Magnetic Separation News, 1985, Vol 1, pp. 205–232
0731-3632/85/0104–0205 $25.00/0

MAGNETIC SEPARATION IN SOUTH AFRICA

IAN JAMES CORRANS* and JAN SVOBODA
Ore-dressing Division, Council for Mineral Technology, Randburg 2125, South Africa

Abstract The use of magnetic separators in the various mineral processing facilities in South Africa is described. A large number are used to recover medium in dense medium plants. The manufacture of various types of magnetic separation machines by three local suppliers is highlighted. The potential use of high-gradient and/or high-intensity magnetic separation in the recovery of gold, uranium, and phosphate minerals is discussed.

1. INTRODUCTION

The aim of this paper is to present a fairly broad survey of magnetic separation as applied to, and practised by the mineral-processing industries in South Africa. Although the treatment of the subject is by no means exhaustive (any such claim would be naive), it is nevertheless considered that the current aspects are covered fairly adequately.

The mineral-processing industry in South Africa is extremely diverse in nature, extremely active, and of great economic significance by any standards. For the sake of clarity, therefore, the paper is divided into three main sections and, where relevant, subdivisions in terms of the individual mineral commodities are introduced.

---

* Present address: Department of Extractive Metallurgy, Western Australian School of Mines, P O Box 597, Kalgoorlie, W.A. 6430, Australia.

2. INDUSTRIAL APPLICATIONS OF MAGNETIC SEPARATION

2.1. Coal, Diamonds, and Iron Ore (in the context of dense-medium separation)

This grouping of mineral commodities may seem somewhat odd, and it may well be asked what they have in common apart from the large amounts of the element carbon probably contained by the first two. The answer is that, in the recovery of all three, much use is made of dense-medium separation (DMS), in which, essentially, a heavy fraction is separated from a light fraction in a sink-float process involving the use of a finely ground suspension of magnetite or ferrosilicon, or both, in water. The ferrosilicon suspension displays more stability in terms of the settling-out of the particles than the magnetite suspension, and behaves as a pseudo-fluid with a relative density of up to 3,6.

Magnetic separation is used to recover ferrosilicon and magnetite for recycling. The separators used are of the wet drum-permanent magnet type, and field strengths of approximately 0,14 to 0,16T are generated by the use of magnetically hard alloys or ceramic materials like barium ferrite. The individual manufacturers of the separators (as described later) have done a great deal of development work to improve the efficiency of these machines for the recovery of the magnetite or ferrosilicon powders in as pure a form as possible. Other developments in terms of cost-effectiveness, compactness, and capacity are continually in progress.

The estimation of the installed capacity of separators functioning in the above duties is difficult, and no official survey has been carried out as yet. A typical coal-washing plant, treating coal of 100 by 12 mm in drums and of 12 mm by 0,58 mm (wedge wire) in dense-medium cyclones, would have the following components:

(a) a drum plant with a capacity of 800 t/h, consisting of 3 drums, and 4 magnetic separators (i.e. 3 primary and 1 secondary), and

(b) a cyclone plant with a capacity of 500 t/h, consisting of 6 magnetic separators (i.e. 5 primary and 1 secondary).

The whole plant therefore comprises 10 magnetic separators. Typically, each machine would have a drum of between 750 and 900 mm diameter, and be up to 2,5m in width. If a more powerful strontium ferrite with a higher energy product, B·H, is used, the thickness of the wall of a drum can be increased, and drums of large diameter up to 4m in width can be manufactured. For drums with a diameter of 600 mm, the capacity of the separator is about 40t/m/h, whereas with a diameter of 1500 mm, the capacity can be as high as 100t/m/h.

In South Africa, approximately 46 coal-washing plants, containing about 200 separators, are in operation; three plants wash iron ore (hematite); and about 15 plants treat diamondiferous material. The iron-ore plants probably contain about 125 wet-drum magnetic separators in all, and the diamond plants about 200.

2.2. DMS for Other Minerals

Wet drum separators of low intensity are also used to recover the medium in DMS plants treating other mineral commodities. Examples of these applications, which are much smaller than those mentioned in Section 2.1, involve the treatment of the tin mineral cassiterite, the refractory mineral andalusite, and the mineral fluorspar.

At the Buffalo Fluorspar Mine, for example, 200t of ore per hour is treated in four heavy-medium cyclones, with ferrosilicon as the medium. A substantial proportion of the gangue is rejected as waste, and the sink product is milled and treated by froth flotation for the recovery of the fluorspar. The economics of the DMS are highly dependent on efficient recovery of the medium, two Sala low-intensity wet drum separators being used in series for this purpose. The operational details available are listed in Table I.

The figures given are typical of the efficiency achieved by other makes of separators in the recovery of the medium.

TABLE I Data for the magnetic separators at the Buffalo Fluorspar Mine

	Primary		Secondary
Type	Sala J188		Sala
Magnetic induction	0,085T		0,085T
Drum diameter, mm	916		916
Drum width, mm	2400		900
Feed capacity, m^3/h	463		73
Medium recovery, t/h	50,8		0,03
Medium loss, t/h		0,035	
Medium recovery, %		99,67	
Medium loss, %		0,07	

2.3. Baddeleyite (ZrO_2)

The ore from the Phalaborwa Complex in the northern Transvaal contains small amounts of the zirconium oxide mineral baddeleyite. Both commercial operations mining this ore, viz the Palabora Mining Company (PMC), which is primarily a producer of copper, and the Phosphate Development Corporation (Foskor), which is primarily a producer of phosphate rock, recover a heavy-mineral concentrate by gravity separation. ZrO_2 is recovered in turn from this concentrate by the reverse separation of ilmenite with dry induced-magnetic roll separators.

At Foskor, the following conditions apply: two parallel line separators are used, and the induction on the surface of the rolls is 1,2T. The capacity of the plant is 1,5 t/h per line, the feed size is 50% smaller than 150µm, and the concentrate size is 50% smaller than 150µm. Typical analyses are given in Table II.

