with the high gradient magnetic separation technology that small separators will be very costly per unit capacity while the capital cost is high. However, the costs decreases dramatically with increasing capacity systems and - when considering total process economics - the high gradient magnetic separators will be cost~~s~~ competitive with other methods such as flotation at relatively modest capacities. It is difficult to glive a rule of thumb as all applications are different, but 10 to 20 TPH for standard glass sand applications is an example.

Robinson discussed the economics for a few application examples for small plants. The total process costs for kyanite cleaning was calculated to $0.336 USD/ton, which would represent a saving of at least $4 USD/ton if the surrently used process be replaced. Similar savings are realized for clays for the reduction of bleach chemicals alone.

High gradient magnetic separation has come closer to practical realization in many applications qustide the high quality kaolin clay area. The greater current potencial is the use to improve the quality of other white filler materials and ceramic raw materials. The most significant future potential is the increase of marginal reserves of many industrial minerals.

The development of the high intensity magnetic separatos of carousel type makes high intensity-high gradient magnetic an interesting alternative in many industrial mineral beneficiation flowsheets as this equipment has overcome the operational problems associated with conventional wet magnetic separators.

High gradient magnetic separation is a process that has potencial use to improve present prodzcts, to make new products, and to increase the marginal reserves of many industrial minerals. The brightness of those industrial minerals used as white pigments can be markedly improved in a number of instances.

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