TABLE II Typical analyses at Foskor (percentage by mass)

Material	TiO_2	Fe_2O_3	ZrO_2
Feed	11,06	4,53	75,0
Non-magnetic fraction	0,29	0,06	>98

2.4. Magnetite

Magnetite for use in DMS plants is recovered as a byproduct from the tailings produced by PMC and Foskor at Phalaborwa. At Foskor, Sala low-intensity wet drum separators are used to remove the magnetite from copper-flotation tailings. The feed to the separators is 25 000 t/d, and the circuit consists of 13 concurrent roughers (2,9m long and 0,9m in diameter, with a magnetic induction at the drum surface of 0,14T), 9 cleaners, and 9 recleaners. About 5 to 8 kt of magnetite per day is recovered, representing a 90 per cent recovery at a grade of 56 per cent iron.

2.5. Heavy Minerals from Beach Sands

At the Richards Bay Minerals operation in Zululand, heavy minerals are extracted from beach sands by conventional dredging and gravity concentration. The concentrate, which contains 85 per cent heavy minerals, is passed first through low-intensity wet drum separators to recover the magnetite. The tailings from this first stage are retreated with Readings wet high-intensity separators in a fairly complex rougher-cleaner circuit to produce a concentrate that consists largely of ilmenite containing 46 per cent TiO_2. The non-magnetic tailings from the recovery circuit for ilmenite contain rutile and zircon. After further upgrading by gravity concentration, the rutile and zircon are separated in a complex circuit involving eletrostatic separation, magnetic separation, gravity concentration, and screening.

2.6. Pyrrhotite

At BCL Ltd's nickel mine in the Republic of Botswana, pyrrhotite is recovered from the flotation tailings to enhance the recovery of the nickel. The material treated is a milled pulp (approximately 55% passing 75μm) in which the minerals present are essential pentlandite and pyrrhotite.

Seven machines are operated in parallel: 6-pole high-gradient Eriez Separators with barium ferrite elements. They were designed to treat 40 to 45t of dry feed per hour at 35% solids per unit, but are currently fed at up to 65 t/h. The drum diameter is 1200 mm, and the width 2500 mm.

The design magnetic induction is given in Table III.

TABLE III Design magnetic induction at BCL (tesla)

	At shell surface	25 mm from shell
Centre of pole	0,141	0,105
Centre of gap between poles	0,221	0,123

They are operated with a shell-to-tank gap of 12 mm, and 5 mm lifter bars have been fitted to the shells to assist in recovery.

The nickel recovery is 51%, and the pyrrhotite recovery is more than 95% of that present in the feed.

2.7. Andalusite

Andalusite is a refractory mineral used extensively for the manufacture of high-duty refractory bricks, porcelains, pyrometer tubes, electrical insulators, and spark-plug bodies. South African andalusite contains iron oxides in excess of 2 per cent, which is highly objectionable when used in the above applications, and considerable work has been done to reduce the iron content to acceptable limits. On current World markets, these limits can be as low as 0,5 per cent Fe_2O_3. Since the major portion of the andalusite is used at its natural crystal size, fine grinding and magnetic separation cannot be applied normally, except in special applications, and most of the magnetic-separation procedures are confined to induced-roll types of separators. At the Council for Mineral Technology (Mintek), where much of the process development for andalusite has been carried out, separations were done on a Dings high-intensity 4-pole crossbelt separator.

The separator was operated under optimum conditions, i.e. by the use of sized feeds, single-layer feeds, low feed rates, and maximum field strengths (1,2 to 1,4T). The results obtained under these conditions were regarded as the optimum, and the performance of all other commercial separators was assessed accordingly. On producing plants, however, these types of separators were found to be unsuitable, and at present only two types of separators are used.

At South Africa's leading producer of andalusite, exhaustive tests were carried out on various makes and types of high-intensity separators. The Readings induced-roll separator was found to give the best results and, at present, 3 machines, each with 8 rolls (4 per side giving 4 stages of magnetic separation), treat about 20t of concentrate per hour. The high-intensity separation is preceded by a low-intensity scalping magnet, and the Fe_2O_3 content is reduced from about 2,5 to 0,55 per cent.

A leading manufacturer of refractories has installed a permanent magnet-roll separator (Permroll) to treat andalusite concentrates from various sources, and claims to have achieved markedly lower Fe_2O_3 contents than those obtained by conventional induced-magnetic roll separators. Considerable reductions in operating costs are also claimed, and the machine is particularly effective on crystals in the size range 3 to 10 mm. Tests at Mintek, in which the performance of the crossbelt, a conventional induced roll, and a permanent roll magnet were compared, confirmed the superior performance of the permanent roll separator. The Permroll usually consists of discs of samarium-cobalt in a sandwich-type configuration. Other materials can be used for lower intensities.

2.8. Diamonds

The Diamond Research Laboratory of the De Beers Industrial Diamond

Division is currently engaged in development work on the separation of diamonds from the host rock, Kimberlite. The Kimberlite is strongly paramagnetic, and suitable dry separators can be used to separate it selectively from an upgraded diamond-rich fraction. A suitable machine is a Permroll similar to that used for andalusite, which operates most effectively in the size range 5 to 25 mm.

2.9. Potential for Other Metals and Minerals

At present, iron-ore beneficiation plants do not treat the fine fraction of hematite below 0,5 mm by DMS; instead, it is stockpiled or discarded. An upgraded fraction could well be produced by gravity concentration or wet high-intensity magnetic separation (WHIMS), as is done in Brazil and Australia by the use of Humboldt-Jones separators with a matrix of grooved plates. However, since the down-turn in the iron-ore market, producers probably find little incentive to do so.

The Merensky Reef and the chromitite reefs of the Bushveld Complex have long been major sources of the platinum-group metals (PGM) nickel and copper and of chromium ores for the manufacture of ferrochromium respectively. Recently, one of the chromitite reefs (the UG-2 Reef) was utilized as a source of the PGM[1]. In operations treating chromite ore, particularly ore from the UG-2 Reef, fine chromite is lost to the tailings. Medium- to low-intensity magnetic separation can be used to recover this chromite efficiently, and it is expected that much more extensive use will be made of these techniques in future.

In the past, Mintek carried out tests on the recovery of the PGM from Merensky Reef ore by magnetic separation. The Merensky Reef is low in chromitite (e.g. 0,1% as compared to 30% for the UG-2 Reef). However, in many areas, the use of WHIMS can yield high mass recoveries, since much of the gangue mineral present, e.g. o-pyroxene, is strongly paramagnetic. The problem is usually one of poor selectivity, except at certain localities where the mineralogical composition of the ore is different and better grades of the PGM can be obtained in the concentrates. It is believed that the use of magnetic separation for the recovery of the PGM from Merensky Reef ore has not been fully optimized.

During the acid leaching of uranium from its minerals in ore from the Witwatersrand reefs, the addition of an oxidant is necessary to oxidize the U^{4+} to U^{6+}. Much fine metallic iron from the milling stage can be present in the pulp (i.e. from mill liners, rods, or balls) and, being a reducing agent, consumes the oxidizing agent. Mintek has shown that the use of magnetic separation can remove much of this iron prior to leaching. However, the ready availability of cheap MnO_2 as an oxidant has mitigated against the implementation of this procedure.

Another extremely interesting concept proposed by Levin(2) is the use of magnetic separation to purify calcined leach residues. On many Witwatersrand gold mines, pyrite (with a gold content up to 5 μg/g) is recovered by flotation. The pyrite is roasted (so that sulphuric acid can be produced from the gases), and the calcine, essentially Fe_2O_3, is leached with cyanide to recover the gold. The leach residues can have a gold content between 0,5 and 15 μg/g. (This occurs on some non-Witwatersrand mines treating refractory ores.) The residual Fe_2O_3 that contains gold can be separated from other impurities such as quartz, and used as a feed material to produce steel grinding balls on the gold mines. Thus, the gold content is ultimately recycled and recovered.

3. MANUFACTURE OF MAGNETIC SEPARATORS

Several companies market and manufacture magnetic-separation equipment in South Africa, e.g. Bateman Equipment, Eriez, Magnapower (Boxmag Rapid), Mechanimag, Polaris (Sala), Readings, and so on. The largest volume of equipment sold consists of wet or dry drum-type separators. To some extent, all the manufacturers carry out programmes of continual design improvements. Some of the best-known are discussed below.

3.1. Bateman Equipment

This South African company has done much development work on separation technology using permanent magnets. The so-called 'Permroll', constructed of discs of samarium-cobalt with a very high energy product, is an example. Barium ferrite magnets are used in specific applications, and the new magnetic alloy, 'neodymium-iron-boron', will soon be introduced to bring the power of the Permroll close to a magnetic induction of 3,0T.

The rolls were initially 62 mm in diameter. Currently, most commercial operations use rolls of 71 mm diameter, but rolls of 100 mm diameter are also available. Magnetic induction (using samarium-cobalt) has been increased from 1,4 to 1,7T on the larger rolls. The roll of large diameter also yields substantially better results on difficult separations owing to the increased residence time of particles on the roll.

This company is currently involved in extensive development work to devise magnetic rolls specifically for individual applications concerned with materials of varying magnetic susceptibility from ferro-magnetic to weakly paramagnetic. Particles up to 30 mm can be treated, and high-capacity applications are being developed. The roll is constructed of alternate discs of magnetic materials, like samarium-cobalt and iron. The ratio of disc widths has a pronounced effect on the efficiency of separation and on the throughput.

In Table IV, the results are shown of some tests at Mintek in which a Permroll was used to upgrade an andalusite concentrate.

TABLE IV Dry high-intensity magnetic separation of an andalusite concentrate (same feed on both separators)

Separator	Product	Grade	
		Al_2O_3, %	Fe_2O_3, %
Crossbelt	Feed	56,2	2,58
	Non-magnetic fraction	57,4	1,03
Permroll	Feed	56,2	2,58
	Non-magnetic fraction	59,6	0,71

3.2. Eriez S.A.

This company, being a subsidiary of Eriez U.S.A., obtains most of its technological input from overseas. Nevertheless, it is traditionally a major supplier of a wide range of magnetic equipment.

Two Eriez WHIMS machines were installed in South Africa about 5 years ago[3,4], one of which is operating at the Buffalo Fluorspar Mine, where it is removing monazite impurities from a fluorspar concentrate. The other machine was installed as a prototype to recover gold and uranium from a gold-mine residue. The operation of the latter machine is described more fully in Section 4.

3.3. Polaris (Sala)

Polaris is a major supplier and manufacturer of Sala wet drum separators for the local industry. Most of these machines are used for the recovery of the medium on DMS plants. Originally, Sala machines were designed for the upgrading of iron ores in Sweden and were, in effect, somewhat overdesigned for the lighter duty required on a DMS plant. For economic reasons, Sala therefore now offers a light-duty model that is specifically designed for medium recovery. Most of the modifications consist of reduction in the amount of rubber lining and a simplified magnet system.

Sala also offers large units of 1200 mm diameter, and over 70 of these are operating locally. These machines have a relatively high capacity and produce good metallurgical results. A local innovation is the feeding arrangement of the 'top-fed wet magnetic separator'. As the name implies, the unit is fed near the top of the drum, and the material is subjected to many magnetic reversals over an arc of 250^{o} on the drum surface. This machine gives more than twice the number of reversals given by many other separators, and has two major advantages, as follows.

(i) The particles, assisted by gravity, are introduced directly into the magnetic field instead of being lifted upwards against gravity in a swift-flowing pulp stream. In effect, the mechanism resembles separation in an inclined magnetic chute like that used in a laboratory.

(ii) The fact that the particles are subjected to many more reversals ensures that the non-magnetic fraction has a far greater chance of being washed out; therefore, entrainment is reduced and the grades of the magnetic concentrates are improved.

4. RESEARCH AND DEVELOPMENT

It would be wrong for us to imply that all aspects of research and development taking place in this field in South Africa are covered in this paper. However, we shall discuss the two areas we know best: the work being done by Mintek in the field of WHIMS and wet high-gradient magnetic separation (HGMS), and by Foskor and its associates in high-intensity magnetic separation (HIMS) and HGMS (dry).

4.1. Mintek

During the late 1940s when a surge of activity related to the recovery of uranium from Witwatersrand ores occurred, Levin of Mintek was able to show that much uranium (and gold) could be recovered by magnetic separation[5]. At the time, the equipment available for magnetic separation was limited to an induced-magnetic roll. Therefore, the separation was done dry and was efficient only at relatively coarse grain sizes, i.e. above 100μm. With the advent of WHIMS machines in the 1950s, it became possible for magnetic separation to be applied to the recovery of uranium and gold at grain sizes down to 20μm or less. In 1967 an Eriez laboratory-batch WHIMS machine was acquired by Mintek, to be followed two years later by a small continuous Carpco carousel-type WHIMS machine. Extensive testwork was done with these machines in investigations on the recovery of gold and uranium from a large number of Witwatersrand ores, tailings, and old deposited residues (i.e. tailings dams). The results varied substantially according to the mineralogical compositions of the materials but, in the majority of cases, it was found that about 60% of the uranium and 50% of the gold could be recovered into a small mass of concentrate, varying between 4% and 12%[6].

The conditions for magnetic separation were optimized eventually and found to be a magnetic induction of 0,8 to 1,0T, with a matrix of steel balls of 4,0 to 6,0 mm diameter. Pulp velocities of up to 15 cm/s could be used to maximize throughput, and pulp densities of up to 40% solids by mass were suitable for pulps from Witwatersrand mines, which are typically 80% passing 75μm.

In the initial phase of that work, the main economic significance of the recovery by magnetic separation of those values was seen in terms of the uranium. Although, at first sight, the recovery of 60% U_3O_8 may be considered low, it must be remembered that uranium is a byproduct of the gold mines, and is recovered from tailings. The uranium grades in gold tailings vary considerably, typically between 40 and 800 μg/g. The higher grades are economically recoverable by acid leaching, but the lower grades are not. Using WHIMS, one could upgrade a tailing of sub-economic grade in terms of its uranium value and economically produce a concentrate from which U_3O_8 could be recovered by acid leaching. Clearly, in times when the demand for and the price of uranium are buoyant, this becomes an attractive proposition.

Therefore, with the recovery of uranium as its main motivation, Mintek acquired an Eriez carousel WHIMS machine of 1 t/h to carry out pilot-scale tests on site so that further operating data could be acquired for purposes of costing and engineering design. The machine was designed to operate under conditions of magnetic induction and gradient similar to those established as the optimum in the batch tests. The first continuous tests were done in 1975 at the Blyvooruitzicht Gold Mine on cyanidation tailings. These tests were initially completely disastrous since, within 2 hours, the matrix of iron balls became completely blocked with stray ferromagnetic material in which fine wood fibres or chips were intimately entrapped.

A long period of soul-searching and innovation then followed, during which a solution to the blockage problem was sought. Fine screening to remove the wood fibre, and low-intensity scalping magnets to separate the barren ferromagnetic material, were introduced. This complicated the circuit and obviously increased the costs, but eventually 7 days of operation of the magnet could be obtained prior to serious blockage. At that point a shut-down became necessary so that the matrix could be cleaned out. The conclusions were clear: it was not possible for matrix blockage to be eliminated entirely by reasonable preparation of the feed. The mining industry was understandably very much opposed to the implementation of operating machines that needed to be shut down every 7 days (or even every 14 days, for that matter) and subjected to a messy, labour-intensive cleaning-out operation that could last for several hours.

The problem was intensified by the fact that second-generation WHIMS machines like the Eriez model, which have an iron-yoke magnetic circuit, are limited to the width of matrix they can utilize effectively. Since the lines of magnetic flux traverse the matrix in a horizontal direction between two iron pole pieces (the yoke), horizontal widths of more than about 150 mm are not feasible without a substantial loss of field intensity or large increases in operating energy, or both. This limits each pole pair to a capacity of 15t of dry solids of Witwatersrand ore per hour. A practical machine with a matrix width of 150 mm and two pole pairs therefore has a capacity of 30 t/h[4]. Typically, any gold mine treating 300t of feed per hour would need at least 10 individual double-pole machines to handle its throughput. A strong argument against the implementation of this technology was that 10 machines would have to be cleaned out about once a week.

To make matters worse, the metallurgical efficiency of the machine would decrease steadily as the blockage built up progressively over the 7 days or so.

At that time (1977) Mintek was therefore faced with a most frustrating dilemma. The uranium market was flourishing and Mintek had at its disposal a most economically attractive magnetic-separation technology to enhance the recovery of that product. The only stumbling block was mechanical: that of matrix blockage. For this reason, a system was developed and patented in which the balls were removed continuously from the matrix, cleaned continuously in an external circuit, and returned to the machine[7]. The system is represented schematically in Fig. 1. The method was developed and tested as rapidly as possible and, in 1979, a full-size CF-60 WHIMS machine (30 t/h) with a Mintek belt-cleaning system was installed as a prototype at the Stilfontein Gold Mine. (A second, identical machine was installed at the Buffalo Fluorspar Mine to remove a magnetic monazite impurity from the fluorspar concentrates.)

The machine on the gold mine ran for over 3 years and recovered gold and uranium from the cyanidation tailings. The concentrates were treated at an adjacent uranium plant. During its period of operation, the performance of the machine was carefully monitored by mine staff and Mintek personnel. The results of this work were recently published[4]. Essentially, the machine ran successfully mechanically and metallurgically, uranium recoveries of 55% and gold recoveries of 50% being obtained, which matched the predicted performance.

It was realized that, at best, the ball-cleaning system could be regarded only as an interim measure to advance the concept that WHIMS could be used in the recovery of gold and uranium. Clearly,

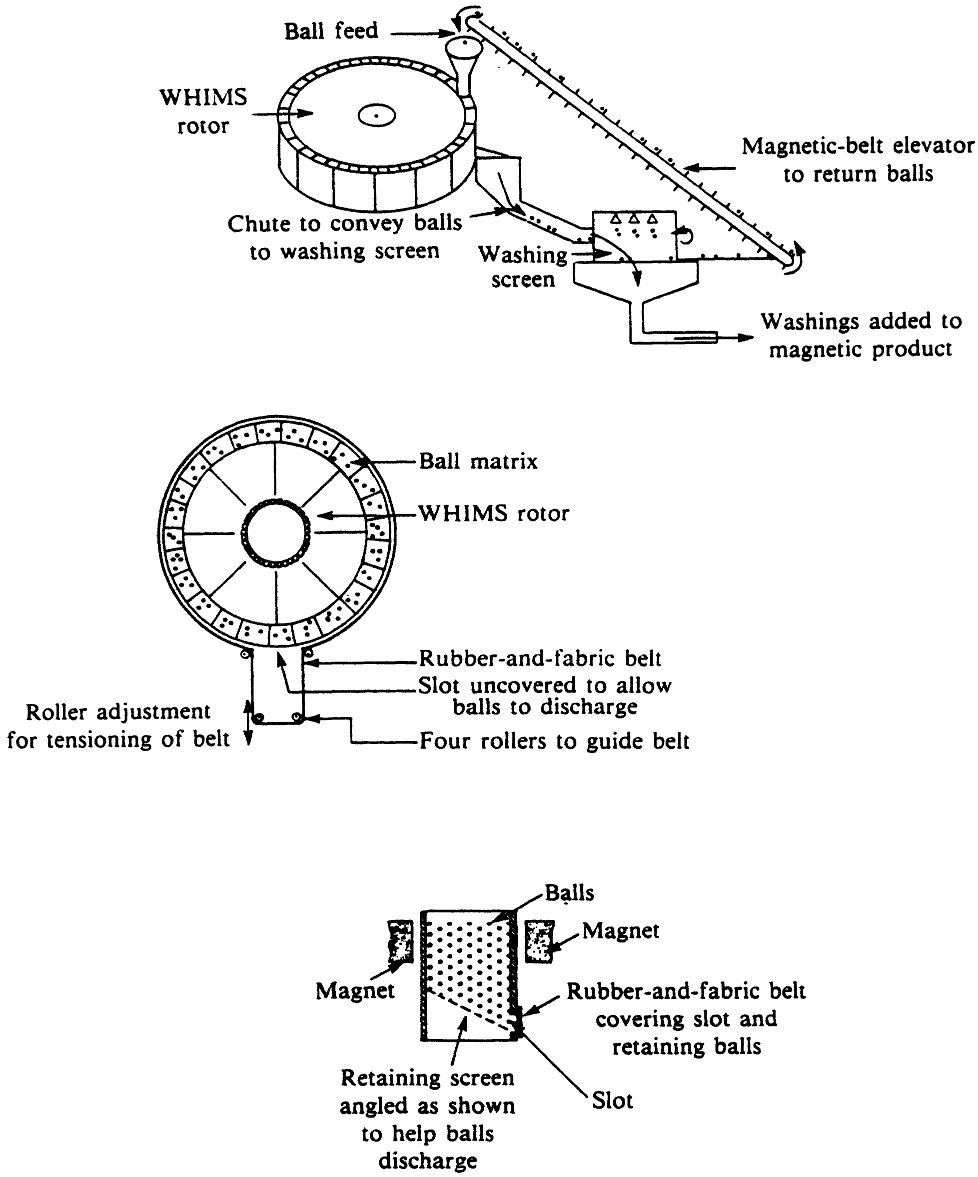


FIGURE 1 Schematic representation of Mintek matrix-cleaning system

the longer-term solution to the problem would be found in the use of third-generation machines, which use solenoid-type coils instead of iron yokes. Sala had already developed this concept to a fairly advanced stage in their HGMS carousel machines, in which the matrix width can be increased substantially with little increase in power. Hence, a smaller number of large-capacity machines can be used to treat large tonnages, thus increasing the cost-effectiveness of the technique. Unfortunately, for a variety of reasons, Sala machines are unobtainable for local testwork in a mining environment. The answers to many questions besides the metallurgical performance obtainable under laboratory conditions need to be established before a magnetic separator, particularly a WHIMS machine, can be considered acceptable for long-term industrial use. In fact, it is our opinion that, in most instances, very specific modifications of the electromechanical design are needed to fully optimize its performance, both metallurgical and mechanical, in this particular application. Manufacturers would be naive to think that a machine developed, say, for an iron-ore application, can provide the solution to all magnetic-separation problems, let alone those encountered in the recovery of gold and uranium.

Feed rates, matrix design, field strength, etc., all need to be fully explored and optimized. As useful tools for the predictive analysis of performance, current mathematical models fall far short, and no substitute has been found for comprehensive empirical testwork. It is considered that, just as reagent recipes have to be optimized in flotation, the electro-mechanical parameters need to be developed in magnetic separation. For these reasons Mintek, through force of circumstance, became involved in the development of a WHIMS machine designed specifically to treat gold tailings.

However, before this development is described in detail, a brief return to the developments affecting the recovery of uranium is relevant.

The uranium market has declined dramatically over the past few years, and therefore, naturally enough, the original motivation for the use of WHIMS to recover additional quantities of this commodity started to wear a bit thin. However, the recovery of gold became steadily more attractive as the recovery of its partner tended to become less desirable.

It took Mintek a while to appreciate the significance of the magnetic recovery of gold, since it is not easily understood at first. Unlike uranium, gold can hardly be considered a byproduct of a gold mine; hence, how can a process that recovers a mere 50% or, at best, 60% of the gold either in the feed or in the tailings, be of any interest? In many instances, fine grinding and cyanidation will recover close to 99% of the gold. What is more, gravity concentration or flotation, which are well-established and accepted techniques, can also recover 50% of the gold in Witwatersrand tailings. For clarification, the mineralogical composition of the magnetic concentrates must be examined. It is beyond the scope of this paper to present anything but a highly simplified version of this aspect, since the mineralogy of the Witwatersrand reef is rather complex[8]. However, simply stated, the magnetic concentrates consist very largely of the silicate minerals quartz and chlorite. Associated with these minerals and locked inside them are heavy-metal oxides of titanium, thorium, and uranium (e.g. uraninite). The magnetic susceptibility of these concentrates was measured and they were found to be strongly paramagnetic[9]. Therefore, the magnetic properties of the concentrates must be due almost entirely to their content of the strongly magnetic heavy-metal oxides. It is clear that the uranium and gold recovered by magnetic forces are selectively associated with the heavy-metal oxides.

Gold that occurs in the tailings from cyanidation plants occurs basically in three forms, as follows:

(a) gold soluble in cyanide, which can be free (metallic) gold that has not had sufficient time to dissolve, or dissolved gold that has formed complexes and has been readsorbed onto minerals like shale,

(b) gold that is locked in silicate minerals and has not been exposed to the dissolving action of the cyanide, and

(c) gold locked in sulphide minerals, mainly pyrite.

Sulphide flotation will clearly concentrate gold of type (c), whereas WHIMS recovers gold of type (b), which has been rendered magnetically susceptible (as described previously) by its selective association with heavy-metal oxides. For the dissolution of type (b) gold in cyanide, fine-grinding of the magnetic concentrates prior to leaching is necessary. In theory, one could fine-grind the whole tailings, but this is economically unthinkable. Therefore, the virtue of WHIMS is that it recovers a specific type of gold left in the tailings into a small (5%) mass of concentrate, which can then be intensively milled and cyanided.

What is more, it is clear that the type of gold recovered by magnetic separation is different from that recovered by flotation; hence, magnetic separation complements flotation. (The recovery of pyrite by WHIMS from Witwatersrand ore is poor.)

Several large retreatment operations are currently recovering gold of type (c) from tailings by sulphide flotation. Mintek has been able to demonstrate that the flotation tailings can still be treated economically by WHIMS to recover additional gold of type (b)[9]; for this, measurement of the performance of the prototype WHIMS machine at Stilfontein Gold Mine was crucial. There, over a 12-month period, the operating costs were measured at 30 cents per ton of material treated. At a large retreatment operation such as that of ERGO, where 1,5 Mt of old residues per month are treated, even a recovery of 0,08g of gold per ton by WHIMS is an attractive proposition if the operating costs are low. At ERGO, the feed to WHIMS is deslimed at 15μm in cyclones prior to separation. The economics of gold recovery are shown in Table V.

TABLE V The economics of gold recovery by WHIMS at ERGO

Unit operation	Treated feed % by mass	Cost of treatment c/t	Cost based on feed to cyclones c/t
Desliming	100	30	30
WHIMS	50	30	15
Milling	5	250	13

Total cost	58 c/t
Income from 0,08g of gold per ton at R15 per gram	120 c/t
Expected revenue	62 c/t

In most instances, the magnetic recovery of gold exceeds 0,08 g/t, and can be as high as 1 g/t or higher. Therefore, considerable interest is being shown in the use of WHIMS in retreatment operations. However, the big drawback so far has been the unavailability of a suitable machine. The Eriez CF-60 tested at Stilfontein has a capacity of 30 t/h and cost about R300 000,00 in 1977. ERGO would require about 85 of these machines for their operation, which would be unacceptable in terms of capital costs, maintenance, feed distribution, pumping, etc.

A novel type of separator was designed and constructed at Mintek to meet the requirements of an ideal machine for the recovery of gold. This separator was recently patented[10]. For a machine to be ideal, several criteria must be met, as follows.

(1) It should be of large capacity. We consider that a single machine capable of treating between 200 and 250 t/h is required, with a maximum of 4 feed stations, i.e. 4 magnetic heads with a capacity of 50 t/h. This needs a matrix of 1m width that can be used only with iron-clad solenoid magnets to generate the field.

(2) The machine should be reasonably priced. Our economic esti-

mates indicate that a capital cost of up to R3000,00 per ton of installed capacity would be acceptable. A machine of 250 t/h would therefore cost approximately R750 000,00. So that this requirement can be met, the coils must be of fairly simple design, and the main structure must be reasonably conventional.

(3) The problem of matrix blockage must be recognized. Ideally, the separator should be designed to incorporate a washing system that will prevent the build-up of material in the matrix. The Mintek system of a belt covering a slot at the bottom of the annular space holding the matrix was adapted with great difficulty to a matrix width of 150 mm. It would not function at all with a matrix of 1m width. Clearly, a completely different system was needed. It was decided that the best solution would be for the matrix to be inverted, and for the design to move away from a horizontal carousel type. Most of the material blocking the matrix is trapped near the top, since this is where it enters under the influence of gravity. In the flushing of a conventional carousel, one has to transport this material down through the matrix bed using water, or employ a complicated back-flushing system. This is obviously a difficult task, since the matrix hinders the flow. If one were to invert the matrix, a reverse flush would be very simple, and the material would virtually fall off the top. With a loose matrix of balls, the balls would simply tumble out and could be cleaned externally as they are in the Mintek washing system.

The matrix chosen eventually for use in the new machine consists of rectangular sections of woven screen, each wire being 1,6 mm in diameter, and the mesh being of 5 mm square. The screen is made of a magnetic stainless steel. Batch tests have shown that this matrix gives results similar to those obtained with 6 mm balls. Furthermore, the filling factor of such a matrix is about 20% compared to 55% with a ball matrix, which reduces the mass of the structure and facilitates the flushing of the matrix. The true flow velocity is also reduced, and, as a result, the probability of particle capture is increased.

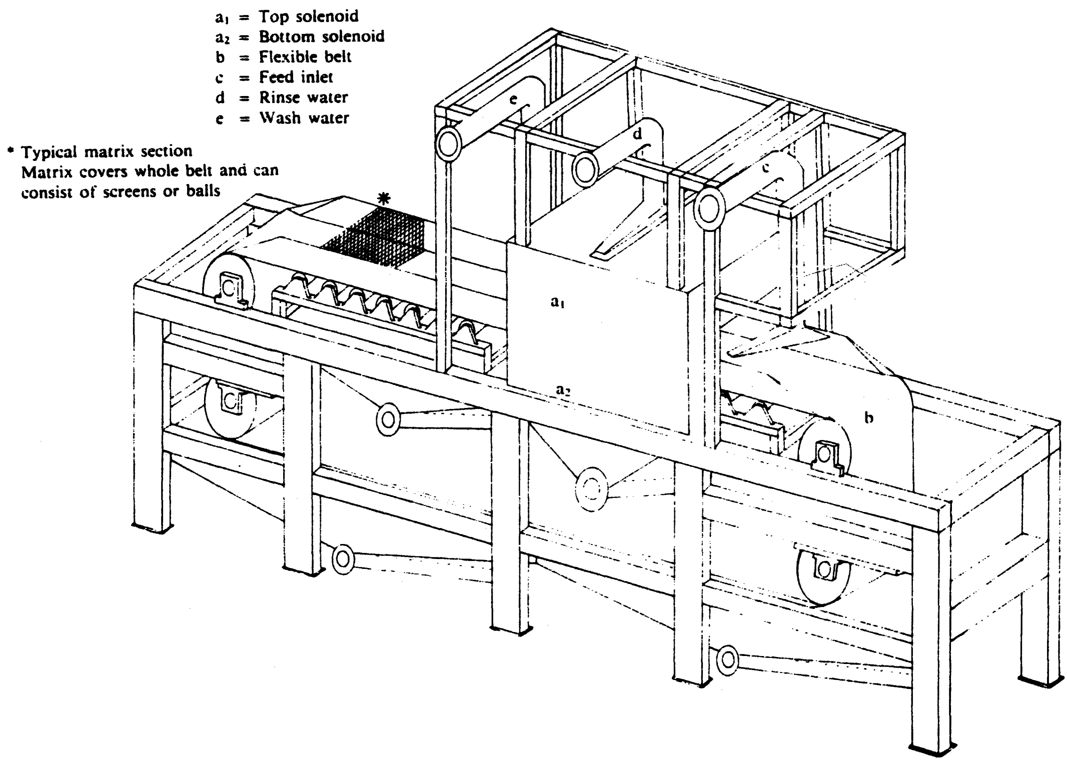


FIGURE 2 Mintek linear magnetic separator

The final design of the first prototype machine constructed is shown in Fig. 2. The matrix is 500 mm wide and 200 mm high; each rectangular piece of screen is cut to this size and held inclined with close packing against the adjacent matrix elements by polyurethane strips moulded to the outer corners. Thus, the matrix is constructed into casettes each 500 mm long. The casettes are bolted onto a flexible stainless-steel belt of honey-comb design that moves linearly in a horizontal direction and inverts back on itself by means of pulleys and idlers. Two sprocket wheels are used to drive the belt.

A magnetic induction of 1,2T is developed by the use of two flat pancake horizontal coils (one above the belt and another below the belt) clad with steel. The internal dimensions of these rectangular coils are 500 mm by 500 mm. The conductor is of hollow copper and is water-cooled. The number of ampere turns needed to generate a required magnetic field is determined solely by the distance between the coils, and therefore by the matrix height. A scaled-up machine would require the same number of ampere turns, and the input power would increase only because of the greater length of the conductor.

As the belt moves round the pulleys, the matrix elements flare out and facilitate the removal of ferromagnetic material.

The prototype has a capacity of 30 t/h and cost Mintek approximately R100 000,00 to build. We estimate that the construction of a similar machine with a matrix of 1000 mm width and 4 feed stations (giving 240 t/h) would cost R600 000,00.

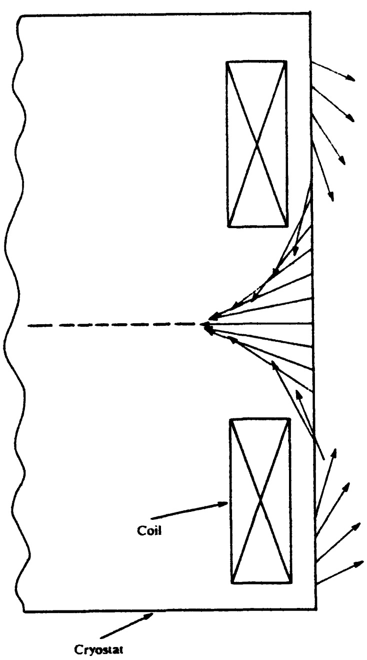
The machine is currently being commissioned, and further production units could be built within the next year.

Basic Research

Basic research is concentrated on studies of the applicability of the theoretical models of HGMS to practical problems. The agreement between theory and experiment is usually good in simple cases of magnetic filtration to remove magnetic impurities or unwanted magnetic components with high efficiency. In more complex instances, for example in the magnetic separation of valuable mineral components from a mixture of finely dispersed minerals, the theoretical models usually fail. These models are incapable of giving a description of the performance of a separator as a function of particle size, matrix size, magnetic induction, viscosity of a slurry, or saturation magnetization of a matrix, and do not include a description of the cooperative phenomena, so important in the separation of dense slurries. The theoretical description of such a process is much more complicated, and requires, besides a high probability of particle capture (and therefore high recovery), a high degree of selectivity so that the grade of the concentrate will be acceptably high. Different rules apply to the beneficiation of minerals by magnetic separation and by magnetic filtration, and a comprehensive research effort is needed with much closer cooperation between industry and academic circles.

SUPERCONDUCTING MAGNET

During 1983, Mintek acquired a superconducting magnet constructed by Cryogenic Consultants Limited (CCL) of London. This is a cylindrical quadrupole machine of 365 mm diameter, which gives a magnetic induction of 3,2T at the surface (Fig. 3). The machine has been described by Cohen and Good[11]. The Mintek machine had originally been purchased by the Anglo American Research Laboratories but, after some initial testwork, they sold the unit to Mintek.



Vectors of magnetic induction on the surface of a cryostat. The absolute values of magnetic induction are a function of the current in the windings

FIGURE 3. Vertical section through the cylindrical superconducting magnet

At Mintek great difficulty was experienced in attempts to run the machine long enough for significant testwork to be carried out. The chief problem was experienced with the refrigeration system, which recycles liquid helium to the cryostat. In our opinion it would be far better for research machines to use liquid helium on a consumable basis.

Very few results have been obtained so far, but an attempt is being made to understand, in simple terms, the interaction of the various parameters affecting the wet magnetic separation of materials in the so-called open-gradient mode. It does seem that a major problem will be the adherence of strongly magnetic material to the surface of the magnet, and some type of mechanical system may be needed to remove this material. In a way this problem is analogous to that experienced with blockage in the Mintek matrix machines.

The machine has the potential of high throughputs and could provide a means for the highly economical separation of impurities in effluents or be used as a roughing stage in a two-stage circuit where cleaning is done on more conventional machines.

4.2. The Phosphate Development Corporation (Foskor)

Foskor extracts rock phosphate (apatite) from the Phalaborwa Igneous Complex in the northern Transvaal. Currently, the apatite is concentrated by grinding and fatty-acid flotation. In future years, Foskor will exploit other areas of the orebody, where the apatite occurs in a pyroxenite gangue rock. The apatite can be separated from the pyroxenite by dry high-intensity magnetic separation (DHIMS). Roux *et al* recently published details of the methods tested at Foskor[12].

Essentially, the apatite is diamagnetic, whereas the minerals of the pyroxenite rock vary from weakly paramagnetic (in the case of one type of pyroxene) to strongly paramagnetic. Liberation of the apatite from the pyroxenite occurs at relatively coarse sizes (up to 500μm) which are ideally suited to dry separation. The proposed dry process would have numerous cost advantages over the wet system used at present. Water consumption, which is a major consideration, would be greatly reduced, and the cost of flotation reagents would be eliminated.

Foskor has carried out an extensive programme of testwork with equipment, e.g. a Franz Isodynamic Separator; induced-magnetic rolls of various manufacture; Permrolls; matrix carousel separators; and a CCL superconducting magnet similar to that owned by Mintek. In many ways Foskor face the same problem that Mintek has encountered in its work on the recovery of gold and uranium, i.e. each possesses a technology that is metallurgically ideally suited to the process, but the currently available equipment is uneconomic, being too small in capacity, too costly, etc.

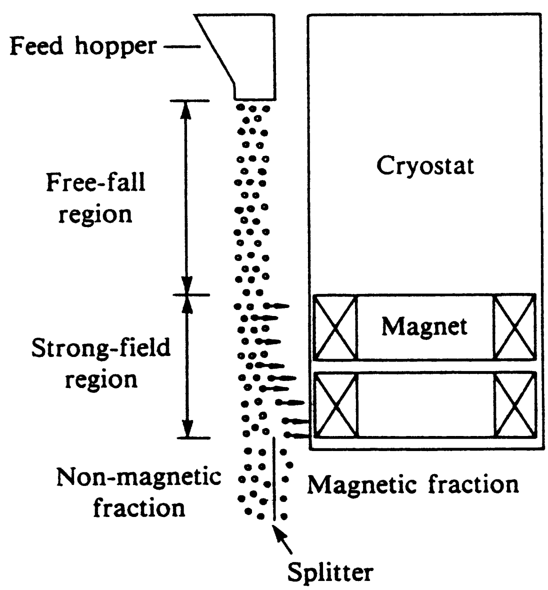


FIGURE 4. Schematic representation of dry falling-curtain separation by use of a superconducting magnet

For this reason, Foskor has undertaken and sponsored the development of equipment suited to its own needs. Much effort has been expended on the utilization of a superconducting magnet in open-gradient configuration, and tests on the CCL laboratory model were fairly successful. The dry mineral grains are run in a falling curtain past the region of high magnetic intensity where deflection of the magnetic material occurs[12]. This is illustrated in Fig. 4. J. Kopp of the University of the Witwatersrand has been working closely with Foskor, and has produced a useful model of the dry falling-curtain separation process[13]. Potentially, the cryogenic magnet can be scaled up to large size to produce highly cost-effective separators to meet Foskor's requirements. CCL is currently completing the construction of a linear magnet 3m in length that can be fed from two sides to give a throughput of approximately 60 t/h.

Good results have also been obtained with a matrix machine operating in a dry mode with pneumatic conveyance of the feed and the products. It is understood that the field strength and matrix design have not been fully optimized as yet, and it is possible that the new Mintek machine could be adapted for dry use in this context.

ACKNOWLEDGEMENTS

This paper is published by permission of the Council for Mineral Technology.

The assistance of the following companies is much appreciated:

Phosphate Development Corporation
De Beers Industrial Diamond Division
Polaris
Eriez
Bateman Equipment
BCL Ltd, Botswana
Anglo American Corporation (Coal and Gold Divisions)
Mitchell Cotts Projects
Samancor (Buffalo Fluorspar.
General Mining Union Corporation)

REFERENCES

1. I.J. CORRANS, *et al.* The recovery of platinum-group metals from ore of the UG-2 Reef in the Bushveld Complex. *PROCEEDINGS, TWELFTH CONGRESS OF THE COUNCIL OF MINING AND METALLURGICAL INSTITUTIONS. Glen, H.W. (ed.).* Johannesburg, The South African Institute of Mining and Metallurgy, 2, 629 (1982).
2. J. LEVIN. Council for Mineral Technology, *Personal Communication* (1984).
3. I.J. CORRANS. A development in the application of wet high-intensity magnetic separation. *FINE PARTICLES PROCESSING. Somasundaran, P. (ed.).* New York, American Institute of Mining, Metallurgical and Petroleum Engineers Inc., 2, 1294 (1980).
4. I.J. CORRANS, *et al. J. S.Afr. Inst. Min. Metall.*, 84, 57 (1984).
5. J. LEVIN. *J. S.Afr. Inst. Min. Metall.*, 57, 209 (1956/57).
6. I.J. CORRANS and J. LEVIN. *J. S.Afr. Inst. Min. Metall.*, 79, 210 (1979).
7. I.J. CORRANS. Relating to magnetic separators. *S.A. Pat. 78/1467* (1978).
8. C.E. FEATHER and G.M. KOEN. *Miner. Sci. Eng.*, 7, 189 (1979).
9. I.J. CORRANS and R.C. DUNNE. Optimization of the recovery of gold and uranium from Witwatersrand residues. To be presented at *XVth INTERNATIONAL MINERAL PROCESSING CONGRESS, Cannes, France*, June 1985. (To be published.)
10. I.J. CORRANS and J. SVOBODA. Magnetic separator. *S.A. Pat. 83/3323* (1983).
11. H.E. COHEN and J.D. GOOD. Principles, design and performance of a superconducting magnet system for mineral separation in magnetic fields of high strength. *XIth INTERNATIONAL MINERAL PROCESSING CONGRESS, Instituto di Arte Mineraria, Rome, Aziende Tipografiche Bardi*, 777 (1976).
12. E.H. ROUX, *et al.* Industrial scale dry beneficiation of phosphate-bearing pyroxenite ore. Paper presented at *MINTEK 50*, Sandton (1984). (To be published.)
13. J. KOPP. *Int. J. Miner. Process.*, 10, 297 (1983).